An Investigation of Olfactory Display Technology for the enhancement of Presence within Virtual Reality Experiences

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Declaration

I hereby declare that the work presented in this thesis has not been submitted for any other degree or professional qualification, and that it is the result of my own independent work.

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Abstract

This thesis examines the impact the inclusion of olfactory stimulus has on virtual reality (VR) for the enhancement of presence. To achieve this, a comprehensive review of past literature was undertaken. This review examines several relevant topics including the physiological process of perceiving scent, the concept of presence, and a discussion of past attempts to integrate olfactory stimulus with VR and visual media. This culminates in the presentation of a series of design heuristics for designing VR experiences that might implement olfaction.

These heuristics provide the foundation for a systematic review into olfactory display technology. The review included 34 studies and examined the technology used as well as the impact on the sense of presence. The investigation has shown that many devices are custom-made by researchers to fit the requirements of their studies. A major knowledge gap that was revealed from this review was the distinct lack of a detailed method in which the olfactory display device might receive its queue to release scent stimulus electronically from interactions within the VR environment.

A prototype olfactory display device is then presented. The proposed design drew on the most common methods found in the systematic review, with the aim of providing an accessible and low-cost method of creating an olfactory display device. The device was then evaluated against selected design heuristics to analyse functionality. It was also used to examine the impact that the inclusion of scent has on presence. This was explored through the use of items adapted from the Temple Presence Inventory (Lombard et al., 2009), a Think-Aloud protocol and series of open-ended questions. The device and its integration into the VR environment functioned as intended and appeared to afford a sense of presence in a small sample of participants. A discussion of the project successes, limitations and avenues for future research is then provided.

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Chapter 1: Introduction

1.1 Background

The use of Virtual Reality (VR) has become commonplace within the gaming and digital entertainment industries. The technology is becoming readily available and affordable. A heightened sense of presence when compared to traditional screen-based media is often claimed to be the driving factor in the appeal of VR technology (Rubin, 2018).

Most commercial VR experiences as designed currently stimulate the visual, auditory, and haptic senses. New input methods within VR attempt to bridge the disconnection between the user and the virtual world which they are experiencing have been developed. For example, the most modern VR devices such as HTC Vive (HTC, 2016), Oculus Rift (Facebook Technologies LLC, 2014), Valve Index (Valve Corporation, 2019) etc., make use of two motion controllers to allow users to implement input similar to that of their own hands.

This sense of feeling present within a game environment, however, currently only stimulates the player's visual, auditory, and haptic senses. A largely unexplored method of providing users with feedback within a gaming environment is olfaction (Olofsson et al., 2017). Olfaction in humans is defined as the sensation of smell derived from the detection of aerosolised odorous substances in the olfactory epithelium in the nasal cavity (Wooten, 2015).

Whilst this integration of scent and media is not an entirely new area of research, many past attempts have often been disregarded as novelties without any real practical application (Olofsson et al., 2017). In recent years, a number of commercial prototype devices have been proposed and developed that aim to integrate VR and scent such as the Feel Real VR (*FEELREAL VR Mask*, 2019) mask and the Cilia VR Development Kit (*Cilia Developer Kit (Smell Device) — HAPTIC SOLUTIONS — HAPTIC SOLUTIONS*, 2019). These are not widely available at the time of writing, but this demonstrates that whilst olfaction's use alongside screen-based media has often been dismissed in the past, there is an ongoing fascination with utilising scent as a feedback stimulus in VR.

It may be that olfactory stimulus, when effectively integrated with VR might offer a richer, more perceptually immersive experience. This may have potential applications in VR gaming and entertainment experiences but also to enhance the player's sense of presence and connection to the virtual environment.

In a number of studies that utilise scent for VR, there is a large range of differing types of scent display devices as well as reasons for including olfaction alongside VR. Devices range from the use of off the shelf candle diffusers (Serrano et al., 2016) to advanced air loops installed into laboratories that allow for near synchronous release of scent with visual stimulus (Ischer et al., 2014). VR environments also appear to have applications beyond entertainment and gaming. It was reported that olfaction within VR might have positive benefits for treating sufferers of post-traumatic stress disorder (Aiken & Berry, 2015) whilst another study examined the integration of scent alongside a cooking game to enhance presence (Nakamoto et al., 2008). It is clear that this variability in scent display devices, purpose for inclusion of scent stimulus and design of VR experiences demonstrates a technology that is still in its infancy but with a range of potential benefits and avenues for future research.

1.2 Aims and Objectives

The primary aim of this thesis is to examine how olfactory display technology might be used to enhance presence within virtual reality. In order to address this aim, the following research questions are posed:

> **RQ1:** To what extent does the inclusion of olfactory stimulus impact an individual's sense of presence within VR?
>
> **RQ2:** How is olfactory display technology currently used alongside VR?
>
> **RQ3:** How can readily available components be used to develop an olfactory display device suitable for use with VR?

To begin to answer these questions, several objectives were identified:

- A review of existing literature on topics relating to olfaction, presence and virtual reality was undertaken to gain insight into the underlying principals useful for developing scent display technology. This was used to present a series of preliminary design heuristics useful for olfactory implementation within VR. This provided insight to begin to answer RQ1 and 2.
- The presentation of a systematic review of scent display technology with potential uses alongside Virtual Reality, identifying a categorisation model from the findings of the literature review. This addressed RQ1 and 2.
- A low cost and accessible prototype scent display device was designed and developed based upon the findings of both the literature review and the systematic review. This objective aimed to address RQ2 and 3.

- An evaluation of the prototype device was undertaken, exploring its potential to impact sense of presence through the use of the Temple Presence Inventory (Lombard et al., 2009), a Think-Aloud Protocol and series of open-ended qualitative questions. This addressed RQ1 and 3.

1.3 Thesis structure

This thesis is structured into the following chapters:

Chapter 2 comprises of a comprehensive literature review surrounding current understandings of olfaction, presence, and virtual reality. Brewster, McGookin & Miller (2006) argue that our understanding of olfaction is much less than that of vision and audition. This makes designing interfaces and technology much more difficult. It is therefore important that the literature review explore a range of areas associated with olfaction including the physiological processes involved in perceiving scents, attempts to categorise, and measure scent as well as an analysis of past attempts to augment visual media and virtual reality with olfactory stimulus. An analysis of these studies along with the findings from previous literature form the foundations of a series of potential heuristics for augmenting VR experiences using olfactory display devices.

Chapter 3 of this thesis presents a methodology for examining the expanding scent display technology. This was carried out through a comprehensive systematic review of current scent display technology used throughout several virtual reality studies. The design heuristics presented in the prior literature formed the basis of the search criteria for this systematic review and include both the physical scent display devices as well as the software required to integrate these with VR.

Chapter 4 presents a low cost and accessible olfactory display device prototype using readily available electronic components. Its design was informed by the findings of the design heuristics as well as the systematic review. An evaluation of the proposed prototype device, analysing the practicalities of the technology used as well as its potential impact on presence was presented. In order to achieve this a small study was outlined and the VR experience using the olfactory display prototype in which a combination of the Temple Presence Inventory (Lombard et al., 2009), a Think-Aloud protocol and a series of open-end questions was utilised.

Chapter 5 summarises the findings and presents a discussion on the current state of olfactory display technology for use alongside virtual reality. Avenues of future research will also be presented.

Chapter 2: Literature review

2.1 Introduction

Scent has been an often underutilised and underexplored sense within human computer interaction (Brewster et al., 2006). Previous attempts at implementing olfaction have often been dismissed as novelties without any deeper practicality (Olofsson et al., 2017). With the advent of higher fidelity virtual reality technology, scent is becoming a more widely discussed and considered implementation (Bordegoni et al., 2019). This literature review has been undertaken with the aim of discussing a range of aspects, vital to understanding how scent might be utilised in a meaningful way. Before discerning how scent display technology can be developed, it is first useful to explore a range of underlying principles that might impact their design.

Section 2.2 of the literature review is an introduction to the current understanding of the human physiology of scent. Topics discussed include the process of perceiving scent and a range of relevant phenomena such as olfactory detection threshold and olfactory adaptation.

Section 2.3 provides information about the attempts to categorise and measure scents. It will discuss some of the first endeavours to do so before following on to a discussion of the current technology used to analyse odour. It will also discuss the issues with the lack of a universally accepted scent unit and the impact it may have on design for scent. Several potential solutions are presented to overcome these issues.

Section 2.4 of the literature review addresses the reasons that researchers and have a lasting interest with introducing scent to media. Namely, a discussion surrounding presence and its relationship with scent is presented, specifically spatial presence. Examples are provided of this relationship that demonstrate mixed results and present an argument for further research into this area.

Section 2.5 presents a history of the relationship between media and scent, beginning with the early attempts to introduce scent to cinema, the issues encountered and how they have endured through the attempts to integrate scents during the dot com revolution of the early 2000's. Case studies of different products are presented as well as a discussion surrounding the continued failure for scent to become a mainstream form of interaction between media and the audience.

Section 2.6 will delve into the implementation of scent specifically for virtual reality. A brief discussion surrounding the state of modern VR will be presented in order to understand how scent might integrate into the experiences provided by these newer, higher fidelity devices. Examples of current and future products and attempts will be discussed.

Section 2.7 will combine the main findings of each section in order to extract potential design heuristics that may need to be considered when implementing scent stimulus within a virtual reality environment. Potential solutions to some recurring issues and limitations will then be discussed critically. These heuristics will then form the foundations of the subsequent systematic review database criteria as well as the development of the low-cost olfactory display prototype.

It has long been suggested that scent has the ability to trigger memory recall (Chu & Downes, 2002). Gilbert (2008) states that this property of scent is referred to as 'Proustian Phenomenon', named after French novelist Marcel Proust. In his novel In Search of Lost Time (1913), Proust recalls a childhood memory of his aunt that is triggered by the scent of a piece of madeleine cake. This recollection of a childhood memory after perceiving as specific scent is a common example of this type of phenomenon. A number of studies have attempted to analyse and validate this property of scent in order to understand how it might occur (Chu & Downes, 2002; Toffolo et al., 2012). The research has shown that the relationship between scent and memory recall is complex and subject to a number of factors. It is suggested that the recalled memories are based on a deeply subjective experience and it is likely very difficult to integrate smell to trigger a response without knowing an individual's past experiences.

This characteristic of scent will not be examined in detail as the complexity it would likely introduce is beyond the scope of this thesis. This may however provide valuable avenues of research upon completion of this project. It might be feasible to examine if it is possible for an individual to navigate a virtual space based on scent induced memory recall.

2.2 Physiology of Smell

To better understand how the sense of smell might be further utilised within a virtual environment it is first important to investigate the physiology of olfaction and the process involved in perceiving a scent. This section will discuss the physiology of the nose as well as how odorant molecules are received in the nose and perceived by the brain.

Following this will be a discussion surrounding odour detection thresholds; the minimum concentration of an odorant required before it can be perceived. The section will also look at the phenomena of sensory adaptation and the issues that it introduces with olfaction before discussing the experimental use of electrical impulses to trigger olfactory perception.

2.2.1 Basic Physiology of the Human Nose

The process of odour perception begins when an odorant molecule enters the nasal cavity through the nostril. For this to occur, some type of nasal airflow, usually a sniff, is required to carry the molecule to the area known as the olfactory mucosa (Walton, 2012). This area is located in the upper, back of the nasal cavity and contains the olfactory epithelium. The olfactory epithelium is a mucus-lined area of specialised tissue where the odorant molecule is absorbed into the body. The mucus is produced by the Bowman's gland in the epithelium's lamina propria (a layer of connective tissue) and it is vital for the absorption of the odorant molecules (Escada et al., 2009). Walton (ibid) suggests that this mucus may also slow the travel time for molecules which in turn separates different types of molecules before reaching the olfactory epithelium. Molecules that have a higher absorption rate may in fact produce less odour as they are absorbed before reaching the olfactory epithelium.

Once a molecule has been absorbed by the olfactory receptor cells in the olfactory epithelium, the original chemical signal (the odorant molecule) is turned into an electrical signal. Receptor neurons then transmit this signal across the cribiform plate of the skull to the olfactory bulb, an area between the brain and nasal cavity and the first connection to the central nervous system (Mackay-Sim & Royet, 2006). This, in turn, sends signals further to the cerebral cortex of the brain; the area associated with the conscious recognition of a scent. The olfactory bulb also transmits signals to the limbic system; the area of the brain which is related to memory and emotion (Walton, 2012). This may explain the close relationship between scent and memory.

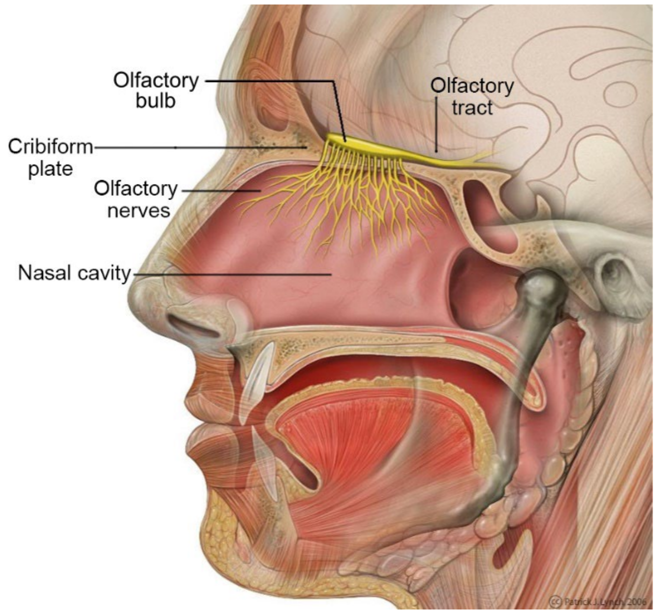

Figure 1. An overview of the nose and olfactory bulb. (Lynch, 2006, Creative Commons Attribution 2.5 License 2006)

Niimura (2009) states that humans are thought to have around 800 olfactory receptor genes, but half of these are pseudogenes, meaning they have lost partial or all functionality. Around 400 genes are used to recognise the range of smells that can be distinguished by humans, making the olfactory receptor gene superfamily the largest in the human genome (Olender et al., 2008). An interesting aspect of olfaction is that, unlike vision, hearing and touch which all function within a limited spectrum of light, sound and pressure respectively. Thus, the range of odorous molecules may be potentially limitless due to their high degree of variability in structure and size. It is argued that this may contribute to why humans have so many receptor genes for olfaction when compared to the visual system which utilises just 3 gene receptors (Mackay-Sim and Royet, 2018). It is commonly believed that humans can distinguish around 10,000 different scents, however, Gilbert (2008) argues that this number, is a basic estimation by chemists Crocker and Henderson in 1927. They arrived at this number after attempting to objectively classify odours. A scale of 0 to 8 was used to rate how closely a scent resembled four basic odour sensations. Extrapolating this scale would then theoretically allow for 6,561 different smells. This was then rather generously rounded up to 10,000.

More recent research by (Bushdid et al., 2014) aimed to validate this claim by testing the capacity of humans to discriminate odour mixtures with varying numbers of shared components. They state that many of the scents people perceive everyday are composed of many different odour molecules but that only a small percentage of these contribute to the perceived smell. They began by reducing the complexity of scents down to 128 molecules that were known to be perceivable by the human nose and brain. By varying how these components were blended they were able to calculate what percentage a mixture must differ before it can be discriminated. They found that in actuality, humans can discriminate over 1 trillion different scents, more than any other human sense in its ability to differentiate stimuli.

Interestingly, whilst humans might be able to discriminate over 1 trillion distinct odours separately, we would be unable to perceive this quantity of smells if they were presented to us all at the same time. Research by (A. Livermore & Laing, 1998) aimed to identify how many distinct odours could be identified from complex odour mixtures. They found that after testing more increasingly complicated odour mixtures, the ability to distinguish component odours from these peaked. It was found humans can only distinguish 4 different component odours from the complex odour mixtures.

2.2.2 Odour Detection Threshold

The ability to perceive scents is dictated by the Odour Detection Threshold. This is the minimum concentration of a certain scent molecule needed to be consciously perceived. Trimmer and Mainland (2016) state that there is a huge degree of variability in the odour detection threshold of individuals. A number of factors can impact this, including: age, genetics, health and environment. (Doty & Kamath, 2014) explored a correlation between increased age and a higher odour detection threshold. They discovered that, through a series of psychophysical tests, around 50% of people between the ages of 65 and 80 have some form of decreased olfactory function. This number increases to 75% when testing individuals over the age of 80. They suggest that this is not due to one specific cause but rather a culmination of different factors including a decreased production of enzymes in the odour absorbing mucus in the nasal cavity, increased propensity for nasal disease and culminative damage to the olfactory epithelium due to viral insult. This research does reinforce the suggestion that increased age plays a major factor in the decreased levels of odour detection. Some reports suggest that gender may play a role in detection variation, however, (C. R. Schubert et al., 2017) found that in a comparison of 832 individuals that gender did not show any significant differences.

It is important to note that the concentration of molecules needed to reach the odour detection threshold will vary greatly depending on the type of molecule and it is very unlikely that multiple molecules will have the exact same concentration requirement. (Gregory Leonardos, 1969) undertook an investigation into the detection threshold levels of 53 different odorant chemicals. Four individuals participated; each was a trained odour expert that had a minimum of a year's experience analysing odour. The experiment was carried out by circulating the odour in an aluminium test chamber, designed to minimise background odour. The test odorants were circulated in the room for 5 minutes using electric fans. Only a single odorant was examined each day by presenting the panel with 5 different concentrations. It is interesting to note that a range of gases, liquids and solids were examined. Both the solids and gases were combined with odour-free water. The research found that Trimethylamine (a component produced during the decomposition of organic matter; it has an odour that is often described as 'fishy') could be detected at just 0.00021 parts per million whilst Methylene Chloride (a chemical with a sweet aroma that is often used as a solvent) had the highest threshold at 214 parts per million. It is important to note that the odorants threshold was decided upon after all the participants could perceive a scent rather than when an individual could perceive a scent. This provides more of an average threshold for each chemical, but this may vary between individuals. The use of trained experts in this experiment may also have an impact on the threshold level due to their experience in acknowledging scents.

2.2.3 Olfactory Fatigue

Sensory adaptation is the reduction of sensitivity after prolonged exposure to a stimulus (Köster & de Wijk, 1991). This phenomenon is found to be present in all senses and is thought to be an evolutionary trait to prevent an overload of sensory information. Köster & de Wuk (1991) also states that sensory adaptation is a temporary phenomenon. The time to recover from this reduced sensitivity to a stimulus is often dependent on the length of time and the intensity of the initial exposure. A short exposure to a low concentration odour would take significantly less time to recover than that of a long exposure to a high concentration odorant. Whilst all senses afford some degree of sensory adaptation, a trait of olfaction is that it can lead to the complete reduction of the perception of a scent after prolonged exposure, effectively removing all perception of it. It is interesting to note that with the introduction of another stimulus, such as a different odorant, the nose will not suffer from any olfactory adaptation to this, but adaptation will begin to occur after prolonged exposure to this new odorant.

There is a common myth that certain specific scents can reset this olfactory fatigue. Perfume sales assistants will often encourage customers to sniff coffee beans every so often whilst sampling the range of perfumes with the claim that this will reset their olfactory sense, allowing them to smell the "true" scent of the perfume. (Grosofsky et al.,

2011) examined this claim that coffee may act as a sort of 'nasal palette cleanser'. 63 college students were asked to smell 3 fragrances multiple times to induce olfactory fatigue. Presenting a third of the students with coffee beans, a third with lemon and a third with no additional scent, they were then asked to identify a fourth, new odour that had not been previously smelled. It was found that neither the coffee or lemon had any significant improvement when identifying which odorant was the new odour.

2.2.4 Perceiving Scents through Electrical Stimulation

Whilst we perceive scents through chemical means of delivery, it may not be the only method of producing the perception of smell. Hariri, Mustafa, Karunanayaka & Cheok (2016) suggest that the use of chemicals to activate the sensation of smell in the context of scent presentation technology has a number of disadvantages. They state that it is complex, expensive and has low controllability.

Hariri et al. (2016) explored the possibility of using electrical impulses to stimulate the olfactory receptors evoke the perception of scent. In order to examine whether this might produce positive results, the researchers used thin, flexible cables tipped with a small camera and a silver electrode. This cable was then inserted into the nostril, with the camera being used to find the participant's olfactory receptor cells. Once the silver electrode was placed on the olfactory receptor, the current and frequency of an electric impulse was manipulated until the researchers had obtained settings that most reliably produced an olfactory response in the individual. 31 participants took part in the study. They most often described the sensation as 'fragrant', with others describing it as "woody", "fruity" or "sweet". As the research was at an early study, it was not possible to determine if a certain electrical impulse in a specific location could create a reproducible olfactory response. The researchers suggest that factors such as gender, age and anatomy may be factors in the different perceived scents between individuals.

A major issue with this method of producing olfactory sensation is the intrusive nature of the stimulation. It was found that many participants did not want to take part in the study again due to the discomfort of having the electrode inserted into the nostril. The researchers suggest that this may be overcome by either making the cable thinner and more flexible or by bypassing the nostril altogether, and directly stimulating the brain. Due to the experimental and invasive nature of this method of inducing scent perception, this technique will not be examined in this project.

The nature of olfactory perception presents a number of challenges in understanding and fully mapping out the process. It is still not fully clear how the human brain processes scent signals in their entirety. The unique nature of how humans perceive scents will certainly add a layer of complexity to any system designed to present scents to an individual in virtual reality. The above factors regarding olfactory physiology in the context of a potential scent display device will be summarised and discussed in the design heuristics section of this review.

2.3 Categorising and Measuring Odour

To understand how to design virtual experiences around aromas, it is important to discern how scents might be measured in order to provide a repeatable and reliable release of olfactory stimulus.

2.3.1 The problem with measuring scent

In an article in the June 1914 issue of National Geographic Magazine, Scottish inventor Alexander Graham Bell posed the following questions:

> *Did you ever try to measure a smell? Can you tell whether one smell is just twice as strong as another? Can you measure the difference between one kind of smell and another? It is very obvious that we have very many different kinds of smells, all the way from the odour of violets and roses up to asafoetida. But until you can measure their likenesses and differences you can have no science of odour. If you are ambitious to found a new science, measure a smell* (1914).

This statement by Bell echoes many of the issues found with attempting to measure and categorise odours. (Wise et al., 2000) state that whilst the chemical components of an odorant can be identified and measured, the perceived characterisation of an odorant is much harder to predict and provide quantifiable data for. Often researchers will rely on enumerative descriptions of scents in experiments. Whilst several attempts have been undertaken to categorise and organise scents, Gilbert (Gilbert, 2008) states that none of these attempts were fully able to efficiently capture the range of scents thought to be perceived by the human nose. Whist there are systems in use to measure scent, there is still no widely accepted universal standard method of measurement agreed upon by the scientific community.

2.3.2 Early Attempts at Categorising Scent

An early attempt to categorise a range of scents was provided by 16th century Swedish scientist Carl Linnaeus (1707 – 1778). He had previously achieved success when he formalised the modern scientific taxonomy for biological organisms, known as Binomial Nomenclature; a system still used today. His penchant for classification extended into olfaction when he began codifying medicinal herbs and plants. Scent was one of the categories he used to organise these. In turn, he distinguished the scents into seven categories: Camphoraceous, Musky, Floral, Pepperminty, Ethereal, Pungent and Putrid (Philpott et al., 2008). Gilbert (ibid) argues that the issue with this form of categorisation was that it was only effective for the medicinal plants it was designed around. This is just a very small percentage of the broad range of scents the nose can perceive.

Dutch physiologist Hendrik Zwaardemaker (1857 – 1930) built upon and revised Linnaeus' classification system. He changed some of the terms used and introduced two new categories until he had the following nine categories (Philpott et al., 2008):

- Ethereal (ether or beeswax)
- Aromatic (spice or camphor)
- Fragrant (lavender or rose petals)
- Ambrosiac (amber or musk)
- Alliaceous (garlic or onions)
- Empyreumatic (roasted coffee or tobacco smoke)
- Hircine (cheese or rancid food)
- Foul (bedbugs or coriander flower)
- Nauseous (faeces or rotten eggs)

This scent organisation system, however, still had the same inherent issue as Linnaeus'; the initial system was only used to categorise medicinal plants. As a method of categorising all types of scent, it was never universally adopted. Zwaardemaker did, arguably, provide a greater contribution to the field of olfactory study than his classification system. In 1888, he invented a device, consisting of a glass tube that was open at both ends that would be able to provide the delivery of an odorant to an individual's nasal cavity. This was one of the first attempts at delivering a consistent and repeatable dosage of odorant. The device, now known as a Zwaardemaker Olfactometer had the ability to vary the intensity of scents. A surface, with absorbed odorant is exposed to the other end of the tube to the individual. How exposed this surface was to the tube until the individual began to perceive a scent became the measurement of the detection threshold of the odorant (Mateson, 1955).

2.3.3 Gas Chromatography

There were many more attempts to produce a scent classification system over the years, but none so far have become a standardised method of olfactometry. This, however, does not mean that scents are entirely unmeasurable. Whilst it may be more problematic to predict the perceived scent of odorants, it is possible to measure their chemical components to give an approximate idea of how a scent might smell.

In 1955, the advent of gas chromatography allowed for scents to be analysed to provide a complete map of the chemicals in its makeup. Odorant samples are mixed with a carrier gas such as helium or hydrogen. This combination then passes into a glass or metal tube where it mixes with a liquid that has a particularly high boiling point. The base components of the sample are separated and pass through a detector as the temperature increases. Each time a certain component passes through the detector it appears as a peak on a chart. The number of peaks on the chart indicate the number of component gases in the odorant sample (Woodford, 2016).

Whilst this technique allows for a full report of all the components in an odorant, it does not provide information on which of these components contribute to the perceived smell. Gas chromatography-olfactometry uses the same process as standard gas chromatography but as the separated samples pass through the detector, a human assessor will sniff the components to decide which are contributing to a certain scent (Delahunty et al., 2006). It is interesting to note that despite the advancement in olfactory technology, the human nose is still involved in this process of analysing scent.

2.3.4 Numeric Olfactory units

Whilst no universal standard unit of scent measurement is available, a number of methods have been proposed and are currently used to provide a numeric measurement value to a scent concentration. One of these units is the European Odour Unit. This is defined as the amount of odorant that when evaporated into 1 cubic metre of neutral air will reach the same detection threshold as a European Reference Odour Mass (EROM). This reference odour is defined as 123µg of n-butanol. One European Odour Unit (OUE/m3) is therefore expressed as a multiple of this EROM value. This unit of measurement is primarily used in environmental bodies and agencies as a method of measuring pollution and air quality. Whilst this method is used in Europe, The United States of America and Australia use a different unit of measurement. Here a molecule's scent is measured by the detection threshold of 50% of individuals (these measurements are undertaken in lab conditions). An olfactory unit is said to be the highest dilution needed to still be perceived by 50% of individuals. The number is presented as a dilution to threshold. For example, an odorant that is diluted 500 times is said to have an Odour Unit of 500OU (*Odour Unit | Scentroid*, n.d.).

2.3.5 Olfactometers and Electric Noses

Over time, the term olfactometer has developed to take on two meanings: One being a device for measuring odorants with the other being a device that emits odorants in a consistent and controlled manner.

Olfactometers for measuring scent and odour have progressed since the first implementation by Zwaardemaker. The ability to measure component content of an odour is now possible electronically. 'Electronic Noses' as they are sometimes colloquially known, share a similar process in their scent recognition as humans do. Many of the proposed electronic noses are still at an experimental stage but some have seen a wider release such as the handheld Cyranose 320 (2002). Odour molecules are detected by a sensor module attached to the unit. Different odour molecules can trigger different electric receptors similar to how olfactory receptor genes are triggered in humans. This can provide a quick and accurate reading of the base components of an odour. The issue of not knowing which chemicals are producing the odour as we perceive it remains with this type of analysis.

For clarity, olfactometers for emitted odour will here on be referred to as olfactory display devices. These devices vary in structure, they are usually built around an air flow system that allows odourless air to be delivered to an individual in a consistent flow. Vaporised odours can then be introduced to the airflow in a controlled manner. (Al Aïn & Frasnelli, 2016) state that whilst these commercial olfactory display devices can present a precise and repeatable release of odour, their extremely high cost and size mean they are impractical for settings outside of controlled laboratories. A more detailed description of the devices that may be used for VR purposes in provided in section 2.6.3.

2.4 Presence and Olfaction

Before examining specific and notable examples of media that have attempted to introduce scent, it is pertinent to understand why these attempts have been made in the first place. What would be the benefits of incorporating scent into a virtual reality experience? This section will explore the current understanding of the term 'presence' and its importance in the use of olfaction. An argument will be made that the desire to improve 'spatial presence' and 'perceptual realism' are the driving force behind these attempts to integrate scent. This section will provide vital context for the remaining content that discuss past attempts at integrating scent into media and the implications it might have for virtual reality.

2.4.1 What is Presence?

There has been varying and broad definitions of the term 'presence' since it was first coined. In 2000, the International Society for Presence Research offered the following definition:

> *Presence (a shortened version of the term "telepresence") is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at *some level* and to *some degree*, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience. Experience is defined as a person's observation of and/or interaction with objects, entities, and/or events in her/his environment; perception, the result of perceiving, is defined as a meaningful interpretation of experience* (2000).

A common term that appears in definitions of presence is the sense of 'being there' (Sas & O'Hare, 2003). At its most basic understanding, presence is the phenomenon of feeling physically present in a mediated world or environment that otherwise only exists virtually (Lombard et al., 2015). The term presence has been loosely interchanged with the term 'immersion'. Biocca & Delaney (1995) defined a term known as Perceptual Immersion. It has long been understood that humans make sense of their surroundings using senses: sight, sound, smell, taste and touch. It is argued that as we increase the number of senses stimulated when absorbing media, the more perceptually immersed we are in the experience (Jamie Madigan, 2010) This, in turn, is likely the main driving force behind the desire to implement olfaction into our media and content.

2.4.2 Evaluating Presence

Most scholars agree that presence can be categorised into two primary forms: spatial presence and social presence (Horvath & Lombard, 2010). Spatial presence can be defined as the feeling of being in the media-created physical environment whilst social presence, as the feeling of being within the media-created social environment. These forms of presence are evaluated through presence questionnaires which are often split into further categories, tailored to specific studies. The Temple Presence Inventory (Lombard et al., 2009) is arguably one of the most robust and thorough of these questionnaires. This inventory has been peer-reviewed and has been shown to provide accurate results to describe an individual's level of presence through different categories. The categories are described below with first-person descriptors:

- **Spatial Presence** – 'I felt like I was in the space or environment created by the technology'.
- **Transportation** – 'I felt like I went somewhere else, people or things came to me, or we went somewhere else together'.
- **Engagement** – 'I felt mentally immersed; I was focused on or absorbed in the experience'.
- **Perceptual Realism** – 'The people, things, and events I experienced through the technology looked, sounded and/or felt as they would in the real world'.
- **Inverse Presence** – Even though I wasn't using technology, I felt like I was.
- **Social Presence** – I felt I was actually with the people who were available via technology.
- **Social Realism** – The people, things, and events I experienced through the technology could (or did) occur in the real world.
- **Medium as a Social Actor** – The technology itself seemed to have a personality (including computers, phones, robots, mannequins, etc.)
- **Actor within Medium** – Even though I couldn't interact with them, I felt I was actually with the people or characters who were available via the technology.
- **Self-Presence** – I felt connected to the avatar or other representation of me in the world created by the technology.

From the above list, Olfactory augmentation of a VR experience would most likely have the closest relationship to spatial presence, and perceptual realism. The feeling of being more within the virtual space might be enhanced by the distinction of olfactory stimulus throughout whilst it is thought perceptual realism would be increased due to the further stimulation of additional senses. The current description for perceptual realism is described as: '*The people, things, and events I experienced through the technology looked, sounded and/or felt as they would in the real world*' (Lombard & Ditton, 1997).

The focus of this is on the sensory response to the virtual experience and it would be plausible to extend this beyond visual, auditory and tactile into the olfactory sense.

2.4.3 The Effect of Olfaction on Presence

Whilst it seems true that stimulating the olfactory sense would produce a heightened sense of spatial presence and perceptual realism as described by the Temple Presence Inventory, literature that demonstrates this relationship is surprisingly sparse. Of the literature available, mixed results are reported on the property of olfaction to increase perceived presence. Some researchers note highly positive results (Carulli et al., 2015; Munyan Iii et al., 2016) whilst others have found that the introduction of scents provided little to no discernible effect (Baus & Bouchard, 2017; Herrera & McMahan, 2014a).

(Nakamoto et al., 2008) developed a scent display device that could present individuals that were playing a cooking game a range of different smells in real time based upon the individual's input. They found that 90% of questionnaire respondents reported that scents increased their sense of spatial presence and sense of realism. It is not clear from this experiment whether a control group was used in which users were split into categories that either experienced the game with olfaction or without.

Conversely, (Dinh et al., 1999)found that scent had only a minor effect on an individual's sense of presence. 322 participants were asked to explore a virtual office suite and report their experience in a series of questionnaires. It is worth noting that this experiment was not designed to examine scent specifically, but rather a range of additional sensory output including visuals, auditory and haptic response. The only scent cue implemented was that of ground coffee, delivered to the participant through an oxygen mask. Individuals were asked to rate their sense of realism on a 100-point scale, with 100 being most realistic. Individuals that were not exposed to any scent rated the experience at 64.7 whilst individuals that did experience the scents rated it at 68.1. Whilst this shows there was an increase in perceived sense of spatial presence, its inclusion has only a minor impact on the sense of presence.

A significant study by (Munyan Iii et al., 2016) investigated olfaction's role in exposure therapy for sufferers of anxiety, stress and trauma disorders. 60 individuals that had passed a standardised test for olfactory function were asked to navigate a virtual environment that approximated an abandoned carnival. Participants were either presented the environment with or without scent. The researchers found that the individuals that experienced the environment with olfactory stimuli reported a higher sense of presence.

Interestingly, levels of anxiety were recorded through the experience and it was found that olfactory stimuli had little to no effect of the reported levels of anxiety in individuals.

There are varying factors in the lab conditions used throughout many experiments which may account for the discrepancy and mixed results found between the above experiments. Examples of these include the range of display devices used, the concentration and number of olfactory stimuli utilised as well as the purpose for examining sense of presence within a virtual environment. Olfaction does indeed appear to have a relationship with spatial presence but how much of an impact it might potentially have is uncertain. This provides an opportunity for further research which will be addressed through the undertaking of the systematic review in the following chapter as well as in the evaluation of the prototype olfactory display device.

2.5 Olfaction and Media

Olfaction when combined with visual media has never quite been adopted in the same way visual and auditory senses have for media experiences, and whilst there has been ventures over the previous few decades to implement scent, these have ultimately yet to become readily and commercially available (Tsaramirsis et al., 2020). Yet, there is a lasting appeal to introducing scent to our media.

This section will discuss this appeal before exploring some notable examples that raised enduring issues as well as design considerations that would still be relevant to virtual reality.

2.5.1 Early attempts to Integrate Scent and Media

The most notable attempt at introducing olfaction into the realm of cinema can be attributed to Hans Laube, a Swiss American entrepreneur. In 1954, after numerous redesigns and trials Laube patented a device that would allow for a range of different scents to be released to an audience in a movie theatre. His device consisted of a turntable that would hold a series of odour canisters in liquid form. An electronic track on the film reel would then rotate the turntable to the required scent after which a nozzle would suck up the scent, vaporise it and emit it from pipes connected to the backs of theatre's seats (Gilbert, 2008)

Scent of Mystery (1960) was to be the first film that was specifically written for Laube's invention, now officially named 'Smell-O-Vision'. But just 3 weeks before the films scheduled premiere, another film that used the same principles of scent was released. *Behind the Great Wall* (1959), a previously available Italian film was re-edited to integrate scents that would be emitted through the air conditioning of the theatre. (Gilbert, 2008 p. 158) Its initial response from critics and audience was mixed. The use of the air conditioning as the delivery method had much less fidelity that Laube's bespoke invention, and it was remarked that as the film progressed the scents became more and more indistinguishable as they began to mix in the theatre. There was no system in place to clear the previously released odour before the next was emitted. The rushed release of *Behind the Great Wall* that led to unfavourable reviews negatively impacted the reception of *Scent of Mystery*, leaving the enthusiasm for scented cinema diminished. *The Scent of Mystery* premiered 3 weeks later and whilst the film itself was warmly received, it was noted that the scents were not particularly detectable or prominent. Scented cinema never became the commercial success that was hoped for, and the concept was often regarded as simply a gimmick (Gilbert, 2008, p. 159).

Whilst Smell-O-Vision never took off, Laube's development process revealed several issues and design considerations that are still likely as relevant to an olfactory experience today as they were in the 1950s. A key issue that Laube encountered was how he might remove a scent from a space after it had been emitted to prevent scents from blending together. This was the issue that led to the poor reviews of *Behind the Great Wall* and effectively stopped any further development of scented cinema. Laube's invention emitted scents from the backs of the theatre's seats, and he found that by reversing the fans that blew out the scented air, he could remove the previous scent before emitting another, keeping scents distinct.

Another key aspect of *Scent of Mystery's* experience was that it was explicitly designed from the ground up to include aromas, rather than being simply augmented with them after production. Gilbert (2008, pg. 136) notes that part of the film's narrative would be revealed to the audience using scent. Smoke from a character's pipe was used to provide a hint to the truth of the film's central mystery.

2.5.2 A VR Pioneer

A year after the release of *Scent of Mystery* (1960) filmmaker Morton Heilig demonstrated a prototype for his project that he had been producing and developing since the mid-1950s. Sensorama is considered to be the first attempt at producing a virtual reality device (Mclellan, 2003). Whilst Sensorama is not virtual reality in the same sense as the term refers to today (it resembled more of a one-person theatre); it did explore many of the key concepts that developers strive to implement today. The device consisted of a seat that emulated the position of sitting on a motorcycle. Viewers would then look through a viewer that presented a film, shot in first person perspective, in a 3D stereoscopic image. Five films were produced to demonstrate the device with 4 of these being shot from the perspective of being in a car or on a motorbike. The last film was footage of a belly-dancer. It was this film the demonstrated Heilig’s ambitious project to its fullest potential. The device would emit a burst of perfumed air when the belly dancer moved closer to the camera. In the film, the belly-dancer had small cymbals on her fingers that could be heard in the appropriate ear when she moved around the scene (Brockwell, 2016).

Figure 2: Heilig's Sensorama (https://www.historyofinformation.com/detail.php?id=2785)

The project was a commercial failure. (Mclellan, 2003) argues that this was due to the ambitious device being created too far ahead of its time as well as the difficult and expensive task of producing films that could be presented in stereoscopic 3D. The features that were attempted in Sensorama are still likely very familiar to developers of VR content today. The use of sound presents an early example of spatialising audio, often referred to as binaural audio today. Other features designed to increase the viewers immersion in the experience included a wind generator that was designed to replicate the feeling of the wind blowing past the passenger on the motorcycle. Vibrations in the seat were implemented to emulate the vibration of the road and engines of the vehicles in the films.

Modern gamepads often use vibration as a form of response to the player, known as haptic feedback. Whilst olfaction in a VR environment has not been adopted in the same manner as binaural audio or even haptic feedback has, it is interesting to note that the first example of VR sought to implement fragrance, demonstrating that olfaction has been an active thought during the development of VR technology.

2.5.3 HCI and Olfaction

There was little in the way of new advancements in scent technology in the years following the failures of Smell-O-Vision and Sensorama. Scent had become something of a marketing gimmick rather than a potential new source of enrichment for media content. Films in the late 1980s and early 2000's occasionally implemented scratch and sniff technology. *Polyester* (Waters, 1981) was a notable example of this. Audience members were given a card that featured 10 different scents that needed to be scratched at different points throughout the film in order to release the contained odour.

This low-cost method of introducing aromas was also implemented into some video games in the mid-1990s. 1995's release of *Earthbound* for the Super Nintendo Entertainment System included a range of scratch and sniff cards. (Olofsson et al., 2017) argue that this technology was implemented as an offbeat novelty, and usually as an afterthought, suggesting that developers lacked confidence in the power of olfaction as a means of interaction within a game.

In 1999, start-up company DigiScents created a product they called 'iSmell'. This was a USB device that was able to deliver scents to users whilst they browsed the web. This would mark the first real exploration of olfaction's use within web technology. In an interview with Wired magazine (1999), the developers claimed that the device was able to combine 128 different primary chemicals into a vast range of odours. Scents were triggered by snippets of code that could be embedded in different digital sources. For example, when a user visited a certain website, a matching scent would begin to emanate, or a certain scent might be produced at a specific point of a film or video.

The project never made it past the prototype stage, but the developers had envisioned how it might be able to produce scents for online video and games and had arranged partnerships with Sony and Microsoft. However, after 2 years and a two million dollar investment, DigiScent closed and iSmell never materialised (Kaye, 2004). The failure of iSmell continued the unenthusiastic trend of scented media. Marc Canter, who worked on the project, in a 2018 interview for The Hustle stated that the failure could be chalked up to ‘lack of demand’. In the same article, iSmell designer Joel Bellenson states that the failure of his project has had a lasting impact on the future of scent based HCI. Another unnamed developer quoted in the interview (Crockett, 2018), also stated that another key issue was that scents would not be able to be cleared before emitting a new scent so eventually an unpleasant blend of different scents was all that could be smelled. A similar issue was encountered almost 40 years prior with scented cinema. It is apparent that this issue of having precise control over the addition and removal of scents offers a challenge to developers of olfactory display devices which should be considered and addressed, particularly when implementing multiple scents. Techniques for this have been attempted that utilise activated carbon meshes in an effort to absorb the scent after it has been released (Kato & Nakamoto, 2018a). Whilst some scent is reported to linger, this method does show positive results compared to using no active method of scent removal.

2.6 Olfaction and Virtual Reality

In order to review the technology available that might be utilised within this study, it is first important to understand the definition of the term virtual reality. Virtual Reality is the simulation of a three-dimensional environment which can be experienced through the realistic interactions such as head and hand tracking (Rubin, 2018). Most VR systems utilise a head-mounted display (HMD) to present the visuals to the individual. When the person moves their head in the physical world, the movement is matched in the virtual space. Virtual Reality technology has advanced and diverged into different forms in recent years. Whilst, the term has also been used to encompass 360-video, Rubin (2018) argues, 360-video does not constitute true VR. 360-video is video that is mapped to a sphere in which individuals generally use smartphones or tablets to view this content by moving the device to act as a “window” onto different parts of the video. Head mounted displays such as the Google Cardboard can be used to simulate an experience closer to the human eye.

In recent years, a range of VR devices have become commercially available. The Oculus Rift’s launch on the crowd-funding site Kickstarter and the subsequent purchase of the technology by Facebook in 2014 is argued to have restarted the interest in Virtual Reality technology (Welch, 2014). Since this point several other high-fidelity devices have been released such as the HTC Vive (HTC, 2016) , Valve Index (Valve Corporation, 2019) and the Oculus Rift (Facebook Technologies LLC, 2014). These devices are head mounted displays that envelope the user’s visual field. They are often combined with high quality spatialised audio. These devices offer 6 degrees of free movement within their virtual environments, meaning that as the user moves their head and body, the visual display will match their position. Handheld controllers that aim to replicate hands allow individuals to manipulate and interact with the virtual environment. It is the augmentation of these types of experience with olfaction that will be investigated by this research.

2.6.1 Examples of Augmenting VR with Olfaction

Proponents of VR gaming technology often cite its ability to provide an increased sense of presence over traditional screen-based experiences (Schwind et al., 2019a). The replication of life-like movement and interaction as well and the encompassing head-mounted display is often credited as the reason for this. It would therefore not be unreasonable to suggest that, when VR is combined with olfaction, it could potentially increase an individual's sense of presence further than if olfaction was not implemented, given the suggestion that the inclusion of olfaction in media experiences may improve presence.

Olfaction within VR has been explored to some degree in studies, however, the lack of a universal or readily available, commercial scent display device has led to a number of different factors in the methodologies utilised.

Ischer et al. (2014) propose a device for use with Virtual Reality HMDs that could be used to release scents for use in laboratory conditions. The device is capable of presenting 28 distinct odours that are stored in glass vials in a liquid state. Each odorant can be released in an evaporated state by opening a dedicated solenoid valve. These odours can be blended by opening multiple valves concurrently. The evaporated odorants are delivered to the nose through built-in medical air supply of the laboratory. The air supply is passed through a charcoal filter to reduce any external odours or contaminants before absorbing the released odorant. The air supply and odorant then travel to the nose through a polyurethane plastic tube to the individual's nostrils. The device is then interfaced to a 3D game engine (in this case, Unity) through a custom-built software toolkit that allowed for the placement of 'olfactory cues' within the virtual environment that would trigger the opening of a specific odorant valve. A fan located in the ceiling of the laboratory was used to clear the air after an odorant is released. A secondary fan near the participant's head is also used to assist with this task.

The researchers examined the latency of the odorant release. It was important that the release of the odour was perceived at the same time as the corresponding visual cues. This involved calculating the time between odorant release and a gas detector as a stand in for a human participant. They found that the length of the air supply impacted this time, with an average result of 440ms. They state however, that this is fast enough to keep up with the visual cues.

The researchers then examined the consistency of the odour concentration over multiple releases and found that the concentration reduced if the same odorant was released in fast succession but would regain their initial concentration if the valve was left closed for a longer period. They suggest that the evaporation time of the odorant was not fast enough to maintain a consistent concentration.

Finally, the researchers examined the level of cross contamination between different odorants. For example, whether a previously released odorant would affect the release of any subsequent scents. The found that whilst cross-contamination might occur if multiple odours were released successively, a period of 500ms between each release was the optimum time needed to prevent any perceptible cross-contamination.

By the researchers own admission, this device has a series of issues that would prevent it being utilised as a universal system for olfactory augmentation. The cost of the components used to build the device are currently prohibitively expensive. The device is also specialist and site-specific as it uses the air supply from the laboratory meaning that it would not be possible to utilise the device in a vast range of locations.

Niedenthal et al, (2019) proposed a handheld olfactory display device, designed to be implemented alongside the HTC Vive VR controllers. The device is capable of emitting 4 distinct odours and uses fans to attempt to prevent the blending of scents by removing existing scent stimulus. The device system utilises a custom script written in Python using the Open Sound Control framework. The study asked participants to pick up visual representations of lemons and lilacs within the virtual space. These had associated scents, also either lemon or lilac. Half of the trial however, randomised the scents with the associated visuals, so scents might no longer match their visual counterpart. Participants were then asked to place the virtual objects they picked up into one of two locations, lemon or lilac, based on the perceived smell. Results showed that the accuracy of the device was high (M=85,2%, SD=14,1%) and participants were able to differentiate scents well.

Interestingly, this design required the participants to actively press a button to release the scent stimulus. This therefore may not be suitable for experiences in which the scents must be delivered passively, based on the individual's location. Individuals would need to be actively reminded to press the button or may often forget to use the scent stimulus. Another potential limitation is that the device is mounted to the VR hand controllers. This might mean there would be instances where the device was at differing distances and orientations to the nose, meaning a potentially noticeable delay in the scent release and the odorant perception depending on the distance from the face.

2.6.2 Olfactory Display Methods

Unlike VR technology (Head Mounted Displays, Motion Controllers, etc) which can be purchased off-the-shelf easily and, more recently, have become much more affordable and ubiquitous, commercial scent display devices do not yet have this availability. It is thought that this lack of standardised device is due to a range of factors including complexity in current olfactory display device designs, the difficulty in storing and emitting multiple scents as well as removing these scents once released. It is also suggested that there is a lack of availability and affordability of commercially available devices and the few that are, are not primarily designed for use with VR (Flavián et al., 2021; Serrano et al., 2016). This lack of standardised device leads researchers to develop more bespoke designs created specifically for studies or they must adapt existing technology that was designed more for installations and 4D cinema than for Virtual Reality (Maggioni et al., 2020a). Often, these devices can be prohibitively expensive for many applications.

Yanagida (Yanagida, 2012) proposes a categorisation of the methods used by potential olfactory display device into two headings: dispersal / vaporisation and delivery. Dispersal refers to the method in which the scent is changed from its stored form to its activated form. Some of methods to achieve this are presented below. It is worth noting that this list is likely not exhaustive:

> **Natural Vaporization:** This method involves vaporising the odorant through natural evaporation. It is suggested that this method provides little active control over the concentration released and is often used for ambient odour when only one consistent scent is required.
>
> **Accelerated Vaporisation by Airflow:** This method involves actively vaporising the odorant by passing air over or through the odorant material. This requires a source of airflow but offers the benefit of being able to turn the air off to start or stop the vaporisation.

Heating: This method requires the odorant to be actively heated to vaporise the scent. This is method used in candle and many electric diffusers. This method has limited control due to the difficulty in rapidly changing the temperature of the odorant source.

Atomisation: This method turns liquid odorant into fine particles able to be transmitted through air. Simple methods include the use of misting spray bottles. More advanced methods can be achieved electronically using ultrasonic waves to atomise the odorant. Usually, a wick is used to draw the liquid odorant to the ultrasonic atomisation disc. When an electronic signal is passed through this it emits a burst of scent. This is the method that many humidifiers adopt. A similar technique known as surface acoustic wave (SAW) atomisation instead has the liquid droplets released onto a surface which become rapidly atomised. Both of these methods offer high controllability and precision as they can be activated and timed electronically.

The delivery categorisation refers to how the odorant, once vaporised is delivered from the site of vaporisation to the nose: Yanagida (ibid) outlines the following methods:

Natural Diffusion / Convection: Scents are naturally diffused from a high-concentration area to a low-concentration area. They are also conveyed by slow airflow, based on natural convection. This method offers low controllability as the air is not directed in a specific direction. This may be beneficial for ambient scents as it requires no active intervention to deliver the scent.

Wind (Air Flow): This method employs the use of directed air to deliver the scent. This usually takes the form of a fan or compressed air to deliver the scent. Usually, the odorant is placed in proximity to the source of the airflow. The benefit of this technique is that the air can act as the vaporisation and delivery method. The airflow can also often be enabled and disabled to release or prevent the prelease of scent stimulus.

Vortex Ring: A vortex ring uses heavily directed bursts of air from an 'air cannon'. Scent is released as a ring of moving air. This offers the benefit that the scent can be delivered from a relatively long distance with the scent diffusing in the air before it reaches the nose.

> **Tubes:** This method employs the use of tubes to direct scented air from the source of vaporisation to a site near the nose of the individual. It may be combined with other methods of delivery such as compressed air. This approach offers benefits for using multiple scents as it prevents blending of scent before they reach the nose as a separate tube can be used for each scent.

Murray (Murray et al., 2016) presents a taxonomy of olfactory display devices in which 2 modalities of olfactory display device are presented: *In The Environment* devices and *Wearable Devices*. *In the Environment* devices are any device that is placed in the physical space and include devices such as scented candles, diffusers, table mounted fans, ceiling mounted devices etc. The benefit of these devices is that they offer a non-intrusive method of delivering scent, but they will often have a greater degree of variability in the perception of the scent as the orientation and location of the VR user will change based on how they move around the physical space. Wearable devices can be described as any device that is mounted on the person and include those that attach to the head mounted display or are worn around the neck. The benefit of these devices is that they can maintain a consistent distance to the VR user's nose, no matter how they move through the physical space. It often required that these devices be small so as not be noticeable to the user and in doing this, may only be capable of releasing a limited number of scent stimuli due to the required smaller form factor. Murray (ibid) goes on to suggest that a wearable device would likely be the most suitable for Virtual Reality due to non-fixed location of the user.

It is clear that there is no one specific methodology for developing a scent display device for use in research. Studies often use bespoke designs, tailored around the research questions. These variations in technology are explored through a systematic review in the next chapter to identify commonalities as well as discuss results, benefits and potential limitations with these presented devices.

2.6.3 Commercial Olfactory VR Attempts

Whilst the above example presented by Ischer et al. (2014) is arguably the most technologically advanced device conceived that could be used to present olfactory stimulus, more affordable and portable commercially viable products have been proposed and prototyped. These include FeelReal (*FEELREAL VR Mask*, 2019), VAQso (*VAQSO VR | Adding a 4th Sense to VR Worlds*, 2018), Cilia VR Kit (*Cilia Developer Kit (Smell*

Device) — HAPTIC SOLUTIONS — HAPTIC SOLUTIONS, 2019)), however, at the time of writing these devices are not yet commercially available.

The FEELREAL VR mask was first unveiled at the 2015 Game Developer's Conference. The device functions by attaching to the underside of a VR HMD and covers the users nose and mouth. The designers suggest that the device can produce 9 distinct scents including flowers, gun powder and burning rubber. In addition to olfactory stimulus, the device is claimed to feature a wind generator as well as a system to spray water mist on the users face (*FEELREAL VR Mask*, 2019). Investment in the product was sought via Kickstarter in 2015, but the developers only reached half the amount of funding they had initially asked for. In April 2019, however, FEELREAL re-launched their campaign through Indiegogo which was this time successfully funded and at the time of writing the company is underway with production of the device.

Figure 3: FEELREAL Device (https://feelreal.com/)

Information regarding how the device functions and integrates with the VR headset is not entirely clear from the initial Kickstarter page and subsequent website, however, a number of journalists experienced the prototype of the device at GDC 2015 give further suggestion as to how the device might function. Mason (2015) suggests that the device uses a series of fragrant oils that are stored in small vials. These are heated up until the scented vapor is released through vents in the device. Interestingly, in the most recent update on the product's Indiegogo page, the company announced that the release of the product would be delayed indefinitely as the product required approval from the Food and Drug Administration due to the liquids used to create the scents being classed as a vaping technology. They stated that the product must undergo more strict testing before it can be made commercially available. (*Feelreal - The World's First Multisensory VR Mask | Indiegogo*, 2019)

In the initial advertisement for the product, it was unclear as to whether the device shown in this demonstration is reacting to any decisions made by the user or whether it is instead a fully pre-scripted demonstration with timed release of scents to synchronise with the visuals. A subsequent video was released in support of the second Kickstarter campaign that explained how the scent features would integrate into the VR experience. In the video (FealReal, 2019), the company states that the mask has a bespoke source development kit available for both Unity and Unreal Engine that would allow developers to give objects and locations scent cues that would be triggered by the player's location or interactions within the virtual environment. Whilst there is little in the way of formal reviews for this second iteration of the FEELREAL device, the response to the initial FEELREAL mask has been overwhelmingly negative. Mason (ibid) describes how the intended scents became 'lost' in the unintended scent of burning plastic and the majority of the scents were reminiscent of cheap air fresheners. Citing the sense of claustrophobia producing by covering the nose and mouth, Robertson (2015) gave the following summation of his experience during a demonstration of the prototype:

> *'In 50 years, when we're all locked in time-dilated mind-jail for selling virtual drugs, a day in the Feelreal will still be considered cruel and unusual punishment.'*

The negative response could perhaps have had an impact on the production of the device and may be the reason as to why the device took so long to be successfully funded. It is interesting to note that the trend of unsuccessful commercial ventures to bring olfaction to media continues into the age of virtual reality and demonstrates that there is further research needed in order to understand how a commercially viable product might be achieved. The recent successful funding of the FEELREAL mask may mark the beginning of a more hopeful future for scent-augmented VR but more time is required to fully realise whether the technology will be successfully integrated.

More established companies have experimented with olfactory stimulus for VR in recent years. With the release of both *The Elder Scrolls V: Skyrim VR* (2018) and *Fallout 4 VR* (2017), the game's producers Bethesda Softworks licenced a series of official matching scented candles that were designed to be lit whilst playing the games in VR. A single candle is available for each game with each trying to capture an approximation of the environments found in each. For example, the candle that is available for Skyrim attempts to emulate the scent of alpine mountains, a distinct virtual environment within the game.

This low-cost method of producing scents has obvious associated issues. By the nature of these candles, only a single scent can be produced which will not be enough to match the variation of environments found within the game and there is no control over the concentration of the scent which means that it cannot be spatialised within the environment. The production of these candles does however, suggest that mainstream game developers have some indication that olfactory stimulus might have some relationship to the overall gameplay experience.

The most recently proposed olfactory device designed specifically for VR comes from a Tokyo-based start-up company called VAQSO. Instead of covering the entire face like the FEELREAL device, the VAQSO is a bar that attaches underneath the head mounted display. The company claims that this is compatible with all currently available VR headsets (*VAQSO VR | Adding a 4th Sense to VR Worlds*, 2018). Interestingly, the company claims that a bespoke API has been developed that allows for this to interface with a wide range of current game engine technologies including Unreal Engine 4 and Unity. Little information is provided about how this functions but they state that objects within a virtual space can be assigned a scent and the device will alter the concentration of the scent based on proximity to the object. The VASQO website states that the intention was to commercially release the device in the first quarter of 2018 but as of the time of writing, the device is not currently available to purchase. It is interesting to note that the description of how this device would function is very similar to that of the FEELREAL VR mask demonstrating that there is a desire to produce fully reactive scent cues that could be triggered instantaneously.

2.7 Design Heuristics for Augmenting VR Experiences with Olfactory Stimulus

The following section aims to condense the findings of the previous literature review sections into a series of design heuristics that might be considered when designing VR experiences that utilise olfaction. Design heuristics offer a series of loosely defined rules and guidelines that may not offer guaranteed correct solutions but can yield reasonable solutions and may help develop more definitive future solutions (Todd, 2001). These are particularly appropriate for largely unexplored areas of study such as olfaction and media integration. These heuristics have been divided into a range of aspects including issues arising from the physiology of how humans perceive scent, the impact that the lack of an empirical measurement of scent has on these designs as well as the impact past attempts at implementing scent into media has had. The section will discuss both a VR experience that would utilise olfaction as well as a potential olfactory display device.

2.7.1 Physiological and Chemical

2.7.1.1 Scent composition

Several heuristics can be identified based upon the physiological process of olfactory function and the perception of smells. As discussed in section 2.2.2 of this review, Livermore and Laing (1998) suggested that the human nose can only pick, on average, 4 distinct odour molecules out of a complex mixture of scents. This ability to identify the base scents that can be perceived by humans may have applications in the augmentation of virtual experiences. As seen in the research by (Bushdid et al., 2014), more than a trillion complex smells can be produced from just 128 base molecules. This might provide a more practical method of implementing scent display for a virtual environment. If the number of base scent molecules could be reduced further to a degree that would still retain a relatively high degree of scent fidelity but also allow for manageable production and a feasible delivery system, this may provide a way of re-producing a scent-scape for certain environments and experiences. Further research would need to be undertaken to identify and prioritise certain molecules so that the widest range of scents can be produced with the smallest number of base molecules.

Whilst the limit of humans to distinguish just 4 component scents in an odour mixture might seem problematic, it may in fact present and advantage from a practical standpoint. Creating a complex smell-scape may not be as complicated as having to produce all possible odorants found in an environment, but rather just the 4 most prominent in a mix. It would most likely not be feasible to create a bank of scents that would approximate every single potential aroma in one single device, instead, the most prominent scents needed for a particular experience might be curated from a larger selection, depending on what scents are needed by the specific virtual experience.

2.7.1.2 Olfactory Detection Threshold

The olfactory detection threshold is the minimum concentration of a scent molecule required in order to be perceived. It was found in section 2.2.3 that there is a suggestion that a number of factors, including age might affect the olfactory detection threshold (Doty & Kamath, 2014). This variation in odour detection thresholds between individuals, particularly as age increases, raises an important design consideration for incorporating scent into a virtual experience. This research shows that the concentrations of odour used may have to be calibrated on a personal level for users to receive the intended experience. A potential system may take queues from a similar system that is often implemented into display options in video games. Commonly, before the player begins a game they are instructed to adjust the gamma and brightness of the game to match their displays in order to provide optimised colours and presentation. A system in which the odour detection threshold is tested at the beginning of the experience by incrementally increasing a scent concentration until the user can perceive it may provide a solution to this variation in thresholds. Any potential scent delivery systems would also need to factor the variation in thresholds between chemicals and odorants to balance the perceived strength of odours in order to ensure certain scents were not over or underpowering.

2.7.1.3 Olfactory Fatigue

It was previously discussed that prolonged exposure to an olfactory source will introduce a phenomenon known as olfactory adaptation or olfactory fatigue, in which a scent will be become less actively perceived over time. The properties associated with olfactory adaptation may present some limitations, but also some advantages to developers utilising olfaction within a virtual environment. Due to the decreased perception of a scent over a prolonged period of time, developers would need to consider the impact this might have on the understanding of an environment. In a virtual environment that requires a persistent odour, perhaps as a form of interaction mechanic with the player, olfactory adaptation would introduce a significant issue. For example, a virtual experience that is split into multiple areas, with each having their own associated single scent. If it was vital that the player be aware which area they are in purely through olfaction, this may become significantly more problematic, the longer the player remains in one area as they begin to adapt to the odour. A potential method of addressing this limitation would be to build an environment that has multiple associated scents that can be alternated as the player might approach a scent-emitting source, meaning that olfactory adaptation would be less likely to occur as the player has a range of different stimuli. One example may be when building an environment in which the player must navigate through a forest. Rather than simply presenting a general woodland, pine scent that remains consistent throughout the experiences, different sources of scent that would commonly be found in that type of environment could be utilised such as flowers, pine and cut grass in short releases to navigate around the onset of olfactory adaptation.

Inversely, a potential advantage of this may be that an experience would not necessarily need to release a scent consistently in the same concentration whilst a player was in a certain environment as they begin to adapt to the scent. For example, when the individual enters a particular area, they might receive a burst of aroma to indicate this change and give an initial understanding of the representative scent associated with the virtual environment. This might also provide a more optimised efficiency in the usage of odorants that may allow users to experience these environments for a longer period of time before needing to refill or replace odorants. This, however, assumes that an odorant delivery system would use finite odour generators such as liquid dispersal methods.

2.7.1.4 Producing olfactory perception through electrical stimulus

Whilst it was mentioned that the use of electrical stimulus as a method of producing the perception of scent would not be examined further in this project, it is worth discussing the applications it might have in future experiences aiming to include olfaction. In the past experiments by Hariri et al. (2016), the primary issue was the extreme discomfort felt by the participants due to the electrical stimulus needing to be introduced by an electrode attached to long cable that was inserted through the nostril. They suggest however, that if the cable might be made thinner and more flexible it may reduce the discomfort felt. This method of olfactory delivery has potential advantages over a system that presents scents chemically. Scents produced through chemical means have a degree of unpredictability and are harder to control concentration levels. An electrical stimulus is arguably faster to perceive than a chemical one since it interfaces directly with the olfactory cells. This would be particularly beneficial to an experience that required immediate synchronisation between visual and olfactory feedback. If a device that used electrical stimulus could be made less invasive then perhaps this could have greater applications within a VR experience. At present, this research appears to be in its infancy, and it will likely be some time before this can be practically examined for commercial use with VR.

2.7.2 Olfactory Measurement

2.7.2.1 The olfactory unit of measurement.

As discussed in section 2.3 of this review, whilst there is no universally used olfactory unit of measurement, a number of methods including the European Odour Unit (EOU) are currently in use. An issue with using this as a method of measuring scents for a VR experience is that scent perception can vary greatly between individuals. Whilst a system like the European Odour Unit may be useful as a starting point for understanding required scent concentrations, designers may need to test each odorant that is required in the experience against one another to ensure that scents are balanced i.e., one scent is not over or underpowering. This use of trial-and-error will likely mean that scent concentrations will need to be designed specifically for each experience rather than simply producing a 'one size fits all' scent display device. If the technology used in lab-based olfactometers could be miniaturised, made more affordable and readily available then this may present a more viable solution for presenting controlled and precise release of odorant within a virtual environment. If a range of developers began to create scent display devices, this lack of universal measurement may present issues where concentrations of scent may vary dramatically between devices and even different experiences utilising them. Whilst it is likely to be a difficult aspect to consolidate between producers of scent-based media, a universal measurement system would likely make greater compatibility and collaboration between devices and experiences.

(Davide et al., 2001) argue that an ideal scent display device should receive information about the type of smell, its concentration, its temporal dynamics, and its spatial localisation from triggers within the virtual environment. They go on to suggest that there is an intrinsic issue with olfaction in this regard that stems from the lack of definitive categorisation and measurement. The ability to codify information to display it is vital in order to reliably replicate the feedback being presented. For example, to present colour on a digital display, this information can be codified into a hexadecimal value that can be used universally to replicate this presentation. (Davide et al., 2001) point out that olfactory stimulus is yet to have this universal digital translation. They go on to suggest that the inability to predict how a scent will be perceived, despite knowing the molecular composition, is at the core of this problem.

This again reinforces that a truly effective scent display device may need to be calibrated with a specific experience in mind rather than a one-size-fits-all device. This will likely have an impact on how this type of media is consumed. Perhaps if a device needs to be specifically calibrated and set up before each VR experience, this would likely mean that consumer level devices for VR would likely lack the required fidelity needed to produce suitable results of olfactory stimulus. A VR experience that utilises olfaction may therefore find more use in purpose-built exhibitions or the increasingly popular VR arcades that can utilise a bespoke physical space. Whether a device is portable or site-specific will likely be decided through the future of VR consumption as a whole. A home consumer VR system would likely need to favour a portable, easy to set-up and store device rather than a device that requires a specific location or fan systems to effectively circulate the scents. How the market for VR develops will therefore have a huge impact on the form of scent display devices.

2.7.2.2 The role olfactometers might play in implementing olfaction in VR

As discussed in section 2.3.5, olfactometers for the purpose of detecting odorous components are becoming more available, more responsive, and easier to use. They may have a practical application in the implementation of odour in a virtual reality experience. The ability to understand the base components of a scent in a real-world environment would likely prove valuable if trying to recreate a realistic scent for a virtual environment. For example, a virtual reality game that takes place in a pine forest may be able to recreate a realistic scent after taking samples from a real forest using a handheld olfactometer. Whilst it would require some analysis by a human assessor to understand which components are creating perceivable odours, it may provide a more refined starting point for experimentation.

2.7.3 Considerations based on past media examples.

Through the previous examination of the early attempts to introduce scent to cinema and early web technology, it is clear that there are a number of issues and considerations that would still need to be taken into account when designing experiences for VR.

2.7.3.1 Visual and Scent Synchronisation Latency.

A major issue found during the Smell-O-Vision and Aroma-Rama that led to luke-warm reviews was caused by the lack of tight synchronisation between visual and olfactory feedback. As stated by Gilbert (2008 p.156) there was a long delay between the imagery and its intended associated scent cue. This delay caused confusion with audience members. This was due to the method of releasing scents through the air conditioning in the ceiling which meant that the scented air had to disperse throughout the large auditorium, this also meant that audience members closer to the air conditioning vents would receive the scents before those seated further away. Fortunately, virtual reality is much better suited to an individual experience which means that a scent display device could be optimised to release scents from an area near the nose. As shown in the previously discussed examples, particularly the research conducted by Ischer et al. (2014) in which the scent was delivered through a tube connected directly under the nostril, this provides a much faster response time between the visual and olfactory stimulus than that emitted from a source further from the individual. A scent display device would therefore ideally emit the scent from as close as possible to nose to minimise this disconnection. An HMD mounted device may offer the benefit of being able to keep the odorant and delivery method closer to the nose, whilst keeping a consistent distance independent of the position and facing of the VR user.

A potential issue may come from the mechanical sounds any scent-emitting device might make. If some form of atomisation dispersal, or fan assisted vaporisation was used, this could potentially introduce unwanted noise likely be heard by the individual before the scent stimulus was perceived. This would likely have an impact on the player's sense of presence through their acknowledgement of the device behind the scent stimulus. A solution to this would be to create experiences that utilise audio headphones whilst attempting to create a system that relies on minimal moving components in order to minimise any mechanical noises.

2.7.3.2 Clearing Olfactory Stimulus.

If a device were to emit scents directly into the air around the individual, it should also be vital that the smell can be removed from the air when needed to prevent cross-contamination between stimuli. It was suggested in section 2.4.5 that this may have been a significant contributing factor in the failure of the iSmell by Digiscent. This was also an issue encountered during the early Smell-O-Vision shows. This was not originally considered but it was noted that this key issue may have led to the early demise of scented cinema. It was found that as the film progressed, the released scents began to blend together, and the audience found it difficult to discriminate the intended smell. It was found later that the smells could be removed by reversing the fans that were emitting the scents. A VR device that might emit scents would have to address this issue in different ways depending on the format of the device. As found in the previously discussed research by (Ischer et al., 2014) their proposed device used fans placed near the individual as well as a ceiling fan that removed previously emitted scents. If producing a device that is intended to be installed permanently into a physical space, these types of fans could be set up in the space and trialled so as to efficiently direct scent to extractors. However, a portable device that is intended to be mounted under a VR headset would likely not be able to utilise this type of set up due to the practicalities of requiring the user to then also transport multiple fans and extractors. A mounted device may have a built-in fan that could 'push' scented air away from the individual's nose, but this would likely lack controllability and may just push scented air around the room rather than clear it entirely. It may be feasible in future devices that some form of extractor be built directly into the device itself. This may however introduce some issues associated with the noise as well as the weight needed to facilitate a series of built-in fans. As used in the device by Ischer et al. (2014), an activated charcoal filter might be used to aid in the neutralisation of lingering odours within the head-mounted device.

2.7.3.3 Bespoke Olfactory VR Experiences

It is interesting to note that many of the previously discussed examples of the media that utilised olfactory augmentation were not specifically designed with scent in mind. For example, the FEELREAL device would be used to enhance already existing VR games and experiences. However, these experiences would likely not allow for many olfactory affordances, particularly if olfaction is required to become an active consideration by individuals as a form of interaction or understanding of the content. Whilst most media have added olfaction as an afterthought rather than as a specific design decision, there are notable exceptions that provide insight into how scent might be utilised further within VR.

The film created to demonstrate Smell-O-Vision, *The Scent of Mystery*, whilst being one of the first examples of scented media, was also the first to be specifically written and filmed around the stimulus of scent. As previously mentioned in section 2.5.2, Gilbert (2008, p. 163) states that the audience is revealed key plot details to the film's mystery through the scent cues, such as the identity of the murderer.

This provides an interesting opportunity for olfaction within VR. A bespoke experience could allow for the scents to become a more integral feature rather than simply an augmentation after the media has been created. This use of scent as a narrative device may have much more potential for storytelling and gameplay mechanics. An exploration game may use an increasing intensity of a specific scent to guide the player towards their objective. A murder-mystery game might associate specific scents with certain suspect and use this as an additional mechanic for investigation by the player.

By constructing these experiences with scent in mind from the initial pre-production, a number of physiological and device-specific issues encountered in previous examples might be minimised or avoided. A commonly cited problem found throughout this research is that when too many scents are released in a short interval, they begin to blend, and it becomes less possible to perceive a single scent cue. Current VR experiences may feature a large number of visual cues that could potentially have a corresponding associated scent cue, but it may then introduce issues around how many scents should be utilised and how they should be prioritised, for example, in a virtual environment set in a forest, how would a developer decide on how many scents to use and which specific objects within this scene should have an associated scent? An experience built with olfactory stimulus in mind however could limit the number of visual cues associated with scents so as to minimise the number of required scents to stop blending and mixing. By including a smaller number of important, distinct scents, it may be feasible to prevent this scent mixing whilst also avoiding olfactory adaptation from setting in within the individual.

2.7.3.4 Spatialised and Reactive scent in VR

When Smell-O-Vision was created, the scents needed to be installed and sequenced before the film's showing. A separate turntable system was used to synchronise the scent to the film reel (Gilbert, 2008 p. 154). Films, however, never change between showings (e.g. the length is always the same and the cuts are always in the same place). This is useful as it means the scents only need to be synchronised once to the film track and this synchronisation can be used over and over for the same film. This, however, would not be feasible for a VR experience in which individuals have freedom of choice and movement within the environment. No two individuals would likely take the same route or the same amount of time through the environment. Therefore, a pre-synchronised scent-track would be inappropriate in this application.

Instead, a truly immersive scent experience in VR would need to use some form of reactive, spatialised scent. These should be released based upon the individual's location within the virtual environment or by specific interactions they make such as picking up an object. A potential way of achieving this might be to assign objects within the virtual environment a specific scent cue. This appears to be a method favoured by both the FEELREAL and VASQO devices. A scent radius might also be defined for each of these cues and as the individual moves closer to these objects within the environment, this radius or gradient could be used to control the concentration of the scent being released.

As the player moves away from the object, fans that might extract the scented air could then be triggered. This system might in theory allow for fully reactive scents that will be released based on the individual's route and time taken to explore the virtual environment. This has been attempted in the research by Ischer et al. (2014) using proprietary software known as Geneva Virtual Reality Elements or GeVRE. This is an extension to the Unity game engine that allows triggers to be assigned a scent type, a location, and a volume size. These features can then be manipulated directly in the Unity interface. There is yet to be a system like this that is commercially available, however this may be set to change with the source development kit of the FEELREAL device. This might allow developers a much more intuitive and user-friendly way of integrating scents within a VR environment.

2.7.4 Design Heuristic Summary

To summarise the findings of this research, a series of considerations needed to fully integrate scent has been provided. These can be broken down into device and VR software considerations.

2.7.4.1 Olfactory Display Device

In the past, scent display devices have taken several different forms. These are influenced by the type of media that the olfactory stimulus should match. As VR is not a shared, group experience but rather an individual, the device can be optimised specifically to

- **Wearable vs In-Environment** – Whilst both are feasible, the future trends of VR will likely have the biggest impact on whether one format becomes more dominant. It is suggested that due to the 6 degrees of freedom offered by VR, portable and wearable device may become the favoured form factor for olfactory display devices (Murray et al., 2016). It is clear from past attempts at producing portable, head-mounted olfactory display devices, this is not an easy feat. The lack of any of these devices becoming commercially available, coupled with disappointing initial reviews further reinforces this. If VR arcades become more commonplace, this may afford more complex and reactive scent display devices that could be integrated into the space through a built-in air supply and ventilation system.
- **Device Accessibility** – It has been found in this research that individuals experience scent in different ways, particularly as we age. A device should be able to cater to people of differing olfactory detection thresholds. Therefore, a device would ideally be calibrated to the individual, perhaps through an initial start-up

experience, similar to how monitor brightness can be calibrated to individual users before a video game begins.

- **Stimulus dispersal, delivery, and removal method** – For a scent to be perceived, molecules must pass to the olfactory bulb through the nose. Scented air is therefore the most commonly presented method of delivering scent stimulus. The source of this scented air should be as close to the nose as possible to prevent desynchronization of olfactory and visual cues. Audio should be implemented through headphones to mask any mechanical sound that pre-empts the release of olfactory stimulus to avoid making the individual actively aware of the system. Scent should also be able to be removed from the individual's perception as soon as possible to prevent scent blending. In past examples, this has taken the form of a fan that blows any remaining scented air away from the individual before the release of the next scent.

2.7.4.2 VR software design

- **Designing the experience with scent in mind** – Scent is likely difficult to integrate into media that never originally intended to include it. Scents should be limited in their use so as not to release too many different scents too close together, resulting in unwanted blending of smells. Instead, experiences should integrate scent in a meaningful way that might become an active method of interaction with the individual. It could be used to enhance a narrative or provide vital information about a task or objective.
- **Location-based release of stimulus** – For a fully immersive VR experience, scent should be reactive to the individual's actions rather than be tied to a never-changing 'scent-track'. A device would ideally be able to vary the concentration of the released scent, based upon the individual's location within the virtual environment, thus allowing for a fully reactive system of scent display.
- **A Standardised and modifiable method of integrating scent interaction into industry standard game engines.** – In order for scent to be utilised within VR experiences, developers would need to be given intuitive and compatible ways of interfacing a scent device with the most common game engines on the market. This would likely take the form of a plugin or API that would allow scent cues to be added directly within the game engine used to create the experience. By integrating the player character's position within the virtual environment, it would

be possible to track how close the individual is from the scent source. This would enable the use of location-based release of scent stimuli as previously detailed.

2.8 Summary

This study of existing literature demonstrates that there are a number of factors that must be accounted for when developing scent display technology. Olfaction is inherently more difficult to design for due to the lack of universal measurement or classification system as well as the lack of understanding of how scents are composed at a molecular level. It has been shown that whilst scent is largely not utilised widely in entertainment and gaming, it has been examined and studied in laboratory conditions. This lack of a universal scent display device has led to several proposed and tested devices through these studies, each offering benefits and limitations based on their intended purpose. This variation extends into the interface technology that links the physical scent display device and the VR environment. Many examples have had to develop custom scripts and interfaces to allow scent display devices to communicate with the VR environment. Whilst only a small sample of recent studies have been included in this literature review, a more in-depth systematic review of technologies will be conducted in the next to help identify any commonalities. The presented design heuristics offer foundation for search terms and categorisation within the systematic review.

Chapter 3: An Investigation into Olfactory Display Technology for Virtual Reality: A Systematic Review

3.1 Introduction

This chapter outlines the method, results, and discussion of a systematic review of studies in which olfactory display technology has been used alongside virtual reality. The aim of this review is to provide researchers and developers of olfactory display technology with an overview of previously used technologies, along with the benefits and limitations of certain implementations. It was previously reported that there are many factors that must be considered when developing olfactory display technology. It is hoped that this might provide a starting point for those that wish to develop an olfactory display device for use with a virtual reality headset by categorising and organising these attempts whilst providing a commentary on the findings.

3.2 Context and Heuristic Considerations

For the purpose of this systematic review, the definition of a scent display device is any tool that has the ability to release an odorant. It does not have to release scents digitally but to be included in this review it should be used alongside a VR head mounted display (HMD). The following heuristic considerations have been identified from the previous literature review to find permutations of technologies as well as understand commonality between studies. Each consideration is posed as a question and the answers to each will aim to address research question 2 of this thesis: How is olfactory display technology currently used alongside VR?:

1. **What methods of odorant dispersal and delivery are commonly used and what is the most prevalent?** As outlined in the previous literature review, Yanagida (Yanagida, 2012) categorised a number of methods of vaporising and delivering an odorant. These range from simple methods such as natural vaporisation to more controllable ultrasonic atomisation. This review aims to identify the methods of dispersal and delivery used in a range of studies that implement olfaction with VR to discover if there is a commonality or a prevalence in any specific methods and if so, what reasons are provided.

2. **What is the prevalence of "in environment" scent display devices compared to wearable devices?** As stated in the literature review, Murray (Murray et al., 2016) presents a taxonomy of olfactory display devices in which 2 modalities of olfactory display device are presented: *In The Environment* devices and *Wearable Devices*, this question aims to identify the prevalence of these formats when integrating olfaction with VR.

3. **To what extent does the Scent Display Device communicate with the Virtual Environment (VE) and how is this achieved?** An important element of the experience of using an olfactory display device alongside VR is whether the device can communicate with the VE and receive commands to release odorants from triggers within the VR environment. This was a prominent heuristic suggestion of the literature review and may offer richer opportunities for interaction. This would allow VR users to trigger scents based on their interactions with the VR environment automatically. For this to function, an electronic communication between the VE and olfactory display device is required (Patnaik et al., 2019). For many devices, this integration is impossible (Candle diffusers, Ambient diffusers etc). Many VR experiences are developed using commercially available game engine software such as Unity or Unreal Engine 4 which allow for interfacing to the olfactory display device. This systematic review aims to identify how many studies utilise this system of automatic triggering as well as if a detailed overview is offered as to how this integration is achieved. It also aims to understand which game engine is the most commonly used within these studies which might help researchers develop the software interface element of a scent display device.

4. **How many scents are used in the study? If more than one, is there a method of preventing contamination between multiple scents?** It may be important for olfactory display devices to be able to emit more than a singular scent. Using multiple scents often introduces an issue of scent contamination in which scents that are supposed to be kept distinct, begin to blend with one another (Kato & Nakamoto, 2019). It is therefore interesting to understand how many studies utilised more than one scent and the methods they implemented, if any, to prevent scent blending and residual odours.

5. **What limitations are presented with the use of the identified scent display devices as identified by the researchers?** Because of the experimental nature of many of the devices used in olfactory studies, there is likely to be issues and limitations to be identified. The objective of this question will be to find common reoccurring issues or limitations as presented by the study's authors. It is hoped that solutions to some of these issues will also be suggested throughout the studies.

6. **How many studies examined the participants sense of presence?** This question is based on a primary aim of the thesis in which it is hypothesised that the inclusion of olfactory stimulus increases an individual's sense or presence within VR. There is some evidence to support this statement (Dinh et al., 1999; Munyan Iii et al., 2016). This phenomenon is also touted as one of the primary reasoning for including smells within a VR environment (Maggioni et al., 2020b). There is, however, also some mixed results from other studies that have examined olfaction as part of a multisensory stimulus study that included haptic and wind interactions. Olfaction was found not to have any significant impact on the individual's sense of presence (Narciso et al., 2019). These mixed results were suggested in the prior literature review and formed an opportunity for further examination into the effects olfaction might have on presence. It is hoped that more clarity on our understanding of this question might be gained by examining the included studies use of olfaction and its role in an individual's sense of presence along with the results they present.

The questions presented above will be analysed quantitively and then discussions regarding the results for each question will be presented.

3.3 Method

The use of a systematic review offers a comprehensive overview of literature related to the olfaction with VR. It allows for an analysis and synthesis of data from a wide range of sources which can be presented quantitatively. Discussions of notable studies provide further context surrounding methodologies and results. In order to identify a comprehensive list of as many possible studies related to the research questions a systematic review framework called Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) was used. This offers a peer-reviewed framework for carrying out systematic reviews and this will be utilised in this systematic review. The PRISMA framework identifies 4 stages that have been used for this systematic review: Identification, Screening, Eligibility and Included.

3.3.1 Search Criteria

An important step in the identification process involves selecting appropriate databases in which to search for literature. In this study, 4 databases were selected: IEEE Xplore, ACM Digital Library, Science Direct and SpringerLink. These were selected due to the quality of literature related to computing and technology (*Computing - Built Environment, Computing and Engineering - LibGuides at Edinburgh Napier University*, n.d.) The following inclusion and exclusion data was defined in order to help refine searching:

- Only studies that state the olfactory display device used should be included.
- Only studies that use Virtual Reality (HMD or CAVE) should be included. It was argued in the previous chapter that 360-video is separate from the 6 degrees of freedom offered by virtual reality, the use of head mounted displays constitute a similar setup from which to draw insight into olfactory display technology. Therefore, this review will include studies that have used HMD 360 video VR.
- Only studies after 2013 will be included. This was selected as it was the release year of the Oculus Rift Developer Kit and was the start of commercially available VR setups.
- Studies that use multisensory stimulus (Wind, Haptics etc) alongside olfaction will be included if the scent display technology is outlined.
- Only studies found in Peer-Reviewed Journals and Conference papers will be included.
- Only studies in English will be included.

Search terms were directly related to both virtual reality and olfaction were used to formulate the search query. Synonyms for Olfaction identified due to the variation in terminology were: “Scent, Smell and Multisensory”. Advanced search functions were used, employing the use of Boolean operators to ensure synonyms were also factored into the search. Exact phrase matches for ‘Virtual Reality’ were also used along with a wildcard search term of “olfact*” in order to isolate any results with the term “olfaction” and “olfactory”. In all database searches, the year of publication was limited to between 2013 – 2021. Search query syntax and the number of results are presented in the table 1.

Table 1: Search terms, dates and result numbers from systematic search of 4 databases: ACM Digital Library, IEEE Xplore, ScineceDirect and SpringerLink

Database	**Date of Search**	**Search Query**	**Number of Results**
ACM Digital Library	14/01/2021	Title:(("Virtual Reality" OR VR) AND (Olfact* OR Scent OR Smell OR Multisensory)) OR Abstract:(("Virtual Reality" OR VR) AND (Olfact* OR Scent OR Smell OR Multisensory))	52
IEEE Xplore	18/01/2021	("Virtual Reality" OR VR) AND (Olfact* OR Scent OR Smell OR Multisensory)	137
ScienceDirect	18/01/2021	("Virtual Reality" OR VR) AND (Olfaction OR Scent OR Smell OR Multisensory) Enabled checkbox for research articles and conference papers only	171
SpringerLink	18/01/2021	This database does not support Boolean searches, instead using input fields for “exact phrase” (Virtual Reality was inserted here) or “with at least one of the following words” (Olfaction, Olfactory, Scent, Smell and Multisensory) were included here.	154

There were 514 recovered studies once the results from each database were combined. These citations were imported into Mendeley using BibTex format export from each database. SpringerLink only allows for CSV format exporting of citations. However, the DOI from this list could be identified using the magic wand search in Zotero. This in turn could be then exported as a BibTex file for import into Mendeley. Using the find duplicate tool in Mendeley, 15 duplicates were removed from the results leaving 499 results. The remaining results were screened by hand using the linked abstract to remove any studies that did not present an olfactory display device or use of olfactory stimulus within the study. On occasion, it was required to examine the body text of some of these studies in order to validate that these should not be included. After completing this round of exclusions, 88 articles remained. Because the focus of this review was for the use of an olfactory display device alongside VR, another round of exclusions was carried out to isolate only studies that had used a VR Head Mounted Display (HMD). Despite 360 Video VR lacking the 6 degrees of free movement, it offers a similar platform in which to implement an olfactory stimulus. After this was filtered by reading through the methodology of the remaining studies, 34 studies remained that fulfilled the criteria for inclusion in this review.

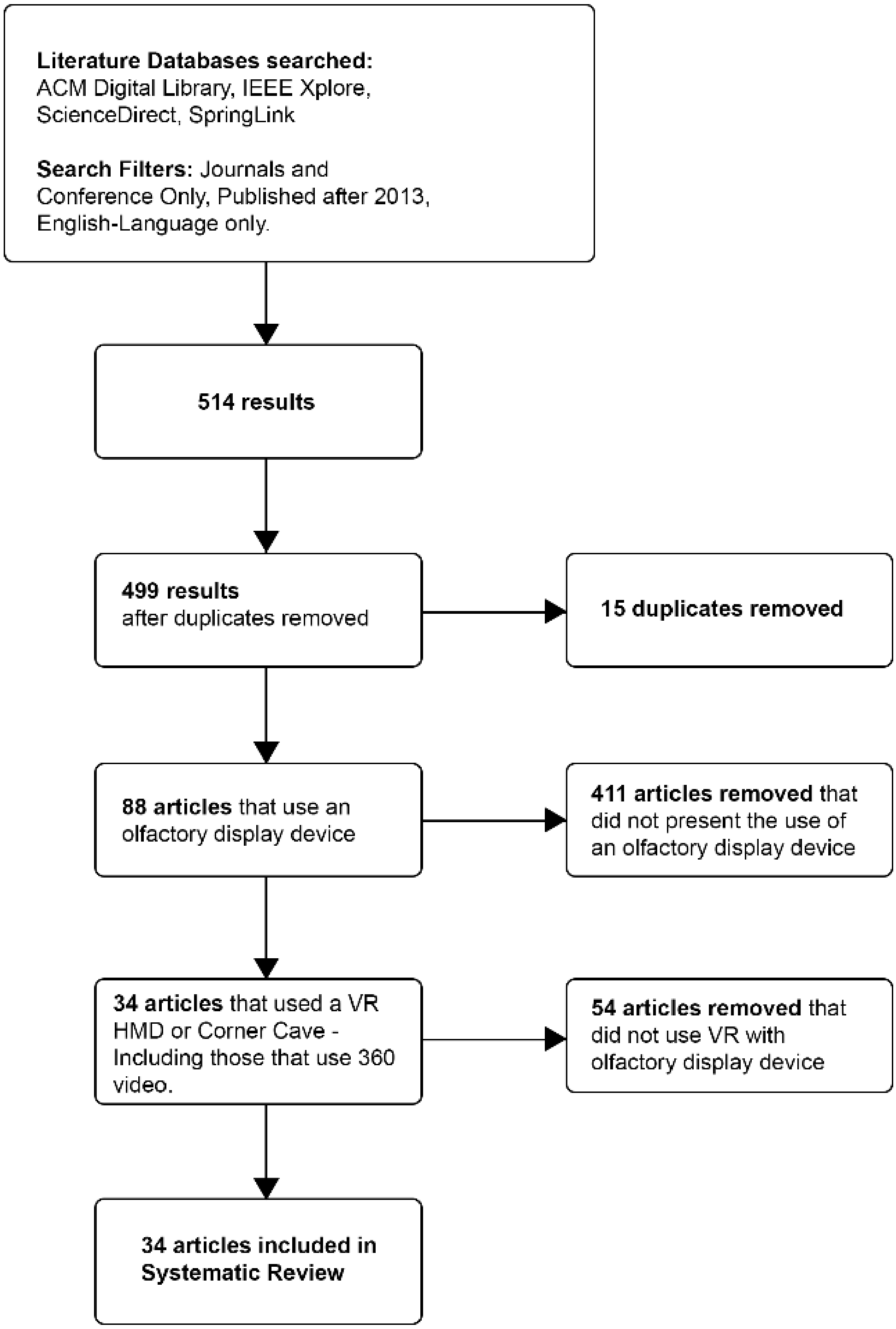

Figure 4: PRIMSA Diagram of Exclusion Terms (Page et al., 2021)

3.3.2 Categorisation

In order to facilitate analysis of the included literature, the articles were given categories based upon the previously outlined research questions. These categories included:

- **The year of publication:** During the identification process, a filter from 2013 to 2021 was applied to identify studies that might utilise commercially available VR technology (2013 was the year in which the Oculus DK1 was released). It is useful to understand if interest in developing olfactory display technology has grown as VR becomes more available and affordable.
- **The Dispersal and Delivery Method:** Each included result was coded with a term to describe what type of odour dispersal and delivery method was used within the study. From this, it is therefore possible to understand the most prevalent and common methods of releasing an odorant to the VR participant. This code is broken into 2 subsections to identify the dispersal (ultrasonic atomisation, electronic diffuser etc.) and delivery to the nose of the participant (Air flow from fans, air flow through tubes etc.). Using this coding convention, it is possible to code a wide range of methods into a consistent categorisation that can be used to provide statistical data on prevalent methods. This categorisation is designed to address research question 1.
- **Whether a device is In-Environment or Wearable:** This category aims to address research question 2 and is based on the categorisation set out by Murray (Murray et al., 2016). It was decided that this categorisation should outline whether the device is in-environment or wearable and what forms the devices take within these categories. For example, an in-environment device might be desk mounted, ceiling mounted, floor mounted etc. whilst a wearable device might be carried around the neck, handheld or head-mounted. It is hoped that this will provide a method of identifying a more detailed range of form factors found within the included studies to better understand the physical methods of utilising an olfactory display device.
- **Whether the device communicates with the VR software:** This category aims to answer research question 3. By isolating examples of studies that have used an olfactory device that can communicate with the VR environment (for example, trigger the release of a scent through the interaction between the individual and the VR environment). This categorisation allows for the removal of these unsupported types of VR so as to isolate any studies that use a game engine

technology such as Unreal Engine or Unity. A subsequent categorisation is designed to identify the method of integration along with the game engine software used.

- **The number of scents the device can emit:** The categorisation allows for the statistical analysis of the number of scents the devices can emit. It must be stated that this does not account for the number of scents used in throughout studies but rather the number of scents the device is able to store and emit at any one time.
- **Whether the device used is custom built for the study or if it uses a pre-built, off the shelf device:** As suggested in the introduction, because of the lack of bespoke commercial standard olfactory display device, studies have to either use pre-built devices that are not necessarily designed for VR or they must design a custom designed device suitable for the purposes of the studies. This categorisation will identify the percentage of these studies that utilise both. If a custom created device is developed, it will examine the components used in the foundation of the design.
- **Whether a study examined presence, and if it did, what method did it use to evaluate:** The examination of presence was not a requirement to be included in this systematic review, however it is interesting to identify the percentage of studies in which it was evaluated. A number of methods are available to examine presence (Reference) and this categorisation includes any methods, including the use of any pre-existing presence questionnaires.

The categories presented above can be used to find the most prevalent technologies used within not only the physical scent display device, but also the process of communication between the device and the VR environment. An objective of this study was to identify limitations as presented by the authors of the included studies but because the purpose and methods change between studies, it is not prudent to provide statistical data on the frequency of the mention of these limitations. Instead, a qualitative approach will be used, providing comments on any issues or problems and the impact they might have on the development of future olfactory display devices.

3.4 Results

The final corpus used for this review can be found in Appendix 1. The results are presented as statistical data for each categorisation, offering insight into the frequency of certain technologies as outlined in the included studies. This will consist of:

- The trend in number of publications each year,
- The frequency of each dispersal and delivery method for odorants, as well as the most common combinations of these.
- The frequency of each format,
- Whether in-environment or wearable, the number of olfactory display device which can communicate with the VR environment,
- The frequency of the number of scents used in studies.
- The frequency of custom-built device versus off the shelf devices
- The frequency of studies that examined presence alongside an olfactory stimulus.

3.4.1 Frequency of Publication by Year

From the inclusion years of 2013 to 2021 (Fig. 5), the results in the number of studies published each year offers an interesting insight into the trends of olfactory research for use with VR. It seen that from 2013 to 2018 there was rising interest in the topic, peaking at 10 studies published in 2018. However, there is decrease in the numbers of studies published in 2020 down to only 5. It is unknown why there is a sudden decline in the number of publications for this year, but it may be due to the impacts of the global Coronavirus Pandemic. At the time of writing, only one study has so far been published in 2021. It is encouraging to see the strong rising interest in this area of study which shows an upward trend in the examination of olfactory augmented VR.

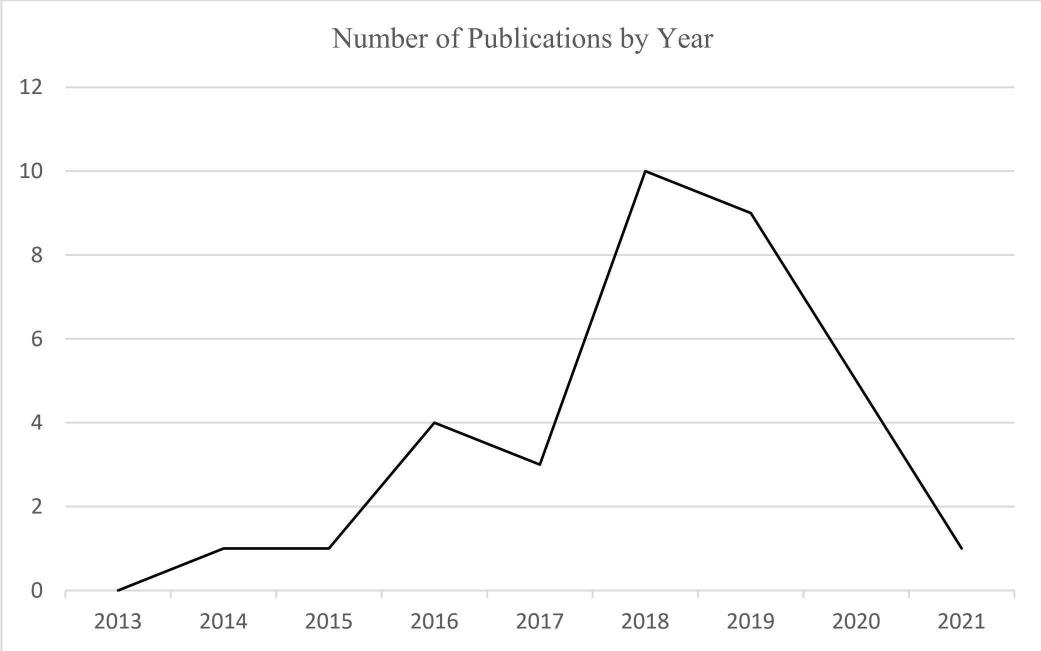

Figure 5: Number of publications by year from 2013 to 2021

3.4.2 Odorant Dispersal and Delivery Methods

From the range of odorant and dispersal methods outlined by Yanagida (Yanagida, 2012), it is clear that there is a prevalence in certain methods for both dispersal and delivery of an odorant (Fig. 6). It was found that the most common form of dispersal was accelerated evaporation by airflow (12 out of the 34 studies used this method). Both the use of ultrasonic atomisation and atomisation by airflow saw frequent use with 6 studies each.

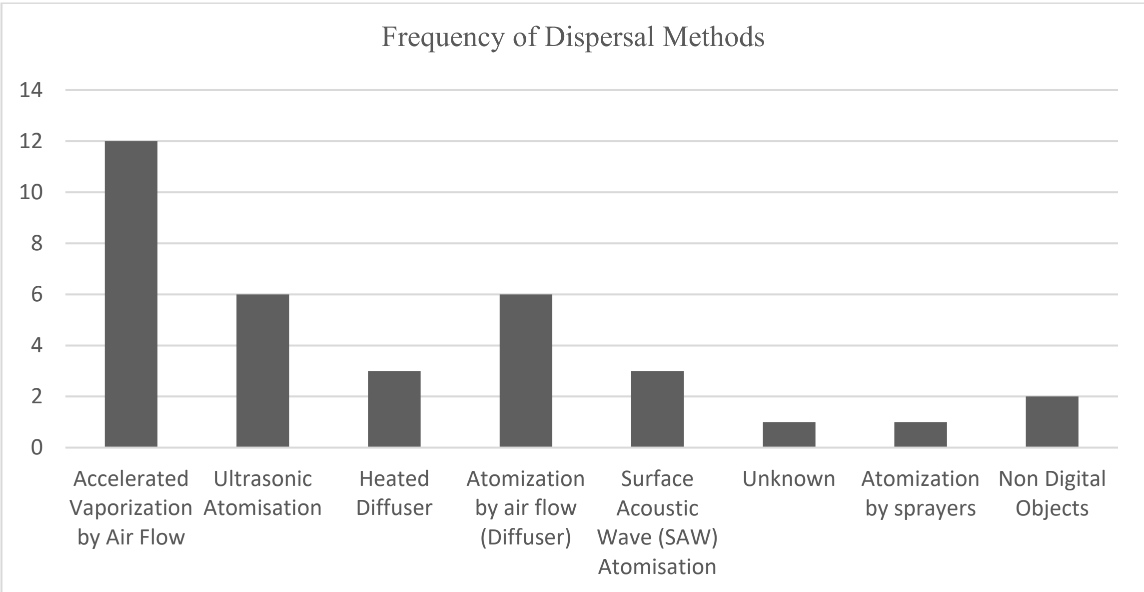

Figure 6: Frequency of Dispersal Methods.

Interestingly, only one study did not provide any detail on the method of dispersal used and 2 study did not use any form of artificial dispersal and instead used physical objects (Harley et al., 2018; Jones & Dawkins, 2018) to introduce scents. These included the use of sunscreen to represent the scents of the beach, and also undertaking the VR study outdoors in a park with the aim of used the natural odours alongside the VR representation of a meadow. The prevalence of the accelerated vaporisation by air flow may be explained by the advantages this offers over the other methods. This method often utilises a simple fan to draw air over the odorant which means that is often affordable and easier to trigger the dispersal of the odorant (Herrera & Mcmahan, 2014). Odorants can also be kept in a range of forms such as liquids (Essential Oils, Scented water etc) or as solids (Scented blocks, Gels etc) This stands in contrast to the other methods such as SAW atomisation which can offer a much smaller latency between triggering the scent and the dispersal but can also be much more complicated and expensive, requiring more specialist physical components.

When comparing the prevalence of delivery methods (how the odorant is delivered to the nose from the site of dispersal), both the use of wind (airflow) and natural diffusion / convection have their proponents in the included studies (Fig. 7). The prevalence of the wind (airflow) (15 studies) method of delivery can be explained by the fact that often the airflow that vaporises the odorant can also be used to deliver it to the nose if angled correctly, thus performing two roles with one component. Both dispersal and delivery of an odorant using these methods can be commenced or stopped simply by turning the airflow on or off respectively which may provide a low cost and accessible scent display system. Natural Diffusion / Convection makes up the second most frequent (12 studies) method of delivery. This is likely due to the simplicity of the delivery method and is more appropriate when presenting simple ambient scents into a room. This method often gives low controllability of the delivery of the scent but offers the benefit of not requiring any active intervention by a device to release the scent into a space. This can be beneficial when only a single ambient scent is required throughout the study (Serrano et al., 2016).

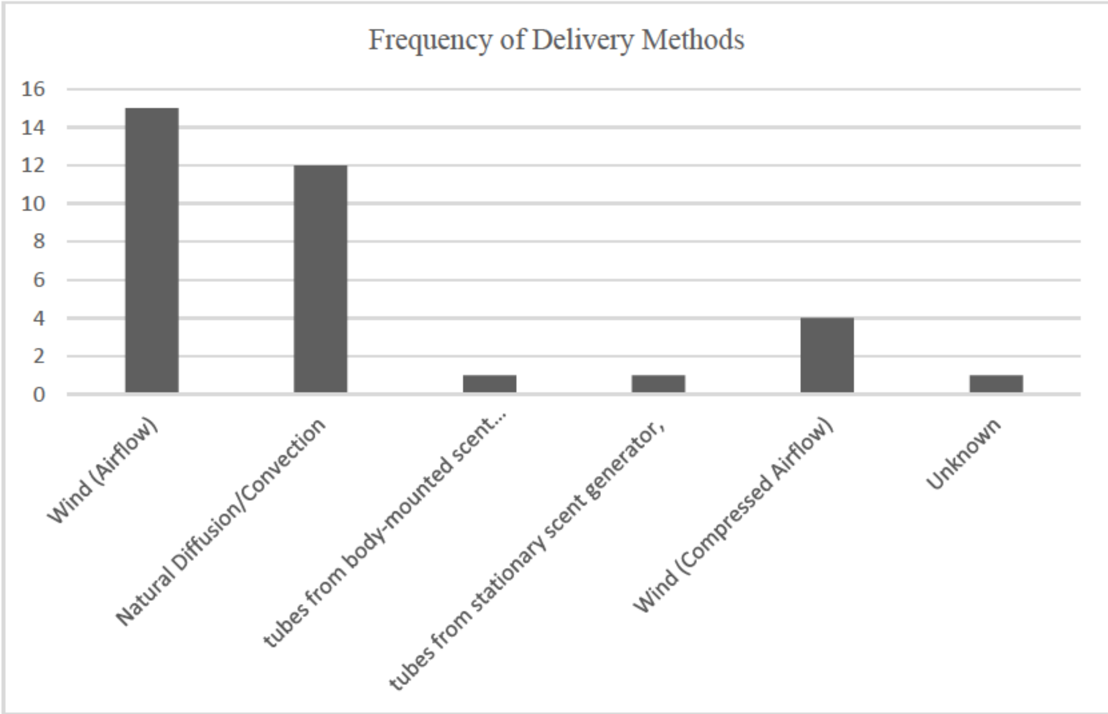

Figure 7: Frequency of Delivery Methods.

The relationship between accelerated vaporisation by airflow and delivery by wind (airflow) can be confirmed when examining the most frequent combination of dispersal and delivery methods (Fig. 8). This combination of accelerated vaporisation by airflow for dispersal and wind (airflow) for delivery is the most commonly used, with 7 of the 34 studies reporting having used an olfactory display device that uses these methods. Interestingly, there are 3 other combination of methods which see the same prevalence across the included studies: Ultrasonic atomisation with natural diffusion / convection, atomisation by airflow (diffuser) with wind (airflow) and accelerated vaporisation by airflow with wind (compressed air). Each of these combinations were reported 4 times within the included studies. Of note is that airflow is featured in all of these methods which suggests that the use of air to control and direct scent offers

Dispersal Method	Delivery Method: Wind (Fan Assisted Airflow)	Natural Diffusion/Convection	Tubes from body-mounted scent generator	Tubes from stationary scent generator,	Wind (Compressed Airflow)	Unknown
Accelerated Vaporization by Air Flow	7		1		4	
Ultrasonic Atomisation	2	4				
Heated Diffuser		3				
Atomization by air flow (Diffuser)	4	1		1		
Surface Acoustic Wave (SAW) Atomisation	2	1				
Atomization by sprayers		1				
Non Digital Objects		2				
Unknown						1

Figure 8: Combination frequency of dispersal and delivery methods. The numbers indicate how many studies used the corresponding combination of methods.

3.4.3 In-Environment or Wearable

When examining the form factor of the olfactory display devices used in the included studies, it was found that there were more (18 of the 34 studies) fixed, in-environment scent display devices than there were portable, wearable devices (12 of the 34 studies). Each of these categories were broken down further into subsections (Fig. 9). Of the included studies only one was described as being capable of functioning as a desktop mounted device or could be attached to an HMD (Patnaik et al., 2019). The most common form of in-environment device were those placed within a room but were too large or had additional components that could not be kept solely on a desktop. It is worth noting that when discussing the in-environment devices and their location with a physical space, this review refers to how each device was used as described in the methodologies. It may be that some of the devices listed in the Room category, may be able to function as a desktop mounted device for example but this was not described in detail in the included studies. Examples of studies included in the in-environment room categories include simple diffusers placed in the corner of a room (Flavián et al., 2021; Serrano et al., 2016) to devices mounted to frames within the physical space (S. Jung et al., 2020; Marquardt et al., 2018; Shimizu et al., 2018). When examining wearable devices, it was found that HMD - mounted formats were the most common (7 of the 12 studies in the wearable category). This appears to be in line with the statements of Murray (Murray et al., 2016) in which it was argued that HMD – Mounted devices may be the most appropriate for VR due to the ability to keep a consistent distance to the individual’s nose, no matter the orientation or facing of their head. Interestingly, the more frequently found dispersal and delivery method combination of accelerated vaporisation by airflow and wind (airflow) does not appear to hold the same percentage of usage within studies when comparing those that only used an HMD mounted olfactory display device. Only 2 studies used the accelerated vaporisation by airflow and wind combination (Covaci et al., 2019; Covarrubias et al., 2019). Another commonly used method of dispersal in studies using HMDs include the use of surface acoustic wave (SAW) atomisation and wind (airflow) for delivery. 2 studies in the HMD category used this combination (Kato & Nakamoto, 2018a, 2019). It worth noting that both of these studies were carried out by the same author, and whilst the devices presented in each study are different, the later device may have been developed from refinements of the first study. The use of Ultrasonic atomisation in this category is also of note in which 2 studies use it (Brooks et al., 2020; Patnaik et al., 2019). It is thought that because the device is attached to the HMD, the atomisation can occur very close to the nose of the participant and the lack of controllability of natural diffusion becomes less of a problem as the scent has only a short distance to travel to the nose. This lack of consistent delivery and dispersal method for HMD device demonstrates that there is still further potential research in order to isolate the most efficient methods of releasing scent stimulus in this format.

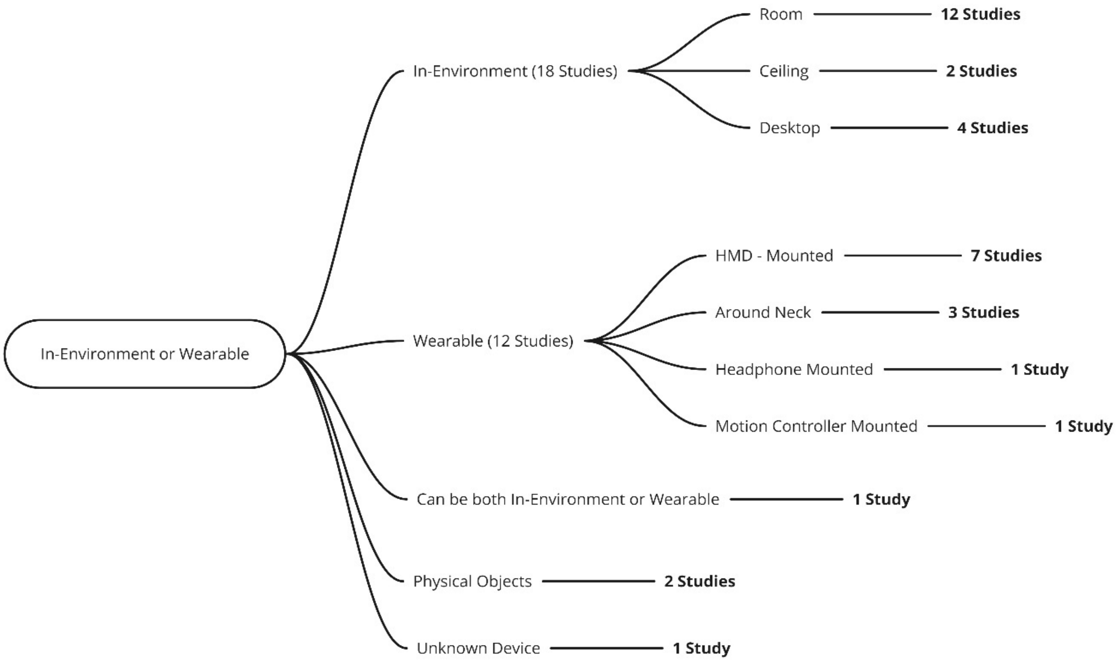

Figure 9: Tree diagram showing the frequency of in-environment or wearable devices, with the frequency of the subcategories within these.

3.4.4 Communication with VR software

Of the 34 studies examined, only 12 could be identified as having some form of communication between the VR environment and the olfactory display device, that is to say the device received its trigger to release scent from something the VR user does within the VR environment. It was found that 18 studies used no direct integration of the device with the VR environment and in 4 studies it was not stated whether there was any integration. This lower number of studies that use integration into the VR environment may be explained by the format of some of the devices such as candle diffusers (Serrano et al., 2016) which offer no way of interfacing with a digital device. Other studies, although they used digital olfactory display devices, also used 360-video VR which is more complicated to offer direct interaction due to the video nature of the content. Interestingly, in a study by Covaci (2019), a olfactory display device was developed for use alongside 360 Video VR content in which the video content was overlayed with a grid and based on where the centre of the viewer's gaze was, could use the grid coordinates to communicate with the olfactory display device to emit an odour. Thus, certain images in the 360 videos could be assigned tags which could be used to trigger the device. Another reason for this lack of communication between hardware and software in studies is that many simply did not require this level of communication, particularly if only one consistent ambient scent was required, then this integration would add a complex and often unnecessary step in the design of a study.

Of the 12 studies that did include some form of communication with the device and software, an analysis of the software used was carried out. Unity was the most commonly used software to develop the VR environment with 6 out of the 12 studies using it. Of these 6 studies, 3 used an Arduino (an open source electronics platform) interface to receive the triggers from the virtual environment (Luo & Vega, 2018; Patnaik et al., 2019; Ranasinghe et al., 2018) and the remaining 3 studies used custom built interface devices to trigger the release of stimulus (Brooks et al., 2020; Kato & Nakamoto, 2018a, 2019). The 6 remaining studies that include some form of communication with software had one using Processing (Herrera & McMahan, 2014a) and another using Virtools 5 (Baus & Bouchard, 2017). The remaining 4 studies did not offer any information on the software used.

In all 12 of the included studies in this section, none offer a detailed methodology of how the communication between the device and the software functions in which the software set up could be repeated. Many are described in experimental outlines in passing as using Serial commands from the software to communicate with the olfactory display device. (Kato & Nakamoto, 2019; Ranasinghe et al., 2018). In one study, the scent is triggered based on the proximity to a virtual scent source. As the VR user gets closer to the source in the virtual environment, the release of scent is triggered (Herrera & McMahan, 2014b). In another study, the scents are triggers when the user collects objects within the virtual environment, encouraging active exploration of the space (Kato et al., 2018).

There is overall a lack of description of the methods used to interface an olfactory display device with the virtual environment software. This gap in detail offers an interesting avenue of research and in response to this, a methodology for this will be provided in the following chapter.

3.4.5 Custom devices VS Commercially Available Devices

As stated in the introduction, the lack of a readily available olfactory display system specifically created for VR has led many researchers to develop their own bespoke designs or to use commercially available products not designed for use in VR. When examined it was found that 15 of the 34 studies used a custom-built device, 13 used an off the shelf device, 2 used physical objects and 4 did not present any details on the format of the device. The custom devices primarily use an Arduino based system to control and trigger scents (9 of the 15 studies used this). 1 study used a Raspberry Pi as the controller and 5 used a custom circuit. The prevalence of the Arduino platform may be explained by the benefits the system offers. Arduino can be used for a range of electronics projects in which many of the parts used for an olfactory display device can be used, such as fans as well as ultrasonic atomisers with relative ease. Because of its open-source nature, this can be adapted to receive commands from a range of additional software. It is this method that many of the previously discussed Unity projects may have used. Because each study has a specific purpose and requirements, the Arduino platform allows for customisation of design to best fit the needs of the researcher. Another factor for its popularity is likely due to the affordability and ease of making a singular prototype instead of manufacturing a device (Banzi et al., 2010).

It was found that there are a range of commercially available devices used in the 13 studies in this category (Fig. 10). These often differ in a wide range of variables from dispersal and delivery methods to the number of scents which the device can emit. The most commonly used device is a simple electronic diffuser with 5 of the 13 studies using this method. These are only capable of emitting a singular scent and do not integrate directly with the VR environment. They are used for studies in which the addition of an ambient scent is being examined. 5 specific commercially available devices were identified in this review: BioPac SDS100 (*Scent Delivery System | SDS100 | Research | BIOPAC*, 2020), a device that is wearable around the neck developed by Exhalia (*Www.Exhalia.Com*, n.d.), a device developed by Olorama capable of emitting 10 scents (*Professional 10-Scents Compact Generator | Olorama Technology*, 2018), a SensoryScent 200 (*SCENT DELIVERY SYSTEMS FOR EDUCATION, RETAIL, CARE PROVIDERS, THE LEISURE AND ENTERTAINMENT INDUSTRIES*, 2015) and a SensoryCo SmX – 4D (*SMX 4D Aroma System Provided by SensoryCo4D*, n.d.). Of these devices, the SmX – 4D was used in 3 studies. This device is primarily designed for 4D cinema experiences and simulators. It works through a proprietary microcontroller that is capable of releasing compressed scented air through a nozzle which can be attached to a static point in the physical space. Availability and cost appear to be the main limiters and perhaps provides insight into why these devices are not used in a greater percentage of the overall studies featured in this review. The BioPac SDS100 (A desktop mounted device that can emit 8 different scents) is also only available for purchase in the United States and only the Olorama device is given a list price of, at the time of writing, €1,949 whilst the other devices require customers to request quotes for orders. This lack of availability and often high cost may be prohibitive to many researchers who require a more tailored approach, more suitable for the purpose of the study at which stage it may be more appropriate to use a custom-made device.

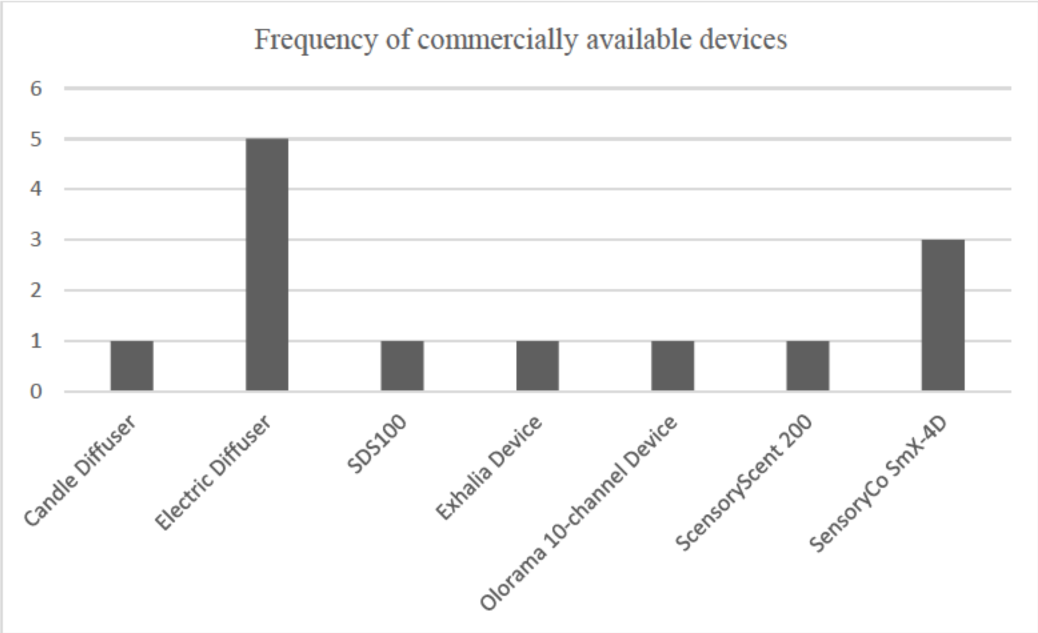

Figure 10: Frequency of commercially available devices

3.4.6 The Number of Scents Devices are Capable of Storing and Emitting

When examining the number of scents each device used could store and emit at any one time (the scents did not have to be manually changed during the study) it was found that a single scent was the most common with 15 of the 34 studies reviewed (Fig. 11). The highest number of scents in any device was 10. This can be attributed to the commercial Oloroma 10 channel device (*Professional 10-Scents Compact Generator | Olorama Technology*, 2018). The second highest was the 8 scents that the SDS100 is capable of emitting. Interestingly, the third highest (6 scents) was from a custom built Arduino controlled device (Patnaik et al., 2019) in which 6 ultrasonic atomisers are lined up under the nose, attached to a HMD. A fan on either side of the atomisers helps guide the scents to the nose. A problem that often occurs when using multiple scents is that scents often blend together and it becomes harder for the VR user to discern the individual scents (Kato & Nakamoto, 2019). Interestingly, the study by Patnaik et al. (2019) was designed so that the scents would blend together as part of the methodology in which participants were tasked with discriminating scent pairs. This scent blending is often an unwanted and problematic side effect of releasing multiple scents in close proximity and may suggest why the majority of studies only chose to use a singular olfactory stimulus. The methodology of a number of studies compared a VR experience with scent and without scent, in which the use of a singular scent was appropriate (Baus & Bouchard, 2017; Herrera & McMahan, 2014b; Jiang et al., 2016).

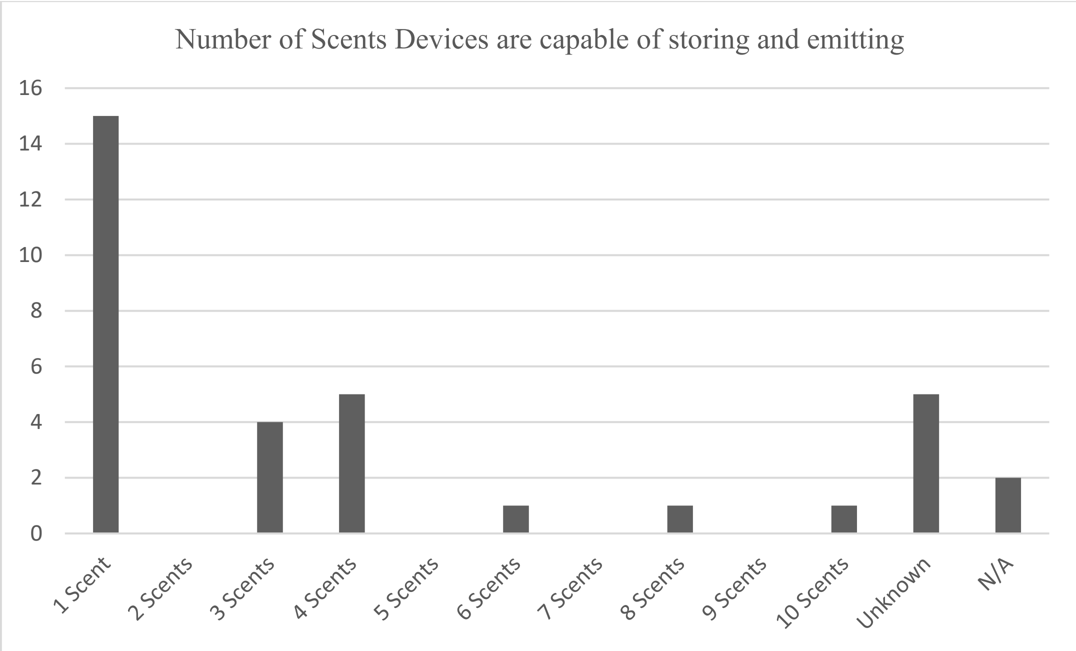

Figure 11: The frequency of the maximum number of scents devices can store and emit.

Interestingly, a number of custom designed devices are able to emit multiple scents and in two of these studies (Chen et al., 2018; Ranasinghe et al., 2018) air fans are utilised as a method of purifying the air around the participant's nose to minimise the scent blending as described previously. In the latter study, participants also commented that some scents were stronger and more noticeable than others which may introduce another complex design challenge: scents should be of the same perceived strength as each other to prevent one singular scent from overpowering another.

3.4.7 Number of Studies to Examine Presence

Although the study of presence was not a requirement for inclusion in this review, a focus of this thesis is the impact the inclusion of scent stimulus has on an individual's sense of presence. It therefore felt prudent to examine how many of the included studies addressed this phenomenon. Of the 34 studies included, 15 evaluated capacity to some degree. (Fig. 12) In some cases, this included the use of items from peer reviewed presence questionnaires (PQs), whilst others developed bespoke questions related to presence and realism of a VR environment with the inclusion of a scent stimulus.

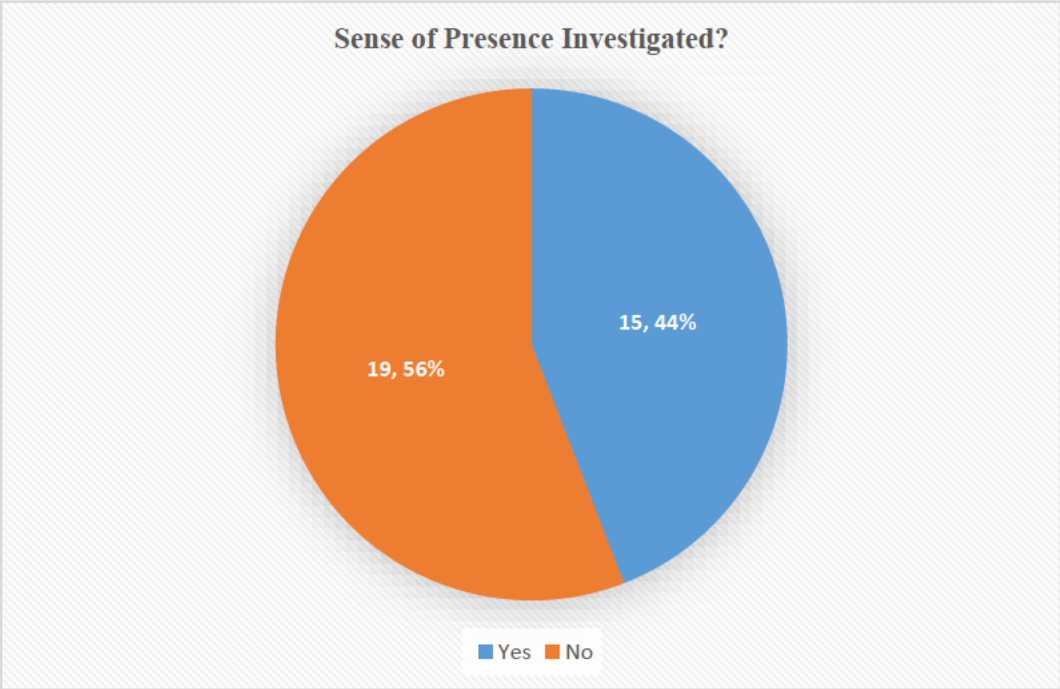

Figure 12: Number and Percentage of studies that investigated presence as part of methodology.

The frequency of existing presence questionnaires was also examined of the 15 studies in this category (Fig. 13). It was found that the following PQs were used: Witmer Singer PQ (Witmer & Singer, 1998), Slater-Usoh-Steed (SUS) PQ (Usoh et al., 2000) Pictorial Presence Self-assessment-manikins (SAM) (Weibel et al., 2015) iGroup PQ (T. Schubert et al., 2001) and the International Telecoms Union Telepresence Questionnaire (ITU-T P.913) (*P.913 : Methods for the Subjective Assessment of Video Quality, Audio Quality and Audiovisual Quality of Internet Video and Distribution Quality Television in Any Environment*, n.d.).

It was found that the iGroup PQ was the most frequently used presence questionnaire followed by the Witmer Singer PQ. Both of these PQs are peer reviewed and offer strong reliability in results (Schwind et al., 2019b). 5 studies used self-created presence questionnaires, and these varied from examining a sense of reality within the VR environment (Covaci et al., 2019) to examining a feeling of immersion (Brooks et al., 2020). It is unclear if these are working to the same definition of presence as intended by the peer-reviewed PQs, for this reason these studies have been binned into this separate category.

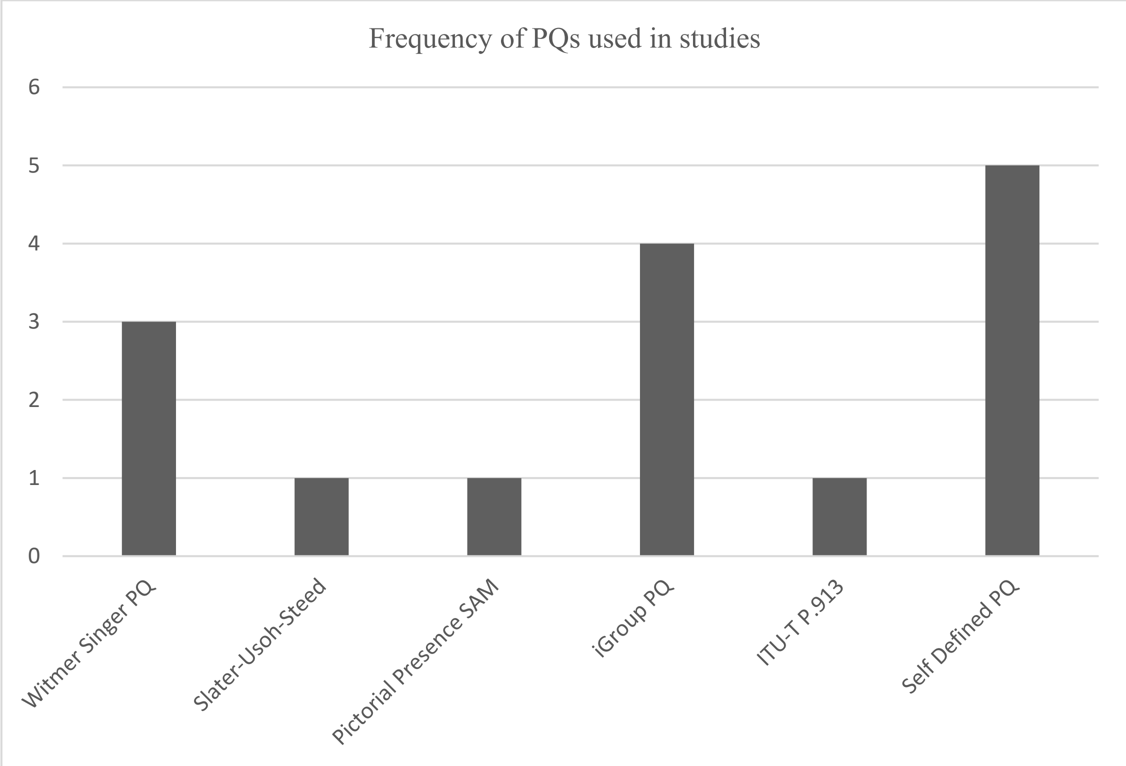

Figure 13: Frequency of Presence Questionaires used in Studies.

The investigation of the impact olfactory stimulus has on sense of presence provides interesting results. It was found that of the 15 studies, 7 presented some degree of positive impact on the participant's sense of presence, 4 studies found no statistical impact and another 4 presented results in which the impact of olfaction was not possible to parse from the results (Fig. 14). This was most often because these studies also examined a range of other multisensory stimulus (Wind, haptics etc,) at the same time. These studies that used multisensory stimulus often examined all stimulus against a control with no stimulus. Therefore, it was not possible to discern the impact olfaction has specifically. These studies did suggest that the inclusion of multisensory stimulus did increase the sense of presence felt by the participants (Covaci et al., 2019; Goncalves et al., 2020; S. Jung et al., 2020). Of the studies that did report a positive impact, it was found that the sense of presence felt was variable. One study found that although olfaction did have a minor positive impact, temperature effects had a greater impact (Jones & Dawkins, 2018). Another study that examined multiple scents found that some scent increase the sense of presence more than others, in particular an orange scent was found to be the most impactful (Carulli et al., 2015). Another study found that although the inclusion of olfactory was seen to have an impact on presence, it was found that this was minimal (Brooks et al., 2020). These mixed results when examining presence appear to substantiate the suggestion made in the previous literature review chapter. It is worth noting that there were a number of different methodologies used to examine presence along with other limitations identified by the authors. A study that found no statistical impact on the sense of presence only used a small sample size of 10 participants (Herrera & Mcmahan, 2014). The results presented here may not be entirely emblematic of the impact scent might have on presence within VR and should not be considered to be entirely conclusive.

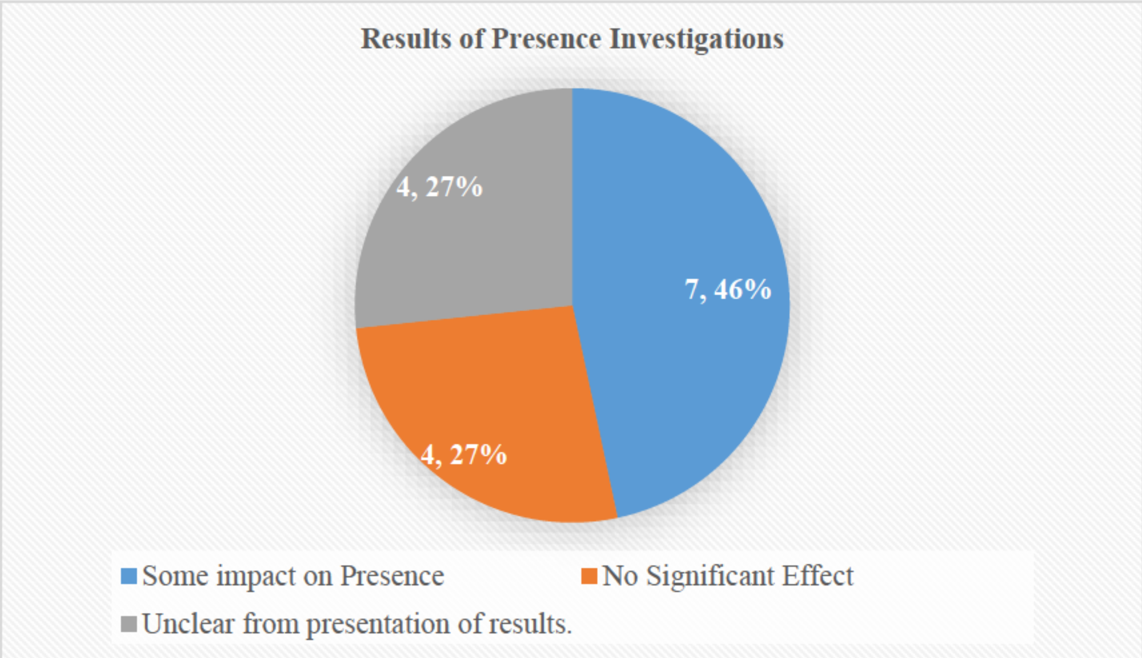

Figure 14: Results of presence investigations in studies presented as numbers of studies as well as percentages.

3.4.8 Author-Identified Limitations

An analysis of the included studies of this review for any limitations and issues of the used devices was worth including. Because the purpose, methodology and devices themselves vary between studies, it was decided that a quantitative analysis of these would not be appropriate when discussing the limitations. However, a quantitative analysis of the number of studies in which a limitation is presented has been carried out. 14 of the 34 studies presented some form of limitation related to the design of the olfactory display device. Some of the limitations presented by the researchers include the design of an fixed, in-environment design meant there was inconsistencies between participants distance to the olfactory display device (Herrera & McMahan, 2014c). Two studies found issues using ambient odours in which it began an issue to keep a consistent odour concentration within a physical space when using diffusers (Jiang et al., 2016; Serrano et al., 2016). There was mention of olfactory fatigue, sometimes referred to as olfactory habituation in which the individual becomes less actively aware of a scent the longer they are exposed to it. This issue was encountered in multiple studies to varying degrees (Flavián et al., 2021; Patnaik et al., 2019; Ranasinghe et al., 2018). Several studies also suggested that the scents that the devices were emitting were not being cleared from the surrounding air sufficiently and this led to lingering scents. (Baus & Bouchard, 2017; Herrera & McMahan, 2014b; Kato & Nakamoto, 2018a). A study that used the scents of an outdoor space as use of the olfactory stimulus suggested that whilst the study worked for that instance, it would be very difficult to provide repeatable results as the outdoor scents would change based on a range of environmental factors that the researcher would not be able to account for in any future design.

The limitations presented here align to those of the phenomena described in the prior literature review relating to olfactory fatigue negatively impacting VR experiences. Studies in which there are little to no methods of removing scent after it has been released appear to also cause detrimental effects on the overall experience. Kato (2019) suggests a method in which scent is prevented from spilling into the surrounding environment by passing the air through an deodorising carbon mesh which is designed to remove excess odour. It is suggested in the results that scent do appear to linger to some degree, however. This is a challenge facing many designers of olfactory display technology and it is noteworthy that this issue still appears to persist in some of these studies.

3.5 Summary

The results presented above aim to provide a comprehensive overview of the current state of technology and studies that have utilised an olfactory display device with VR using a systematic method of inclusion. The criteria for inclusion successfully addressed a series of the design heuristics as presented in the previous literature review and further adds validation to these. A number of the potential issues as outlined in that chapter, including the problems of lingering scent, olfactory fatigue were confirmed to be prominent issues. The mixed results when examining the impact olfactory stimulus has on presence reinforces the argument suggested in the literature review that further research is required to confirm these results.

It is clear that there are a wide range of different methods for dispersing and delivering olfactory stimulus. It is suggested that there is not necessarily a universally more common scent display system and recommendations will likely be determined by the requirements of the study. It is worth noting that this review only examined the use of olfactory stimulus alongside virtual reality. When identifying studies for inclusion, several studies were found that, although they did not examine the use of VR, did present an olfactory display device that had commonality with the included examples. It may be feasible to adapt these methods into a virtual reality setup. A further systematic review which might broaden the inclusion of studies that simply examined electronic olfactory display devices might offer even more insight into the state of the technology. This was beyond the scope of this review; however, it does offer a potentially beneficial avenue for further research.

A major finding, that will be explored more in the next chapter is the distinct lack of detailed method in which the olfactory display device communicates and interfaces with the VR environment. This was one of the suggested heuristics from the literature review and the lack of clear definition presents a gap in the current knowledge and would likely provide a valuable method for future researchers interesting in developing olfactory display technology for use alongside virtual reality. This will be examined through the development of a prototype olfactory display device that will draw from the findings of this systematic review, particularly the dispersal and delivery method and will provide a detailed description of the construction and integration method. It was found in the review of studies that used commercially available devices that they were often expensive and required specialist purchase orders to be raised. A key element of this prototype will be the focus on developing it using a low cost and accessible ethos in order to provide an alternative to researchers and designers working with olfaction in VR to examine its impact further without the potentially prohibitive cost.

Chapter 4: The design and evaluation of a head-mounted, open-source prototype olfactory display device for use in Virtual Reality.

4.1 Introduction

As part of the methodology to explore the development of olfactory display technology for virtual reality, a prototype olfactory display device will be proposed and developed. This will be developed from the design heuristics identified through the literature as well as the findings of the systematic review. Prototyping offers the ability to test theoretical ideas and can allow a practical method of evaluating the main design elements (Benyon, 2005). A prototype device provides the benefits of evaluating the design heuristics at a practical and technological level to identify potential design flaws and areas of future development. An objective of this thesis was to propose the design of an olfactory display device (ODD) that could be utilised with a range of off-the-shelf products and be made compatible with current game engine technology and software. A finding of the systematic review presented in the previous chapter shows a gap in the knowledge of methodology for interfacing an olfactory display device with the VR Environment. As stated in that chapter, whilst this has been done in a number of studies, the methods were not described in enough detail to be repeated. The main heuristics and categories addressed by this prototype are:

- **Triggering the device through interaction with the VR environment** – As discussed in the literature review and systematic review, there was sparse information provided on any methods used to integrate an olfactory display device with the VR environment so that it receives its triggers release scent from interactions or the VR users' locations within the virtual space. This offers the benefit of providing olfactory stimulus without any active input from the VR user, instead scent is released naturally based on their interactions within the environment. A detailed method for producing this integration will be presented as part of this chapter.
- **Spatialised Scent Triggers** – Because the environment within virtual reality is three-dimensional, allowing the individual to move freely around inside, scent cues would have a locational trigger within the space. These would be defined within the game engine and tell the device when to release the scent stimulus. These would be spaced throughout the environment and would likely have an associated visual cue. For example, as the individual gets closer to a patch of lavender within the virtual space,

the concentration of the scent would increase. The prototype utilises a basic method of placing scent cues throughout the virtual environment.

- **Portability of the Device and Scent / Visual Stimulus Latency** – Because VR offers individuals 6 degrees of freedom when moving, an olfactory device should be able to emit a consistent smell no matter the orientation or position of the VR user. A fixed device introduces a problem because it does not adjust in relation to the VR user's location in the physical space, meaning that if the user were to face away from the device, the perception of the released scent stimulus would be inconsistent to that if they faced the device. A solution to this is to develop a device that can keep a consistent distance from the user's nose, no matter where they are within the physical space. For this to be achieved, the device must be mounted on the body of the individual. A number of studies have used devices that are worn around the neck like a necklace. However, this also introduces variability in the distance from the individuals nose if they were to tilt their head up or down. In order to keep the consistency of distance from the device to the nose, the device will be designed to be affixed to the head-mounted display (HMD).
- **Be Affordable and Accessible** – It was found in the prior literature review that there is large amount of variation in olfactory display technology in VR, often changing based on the requirements of the researcher. A number of studies make use of commercially available scent display technology; however these are often expensive and require them to be ordered directly through the manufacturer. These devices are often not designed for use alongside VR and are instead optimised for releasing scent into a room for installations or 4D cinema. A requirement of this prototype is that it be affordable to produce as well made from readily available commercial, off-the-shelf products. In an effort to keep the development of this prototype as open as possible, it should integrate with the VR environment using readily available and open-source software.

This chapter provides details of a low cost, accessible olfactory display device for use with a VR HMD. It discusses both the development of the prototype device as well as the system used to trigger the release of scent through interactions within the VR environment. A study with a small number of participants was undertaken to evaluate the device and the experience of using it within VR. As part of this, the evaluation aims to investigate the role this device might have on an individual's sense of presence within the VR environment as well as their experience using the device. The results, along with a discussion of the limitations of the prototype and study will also be presented. This chapter will aim to answer RQ3: How can readily available components be used to develop an olfactory display device suitable for use with VR?

4.2 Developing the Prototype Device

With the aim to provide a low cost and openly accessible olfactory display device, it was decided after researching communication between hardware and software interaction that an Arduino based system would offer the affordability and accessibility required for this device. The use of Arduino is supported by the data from the previous systematic review. Of the 15 identified studies that used a custom-built olfactory display device, 9 used the platform as a foundation to control the release of the scent stimulus, demonstrating there is precedent for its use in prototyping of olfactory display devices. Arduino is an open-source hardware and software platform that allows for development of physical computing and interaction. Because physical electrical components to be controlled through use of the Arduino Integrated Development Environment (IDE), it offers a method of transmitting communications from the VR software to the olfactory display device.

The findings of the previous systematic review presented two modalities for olfactory display devices: In-environment or Wearable. In-environment devices introduce the issue of the lack of control over scent concentration consistency. If the device is placed at a set point in the physical space, the device may function as intended whilst the VR user is oriented towards it, however, if the user were to turn to face the opposite direction, the scent would have to travel much further, thus adding latency to perception of scent. A solution is to mount the device on the head mounted display (HMD) which allows for a consistent distance between the olfactory display device and the individual's nose, no matter the facing or movement of the head (Murray et al., 2016). Both desktop-mounted in-environment and HMD Mounted wearable prototypes were developed.

4.2.1 Odour Dispersal and Delivery Methods

Several different dispersal and delivery methods have been suggested, including the use of vaporisation (the use of airflow over a solid or liquid odorant to deliver a scent), atomisation through diffusers, humidifiers, or ultrasonic methods. Two of the most commonly used combinations found in the systematic review favoured accelerated vaporisation with airflow which would be delivered through wind (airflow) and ultrasonic atomisation which would be delivered through natural diffusion. It was decided that both of these methods would be examined.

An initial prototype was developed that would use an ultrasonic atomiser to disperse the odorant. This was developed using an Arduino-based system called Seeeduino. Whilst the Seeeduino devices are similar to the Arduino platform they offer a unique system named GROVE which allows for the rapid connection of physical components that support this interface. Of these components, the GROVE Atomiser was examined. The atomiser works when the atomisation disc is placed on a wet surface. When a digital signal is received it atomises the water from the surface of the disc. It is recommended that a wick is used to ensure constant contact with the liquid. Initial tests of this method demonstrated that the system was able to produce a mist of atomised liquid on command, however, it was found that when adding diluted oils, the atomiser would offer inconsistent dispersals of the scent. This is most likely due to the more viscous oils clogging the intake nozzle of the atomisation disc. For the atomiser to function correctly, scents should not be derived from oils and instead should be soluble in water. It was also found that for efficient atomisation to occur, the disc needed to be placed at a specific angle to the liquid. This presents the problem that if the device were to be mounted to the HMD, the VR user would often be tilting and rotating their head as they explore the VR environment which means that it would be much harder to guarantee a consistent scent release.

Another dispersal method that was examined was vaporisation through airflow. In this method, an odorant in either liquid or solid form is placed near a fan, when the fan is turned on and pointed towards an individual's nose, the odorant evaporates from the surface and is perceived by the individual. Several variables were examined during this design process including the type of fan used, as well as the location of the odorant in relation to the fan. Three different types of fans were tested: A 120mm 12V computer fan, a 40mm 5V computer fan, and a small DC motor fan available as part of the GROVE components compatible with the Seeeduino system (Fig. 15). Initial tests of these suggested that the 120mm 12V fan was too powerful for this application and introduced noticeable wind on the VR user's face. This fan also required an external 12V power supply. Both of these factors would mean that a device using these would only be suitable for an in-environment device rather than a wearable device. The GROVE mini fan offered good controllability and did not require an external power supply, but it lacked the ability to safely mount it to a device without building a custom housing. The 40mm 5V computer fan was opted for due to its small form factor and ability to mount to a device due to the built-in mounting bracket. Another important feature when choosing this fan came from its operating volume. When powered, the 5V fan provided the quietest operation (26 dBA) when compared to both the 12V 120mm fan (36.4 dBA) and the GROVE mini fan (No dBA is listed on the manufacturer's information sheet, but it was noticeably louder than both other fans when powered).

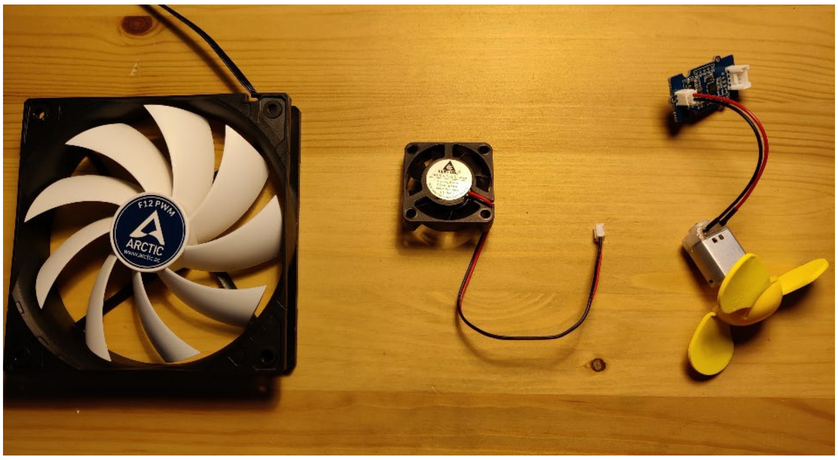

Figure 15: Left to Right: 120mm 12V Fan, 40mm 5V fan, GROVE 5V Mini fan.

In order to keep the design as accessible as possible it was decided that the scents should also be versatile. Essential oils offer an affordable but diverse range of scents. An initial test simply had a piece of cotton wool dowsed with essential oil placed behind the 5V fan. When the fan was turned on the air was pulled over and through the wool causing accelerated vaporisation. With the fan aimed at the face, scented air was emitted from the fan to the nose. To stop the oils contaminating any surface of a display device, the dowsed cotton wool was placed inside small 2cm cylindrical acrylic glass containers (Fig. 16) Because the air is required to flow through the wool in order to vaporise the scent, holes were drilled into the tops and bottoms of the containers using a small drill. These scent cartridges facilitated the passage of air whilst preventing oils from physically contacting any points of the olfactory display device. Oils were also diluted with a 50/50 mix of carrier oil (jojoba oil) to prevent scents from becoming overpowering. A benefit of this cartridge system meant that scents could be swapped out quickly by simply replacing the container with another.

Figure 16: The developed olfactory 'cartridge' Note there are matching holes drilled in the bottom to facilitate the passage of air.

4.2.2 The Circuit

Controlling the 40mm fan through the Arduino required it to be connected to a MOSFET which acts as the electronic switch that enables the fan to start or stop spinning. Using the Seeeduino Nano provided the use of the GROVE connection for which a specific MOSFET is available. The positive and negative ends of the fans were then connected to the corresponding connections of the MOSFET (Fig. 17). The 5V fan current draw is within the limits of the current output of the Seeduino Nano meaning that no external power supply is required and can simply be powered by the USB C connection to the desktop PC. The affordable and readily available parts used are listed below:

- 1X Seeeduino Nano – This device is a replica of the original Arduino Nano but offers a range of rapid prototyping options through the use of its GROVE connections (*Seeeduino Nano - Seeed Studio*, 2021)
- 1X Grove MOSFET
- 1X 5V Brushless CPU fan, 40mm X 40mm X 10mm

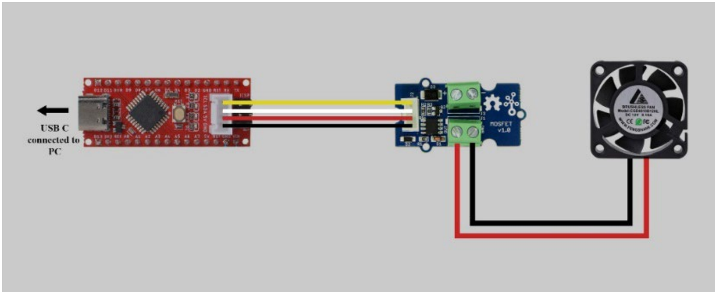

Figure 17: Circuit Diagram of Prototype.

4.2.3 Prototype Form Factor

When building the circuit, both an in-environment desktop version and an HMD mounted prototype were developed. An in-environment design was created to test the practicalities of the technology and ensure the electronics and dispersal / delivery system would function as required before adding it to the more complex wearable form factor. The desktop device (Fig. 18) was created as a simple box made from foam core board in which the fan was mounted to a hinged lid. The design was inspired by the work set out by Herrara (2014a) in which a low cost desktop olfactory display was developed. In this study the researchers found that angling the fan slightly forward to aim directly at the nose of the participant who would be sitting with the device on the desktop in front of them produced the best results. This design feature was also implemented into the structure of this prototype. The hinge allows for the placement of the scent cartridge on an internal shelf 3 cm lower than the fan. A hole is cut at the back to allow for fresh air intake as well as for routing cabling. An initial test of this device was carried out with a single participant with the goal of gaining informal feedback to refine the design before presenting it to a wider range of participants. It was found that the issue due to the device being static whilst the participant moved their head to navigate the virtual space immediately caused a noticeable disconnect between the visual stimulus and the scent stimulus. It was found that there was a huge degree of inconsistency in the perceived strength of scent and latency because of this variability. This initial test confirmed that an HMD mounted device would be a more suitable application for this design as it can keep a consistent distance from the nose, no matter the position or facing of the VR user.

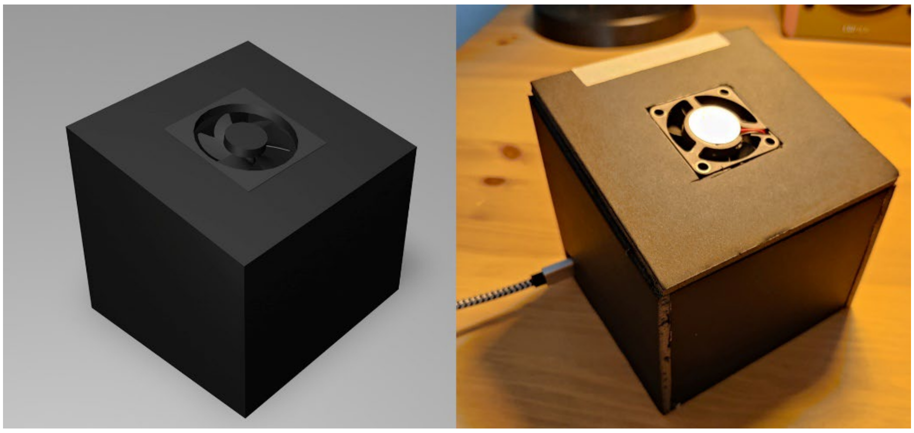

Figure 18: Render of design along with the functioning desktop prototype.

The HMD mounted prototype uses the same circuit and construction material (Foamboard and glue) as the desktop version but features a different form factor which makes it more compact and more suitable for attachment to the HMD. This design was modelled in 3D before constructing the final prototype in order to decide on the scale of the device compared to the HMD (Fig. 20). The form was designed to be as small as possible so as to still accommodate the fan but not add an uncomfortable additional weight to the HMD. The L-shaped form is designed to draw air in from the top of the device, over the scent cartridge to vaporise the smell. The scented air passes through the device towards the front where the fan is mounted. This fan then expels the scented air towards the nose. The L shape is designed so that the scent cartridge is kept away from the proximity of the nose in order to prevent the VR users from perceiving the scent when the fan is not activated (Fig. 19). The device is affixed to the HMD using a Velcro strap that attached to the central head strap of the HMD. A small amount of double-sided sticky tape can be used to attach the mounting brackets of the prototype to the front panel of the HMD to prevent it moving when in use.

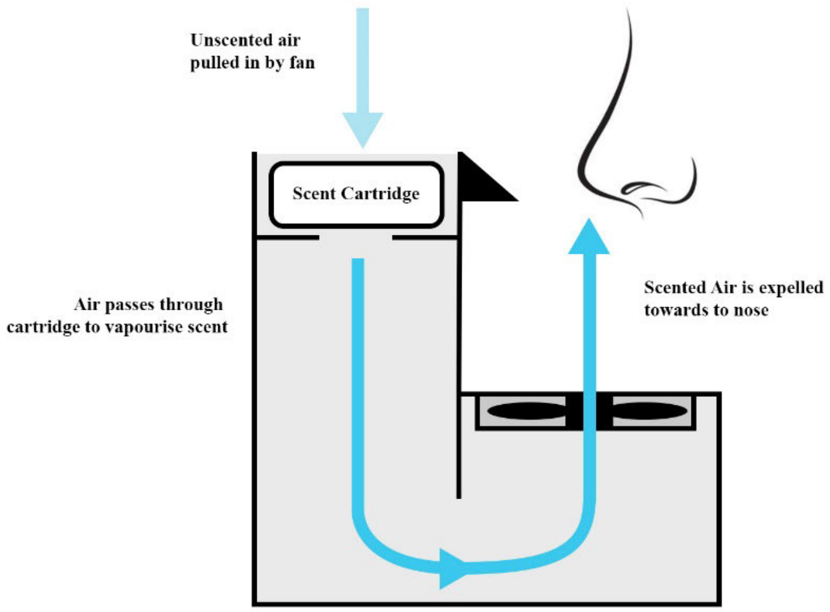

Figure 19: Cross section of prototype demonstrating the vaporisation of the scent and how it is delivered to the nose using the fan.

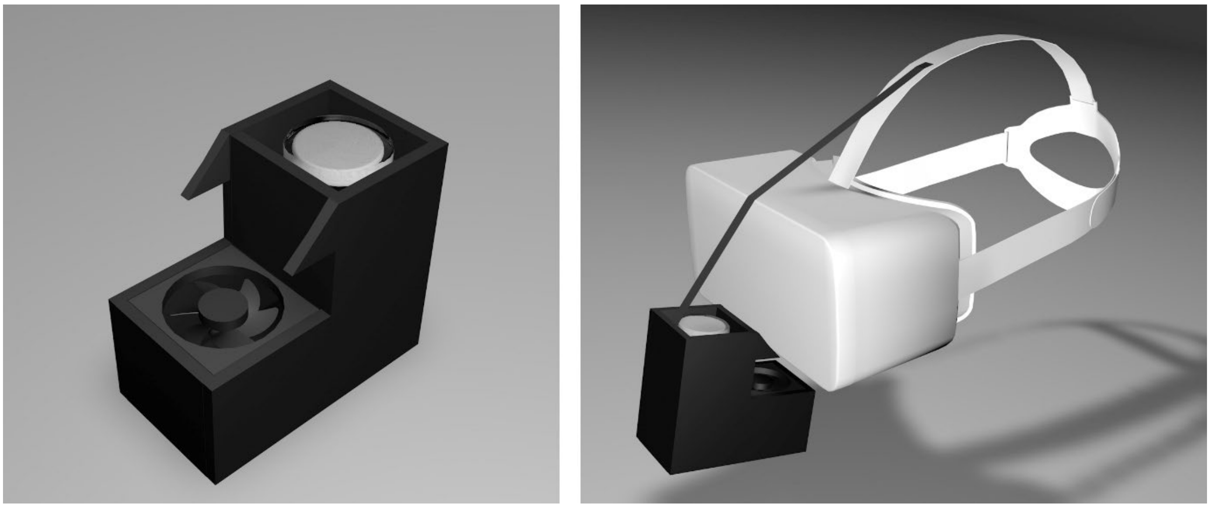

Figure 20: 3D Renders of the prototype device and a demonstration of how it attaches to the HMD (HMD Model created by VitaminCo** (2018)**).

The Seeeduino Nano is attached to the external side of the prototype simply by inserting the pins into the foamboard to facilitate easy access for the USB-C (Fig. 21) For this study, a 3 metre USB – C cable was used and routed along the existing HMD cable and held in place using additional Velcro cable tidy straps to minimise the intrusiveness of the device.

Figure 21: Left: The physical prototype device demonstrating how the Seeeduino nano is attached. Right: The prorotpye attached to an Oculus Quest 2

4.2.4 Communicating with the Prototype.

It was found in the systematic review chapter of this thesis that there were previous studies that made use of olfactory display devices that were able to communicate with the virtual environment to receive the commands to emit smells directly through interactions the individual has in the virtual space. However, none of the studies presented a detailed method on how this was achieved so as to be fully repeatable. The majority of studies used Unity as the primary VR software in order to send serial commands to the olfactory display device, however very little further detail was provided. This lack of detail in the method presents a gap in the knowledge for integrating an olfactory display device effectively with the virtual environment. It is hoped that by detailing this information below, researchers may use this method as a foundation for further study.

The software that the device requires can be separated into 3 packages: Arduino, Unreal Engine 4 and UE4Duino. Each is described below with the reasons for their inclusion:

- **Arduino IDE:** The physical prototype is built using the Seeeduino platform which is fully compatible with the Arduino IDE package. It is this software that allows the device to receive digital signals to command the fan to start spinning. The Arduino IDE is available to download freely and is open source. It is this reason that the Seeeduino device is compatible with this platform.

- **Unreal Engine 4:** Whilst most of the previously examined studies made use of Unity to develop the virtual environment, Unreal Engine 4 (Epic Games, 2014) offers a beneficial alternative. Unreal Engine 4 can be downloaded freely (Unity uses a paid subscription service in order to access all features) and makes use of a visual scripting language known as Blueprints. This offers an accessible method of building interactions for researchers who may not have extensive prior knowledge of game engine programming. The game engine is used to create the virtual environment the individual will experience within virtual reality. It is also used to create the virtual triggers which start the chain of events which releases the scent stimulus.
- **UE4Duino** (grizly32, 2015)**:** This plugin for Unreal Engine 4 is a freely available and is required as it acts as the interface between Unreal Engine 4 and Arduino.

4.2.5 Triggering a Scent through Interaction

The process of triggering a scent to be released through interaction can be outlined in the following steps:

1: Within the virtual environment inside Unreal Engine 4, a series of trigger volumes can be placed. These can be scaled, shaped, and placed in a variety of ways (Fig. 22). This is useful as it allows scents which might have a larger range and be less localised to be released through a larger trigger area, whilst a small specific scent might have a smaller trigger area, so the scent is only released when the individual gets within close proximity. For example, a pine forest might use a larger trigger box for a general pine scent whilst using smaller trigger boxes for specific foliage and plants within the environment.

Figure 22: Triggers in Unreal Engine 4. Both spherical and box shaped triggers are displayed.

2: Upon the VR user's avatar overlapping one of these trigger areas, Unreal Engine 4 sends an event command using the Blueprint system (Fig. 23). This integrates fully with the UE4Duino plugin which is installed directly into the Unreal Engine project. UE4Duino offers a range of new blueprints that can relay messages out of Unreal Engine into the Arduino programming language.

The event called by the trigger volumes sends a single numeric value through a string variable in UE4Duino into the serial port to the connected Seeeduino through a simple code. These are presented to the Arduino IDE as simple numerical values. In this example, when the player passes into a trigger box is sends a command of '1' to the Arduino IDE. When the player leaves a trigger boxes it sends a value of '0'.

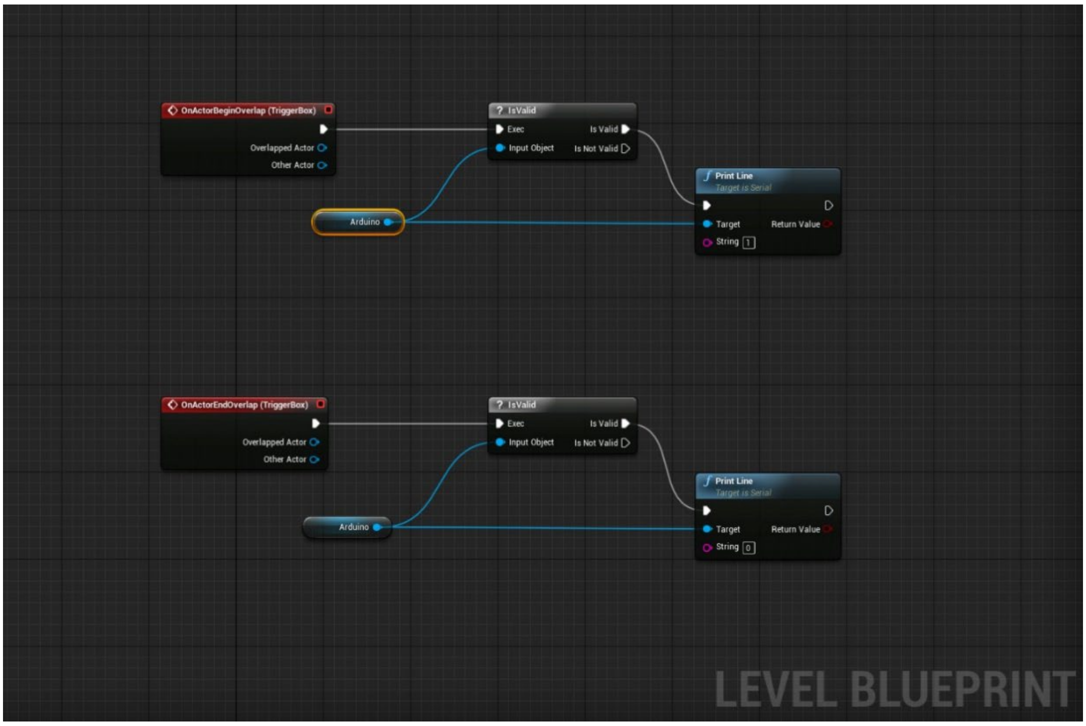

Figure 23: A sample script for triggering a single scent release. The script sends a value of 1 when inside the trigger area and a value of 0 when outside.

3: In the Arduino programming language, certain functions can be defined for each numeric string value it receives. If a value of 1 is sent from Unreal Engine at this stage, it is used to turn on the fan. If the Arduino would receive a value of 0 after this, it would tell the fan to stop spinning. In Arduino, the spinning state can be set using the *digital_write* function (Fig. 24).

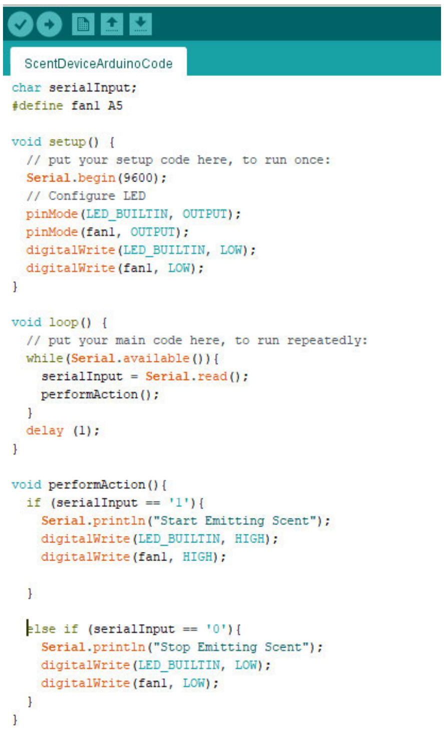

Figure 24: The code in Arduino can be seen here which tells the fan to spin if it receives a value of 1 from Unreal Engine 4, or stop spinning if it receives a value of 0.

Using this system, the trigger boxes are used to define the scale of the area in which scents are required to be emitted and scents are trigger based on the VR user's position within the game world, requiring no active triggering from the user. This system offers a versatile method of triggering different scents. For example, it would be entirely feasible to change the script in Unreal to send the same code to the Arduino when the player picked up an object so as to emit the scent only when the player is actively interacting with the environment. This offers a highly modular approach to the design of interactions that could be adapted to the needs of the researcher.

4.3 Prototype Evaluation Methods and Procedure

The evaluation of the prototype was carried out with two aims: Firstly, to identify the prototypes fitness for purpose, secondly to use the device alongside a VR environment to examine an individual's sense of presence.

4.3.1 Participants

A small study was devised in which 10 participants (7 male, 3 female) were asked to experience a short VR environment built with the trigger system as outlined in the previous section to release a singular scent. Participants were selected based on their ownership or having access to a VR headset as well as a desktop computer that was suitable for running the virtual environment. This priority for selection was due to COVID – 19 restrictions the study took place under meaning that all instances of the study were carried out remotely. A benefit of this selection criteria meant that all participants had previous experience with virtual reality in which they could compare the use of olfaction against past experiences of VR with no scent stimulus. All participants except for Participant 7 had occupations that involved regular usage of digital technologies (Table. 2). Further information regarding how these COVID-19 restrictions were addressed are discussed in section 4.3.4. Participants all gave informed consent (See Appendix 2) to take part and a short pre-study questionnaire was administered which asked if the participant had experienced VR before and if so, did it make them feel ill, uncomfortable or produce any signs of motion sickness. If they had, participants were asked not to take part in the study. A second question asked if participants had any known allergies to essential oils. This was deemed to be a minimal risk as the oils within the scent cartridge should not come into physical contact with the individual, however it was decided that if there was any uncertainty about this, participants should also not take part in the study.

Table 2: Participant Characteristics Table

Participant Number	Age	Gender	Previous Experience with VR	Occupation
1	29	Male	Yes	Student - College
2	29	Female	Yes	Digital Artist
3	30	Female	Yes	Digital Artist
4	21	Male	Yes	Student - University
5	22	Male	Yes	Student - University
6	22	Male	Yes	Student - University
7	21	Female	Yes	Student - University
8	24	Male	Yes	3D Modeller and Animator
9	40	Male	Yes	Computing Lecturer - University
10	20	Male	Yes	Game Developer

4.3.2 Measures:

Data collection was undertaken with the following methods. Each is outlined and the reasons for use in this study are provided:

Temple Presence Inventory: Presence questionnaires have been used extensively for providing a subjective approach to the assessment of levels of presence within virtual experiences. Several different tested and peer reviewed questionnaires have been developed for a range of different experiences. Notable examples include Witmer and Singer's (1998) Presence Questionnaire (PQ) and Immersive Tendencies Questionnaire (ITQ), the I-Group Presence Questionnaire (T. Schubert et al., 2001) and the Temple Presence Inventory (Lombard et al., 2009). It was decided that the Temple Presence Inventory (TPI) was most suitable for examining the role of olfaction due to its focus on not only Spatial Presence, but also Perceptual Realism, the focus on how the senses are engaged might impact the level of presence felt. The inventory has shown to demonstrate a high level of reliability and has been peer-reviewed and tested (Lombard et al., 2011). The inventory offers 42 items associated with different aspects of presence (Spatial, Social etc.) that can be adapted and modified if need be. 6 items from the TPI were used in this study. The TPI as written does not use phrasing focussed specifically on olfaction, instead focussing on things the participants saw / heard. Some questions were adapted to include the sense of smell. An example question for assessing spatial presence is "To what extent did it seem that sounds came from specific different locations?" To assess olfaction this question was adapted to "To what extent did it seem that scents came from specific different locations? Each item is presented on a 7-point Likert scale and the full list of items used from the inventory can be found in Appendix 2.

Think Aloud Protocol: Whilst the Temple Presence Inventory offers useful quantitative data, it was decided that a Think Aloud Protocol allows for qualitative data to be collected during the experiment. Lombard et al. (2009) suggest that this method, when used alone offers low reliability and external validity, however, when used in conjunction with a presence questionnaire offers valuable data additional data. The think - aloud protocol encouraged participants to verbalise their experience whilst in the Virtual Environment in order to capture immediate responses to the experiences and stimulus presented. The participants actions and gestures were also captured from this. These verbal responses were analysed using a thematic analysis. Data from this was recorded as a screen capture of the VR environment along with audio recordings of the participants verbal thought process.

Qualitative and quantitative questions related to enjoyment of the experience: A series of open-ended questions were devised which aimed to identify the overall experience of the participant as well as to identify the strengths of the prototype design as well as any limitations. These questions were also used to capture any suggestions for further improvement to the prototype device and VR environment. Alongside this, 3 quantitative questions asked to what extent the inclusion of scents made the experience more or less enjoyable and whether the experience using the olfactory display device was positive or negative. Finally, participants were asked to what extent they perceived a change in the strength of a scent. For these response in full, please see Appendix 4.

4.3.3 The VR Environment

The participants were presented with a short VR experience built in Unreal Engine 4. A pre-made virtual environment (NatureManufacture, 2017) was used that approximated a path through a pine forest. Additional way markers were added to ensure participants could visibly see the route through the environment. Along the pre-defined route, 3 distinct patches of heather were placed across the path at different intervals. A trigger box was also placed to encompass each of these patches which would act as the scent trigger when participant entered the trigger box (Fig. 25 & 26). The heather was used to provide a visual stimulus to match the scent stimulus. Whilst the participant remains inside the boundaries of the trigger area, the olfactory display device activates and releases the scent stimulus. When the participant leaves the trigger area, the device automatically deactivates.

Figure 25: Image showing the patch of heather. The trigger box is visible as the yellow lines around the heather. Note the wooden way marker post used to provide navigation.

Figure 26: Plan of the route through the VR environment. The perimeters of the 3 scent areas are outlined in yellow. There is a noticeable cave area built into the environment which is detailed in this image.

Audio is added to the VR environment which approximates the sound of tree's rustling and birdsong. A dripping water sound was added to the cave area. This was designed to be in congruence to the visuals, it was also included so as to mask the sound of the olfactory display device activating, which can be heard before the scent stimulus can often be perceived. This therefore avoids the anticipation of a scent stimulus before it has been released. An ambient music track plays throughout the experience to cover moments where the birdsong and tree rustling is not playing.

Movement was provided through the use of a teleport system in which the participant pushes a button on the motion controller which cast out an indicator of where they wish to move to, when the button is released, they teleport to that location. This method of navigation is often thought to reduce feelings of cybersickness within VR.

4.3.4 COVID-19 Mitigation

Because this study was being carried out under strict COVID-19 lockdown conditions, it was required that the procedure be carried out remotely. This meant that there could be no physical contact between participants and researcher. In order to do this, participants were chosen who had access to a powerful enough desktop PC which was capable of running the VR environment in VR. They also required access to a virtual reality HMD and motion controllers. The environment was setup and tested by the researcher on a Windows desktop PC with the following specifications: Intel I7 8700k processor, 32GB RAM, an AMD 6800XT with the software installed on a solid-state drive. This device was above the recommended specifications for running Unreal Engine smoothly. All participants used slightly differing specifications but all were well above the recommended specifications by Epic Games (*Hardware and Software Specifications | Unreal Engine Documentation*, 2020). Throughout, the study, three different VR Headsets and motion controllers were used (HTC Vive Pro, Oculus Rift S and Oculus Quest 2 in link mode). This introduced a number of variables due to lack of consistency between hardware, however it could be argued that this is closer to a more realistic representation of how the olfactory display device would be used in a more real-world setting. The olfactory display device was delivered to the participant's home after being disinfected with odour-free antibacterial wipes. The 10 participants made up 3 different households. When one household had completed the study, this disinfection process was repeated before being delivered to the next household.

Setting the device up remotely provided a challenge in that each desktop had to have the pre-requisite version of Unreal Engine 4 installed (the version used specifically for this study was 4.21). The drivers for the Seeeduino Nano had to also be installed and the large project files must be sent via file hosting applications. Video conferencing was set up with one participant from each household to guide them through the installation process and run the pre-study checks to ensure the device was functioning as intended. There were found to be no major issues during this setup process with each household which suggests that the system is very adaptable to a range of different systems and hardware combinations.

4.3.5 Control Group

A control group was not used in this study due to the limited participant numbers that had access to suitable hardware to run the virtual environment. A control study would have had an equal number of participants experience the virtual environment using the VR headset, but without the olfactory display device attached. Both the Think-Aloud protocol and items from the Temple Presence Inventory (Lombard et al., 2009) would be used, including the modified questions to address olfaction. This would offer a baseline to compare the sense of presence felt by both groups to ascertain if the inclusion of scent did have an impact on an individual's sense of presence within the VR environment. It was decided that because of the small participant group, data would be collected by only running the study with the group who would receive the olfactory stimulus. This would allow for more data to be gathered to examine the technical elements of the display device based on the outlined design heuristics.

4.3.6 The Procedure

The prototype was loaded with a single scent cartridge containing diluted heather scented essential oil. Participants were asked to undertake the study from their own homes, with the researcher present via video conferencing to capture the screen recording of the VR content and the audio from the participant's think aloud responses. Participants were asked to undertake the VR experience twice. Before starting the first instance, participants were given instructions to stay on the route indicated by the way markers (The participants were also shown these at this point, so they were aware of what to look for if they felt lost). They were also informed that they may take as long as they like to move along the route and that they may also move forwards or backwards along the route whenever they wished.

Figure 27: A Participant undertaking the study. Note the device mounted on the headset. The Seeeduino Nano can also be seen attached to the device. Movement in the virtual space is provided through the use of the motion controllers.

In the first instance, participants were informed that although there were scents present within the environment, no information was provided on the number of scents, the number of times the scents would be released or where the scents would be released within the virtual environment. After this first instance, participants were asked to remove the VR HMD and fill in three questions asking how many times they thought scent was release, what the source of the scent was (the heather) and also how many different scents could they smell.

Participants were then verbally provided further information by the researcher in which the source of the smell was confirmed to be the heather, they were also told that there were 3 locations in which scent was released and only a singular scent was used. With this new knowledge, participants were asked to repeat the experience for a second time. This time, they were encouraged, using the think aloud protocol, to discuss the differences they felt between the first exposure and the second. The aim of the second exposure was to provide information on the latency of the device between seeing a visual stimulus and then perceiving its scent as it could be confirmed that the participants knew the physical locations of where the scent was released. This second instance was also used by the researcher to ask any verbal follow up questions to comments made in the think-aloud protocol which it was felt could be useful to elaborate further on. Upon completion of both instances of the VR experience, participants were presented with the 6 questions adapted from the Temple Presence Inventory and the 3 open-ended questions. These questions were administered using a digital questionnaire which could be analysed, and data collated later by the researcher. The headset used by each Participant, along with the times taken to each instance of the study can be seen in Table 2.

Table 3: Overview of Participant information including the VR headset each used and the time each took to complete each instance of the study.

Participant Number	VR HMD Used	Time Taken to Complete Instance 1 (Mins:Secs)	Time Taken to Complete Instance 2 (Mins:Secs)
1	Oculus Rift S	05:24	05:20
2	Oculus Rift S	03:24	03:14
3	Oculus Quest 2	09:53	05:27
4	HTC Vive Pro	02:54	01:40
5	HTC Vive Pro	05:31	03:57
6	HTC Vive Pro	03:40	03:30
7	HTC Vive Pro	02:08	02:45
8	Oculus Rift S	03:26	04:28
9	Oculus Rift S	06:19	05:01
10	Oculus Rift S	04:38	02:10

4.4 Results

The results of the study are presented for the responses to the questions answered after the first instance of the VR experience, they are then presented for the quantitative presence data provided by the items of the Temple Presence Inventory and finally as a thematic analysis for the themes identified from both the think-aloud protocol as well as the open-ended questions.

4.4.1 Questions after First Instance

Participants were firstly asked in how many areas did they notice a scent being released. There were 3 instances of scent release around the environment. Participants on average stated that scents were released slightly more than there actually was (Mean = 3.4, Mode = 4, SD = 0.97). The lowest number of times was 2 and the highest was 5.

Participants were then asked what they thought the source of the scent was in the VR environment. 100% of participants correctly identified the source as the patches of heather.

Participants were then asked how many different scents they could smell throughout the experience. Despite the device only being capable of emitting one single scent, participants on average stated they could smell more than that (Mean = 2, Mode = 2, SD = 0.82). Only 3 of the 10 participants stated they could smell only a single scent. 3 stated they could smell 3 different scents whilst the remaining 4 stated they could smell 2 different scents.

4.4.2 Temple Presence Inventory Items.

The following 7 questions were presented on a 7-point Likert scale (Cronbach's α = 0.82)

To what extent did you experience a sense of being there inside the environment? (0 = Not at All, 7 = Very Much): It was found that participants experienced a high sense of being inside the environment (Mean = 5.8, Mode = 6, SD = 0.79) (Fig. 28).

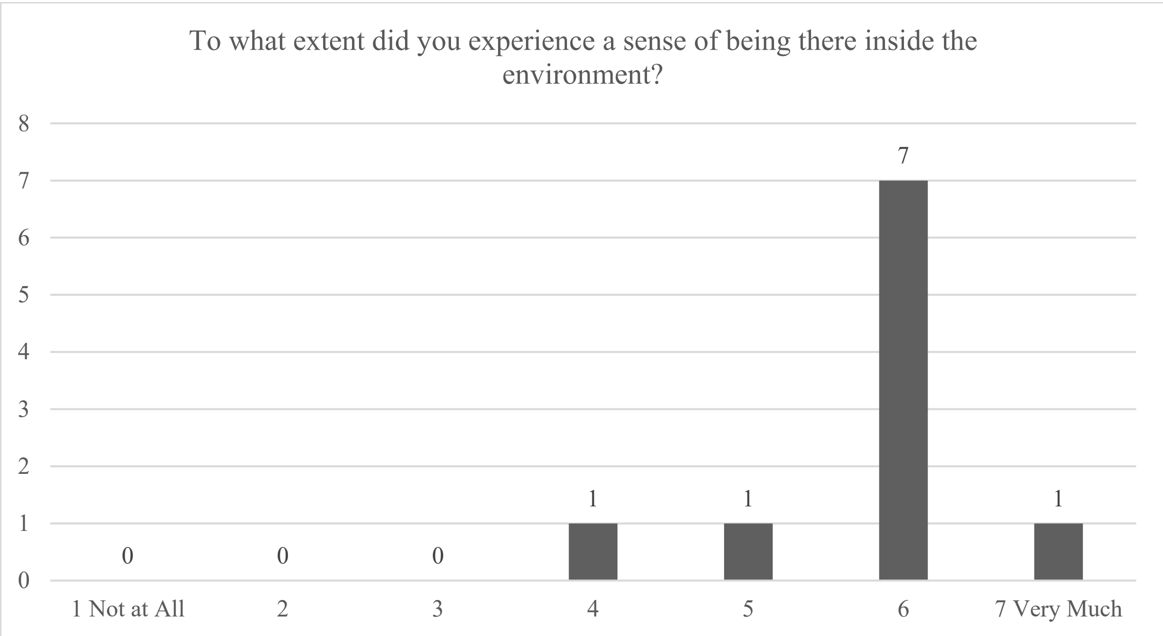

Figure 28: To what extent did you experience a sense of being there inside the environment?

To what extent did it seem that smells came from specific different locations? (0 = Not at All, 7 = Very Much): It was found that most participants felt that scents were coming from a specific different location within the virtual environment (Mean = 5.7, Mode = 7, SD = 1.57) (Fig. 29).

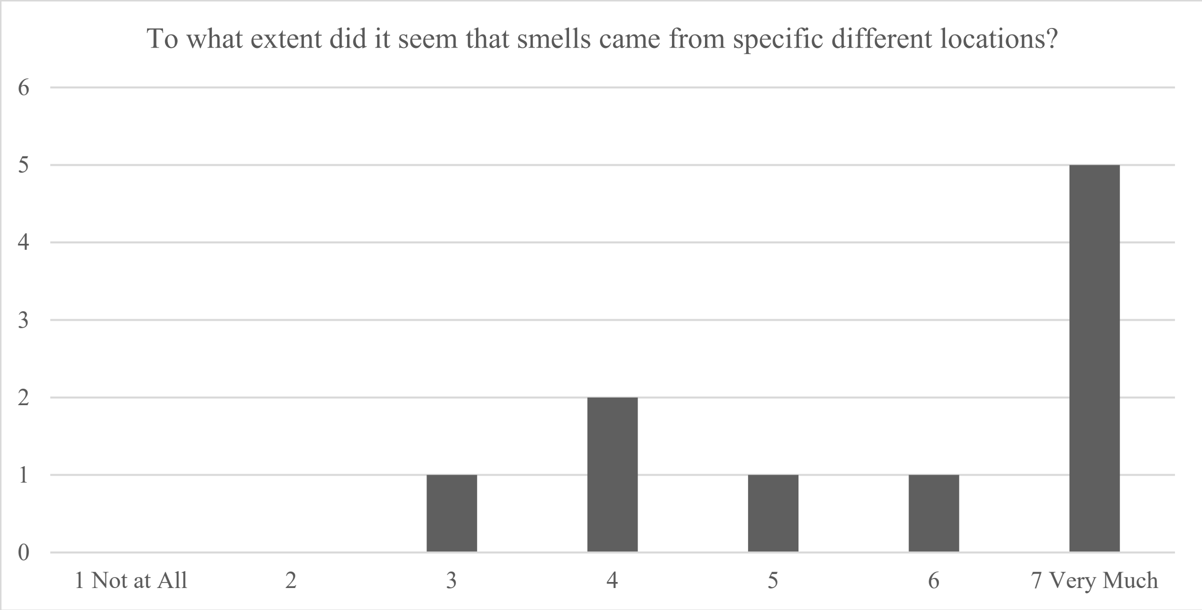

Figure 29: To what extent did it seem that smells came from specific different locations?

To what extent did the things you smelled match the things you saw in the virtual environment? (0 = Not at All, 7 = Very Much): It was found that most participants felt that scents did match the visuals that they saw within the VR environment (Mean = 6.1, Mode = 6, SD = 0.74) (Fig. 30).

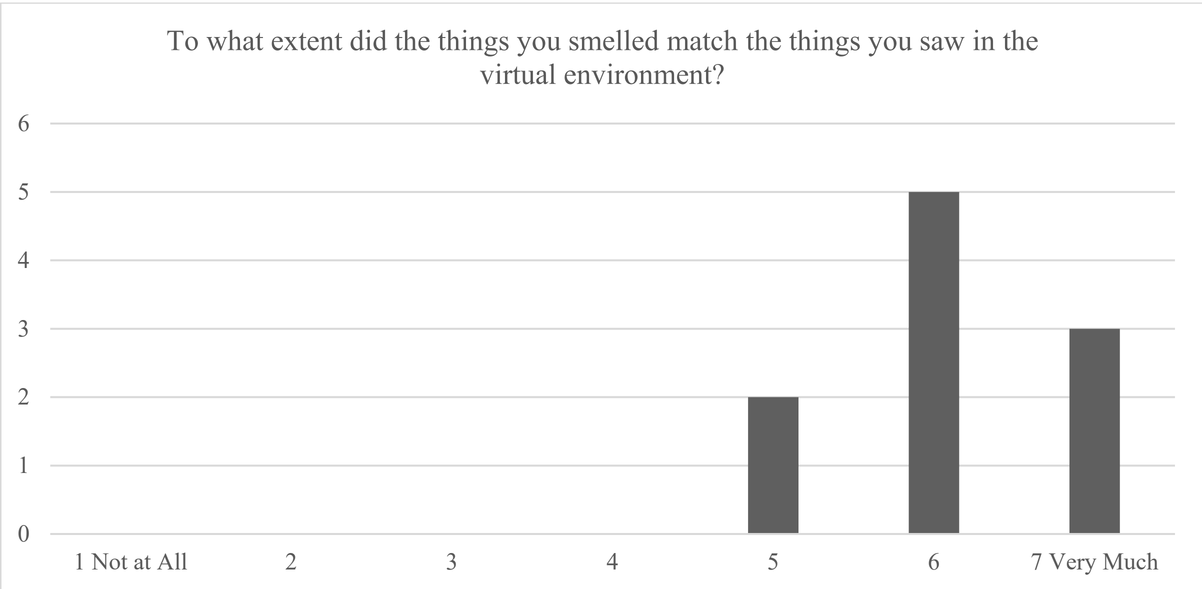

Figure 30: To what extent did the things you smelled match the things you saw in the virtual environment?

To what extent did you feel mentally immersed in the experience? (0 = Not at All, 7 = Very Much): It was found that most participants felt some degree of mental immersion while taking part in the VR experience (Mean = 5.7, Mode = 6, SD = 1.42) (Fig. 31).

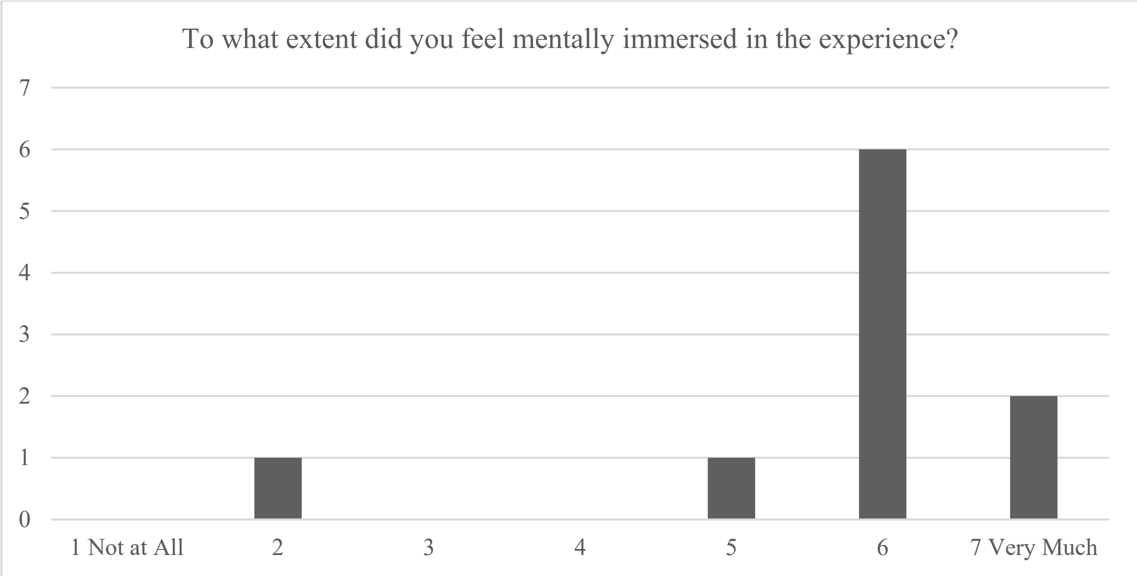

Figure 31: To what extent did you feel mentally immersed in the experience?

How completely were your senses engaged? (0 = Not at All, 7 = Very Much): It was found that most participants felt a high degree of their senses being engaged whilst undertaking the VR experience (Mean = 6.2, Mode = 6, SD = 0.63) (Fig. 32).

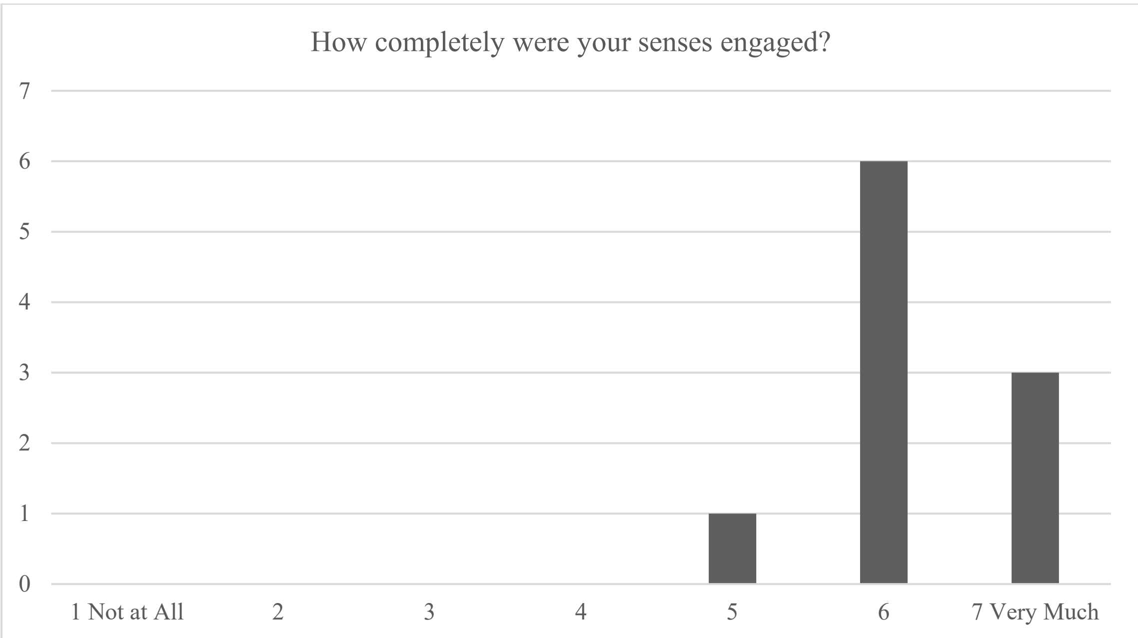

Figure 32: How completely were your senses engaged?

To what extent did you experience a sensation of reality? (0 = Not at All, 7 = Very Much): It was found that most participants generally felt some degree of reality whilst undertaking the VR experience (Mean = 5.2, Mode = 5 & 6, SD = 0.92) (Fig. 33).

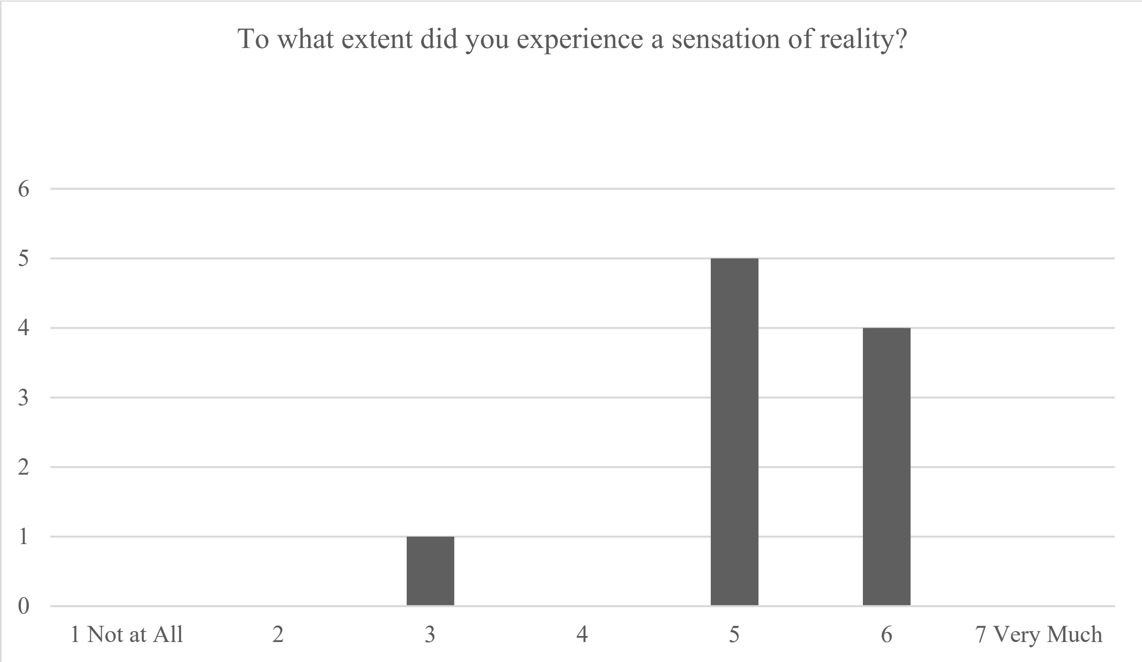

Figure 33: To what extent did you experience a sensation of reality?

4.4.3 Additional Quantitative Data

Participants were asked the following 3 questions designed to gain insight into the perception of the change in the strength of scent as well as understand the enjoyment of the experience felt by participants:

To what extent, if any, did you notice a change in strength of the scent? (0 = Not at All, 7 = Very Much): It was found that most participants experienced a notable change in the strength of the perceived scent whilst in the VR experience (Mean = 6, Mode = 5 & 7, SD = 0.94) (Fig. 34).

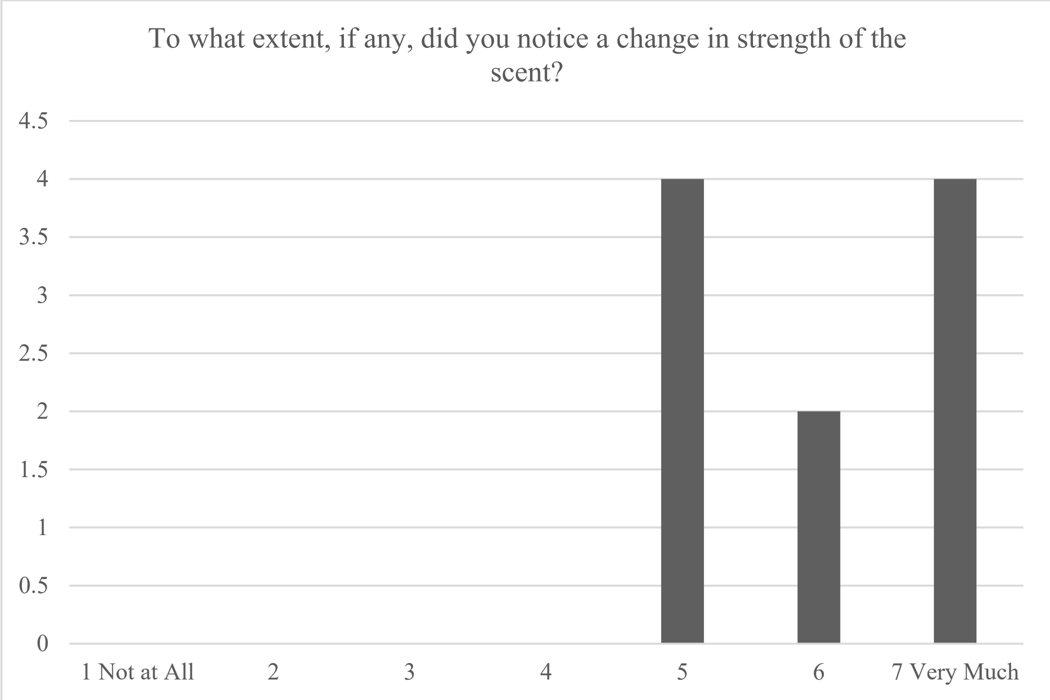

Figure 34: To what extent, if any, did you notice a change in strength of the scent?

Was your experience using the smell emitting device positive or negative? (0 = Negative, 7 = Positive): It was found that all participants had a positive experience using the olfactory display device (Mean = 6.5, Mode = 7, SD = 0.71) (Fig. 35).

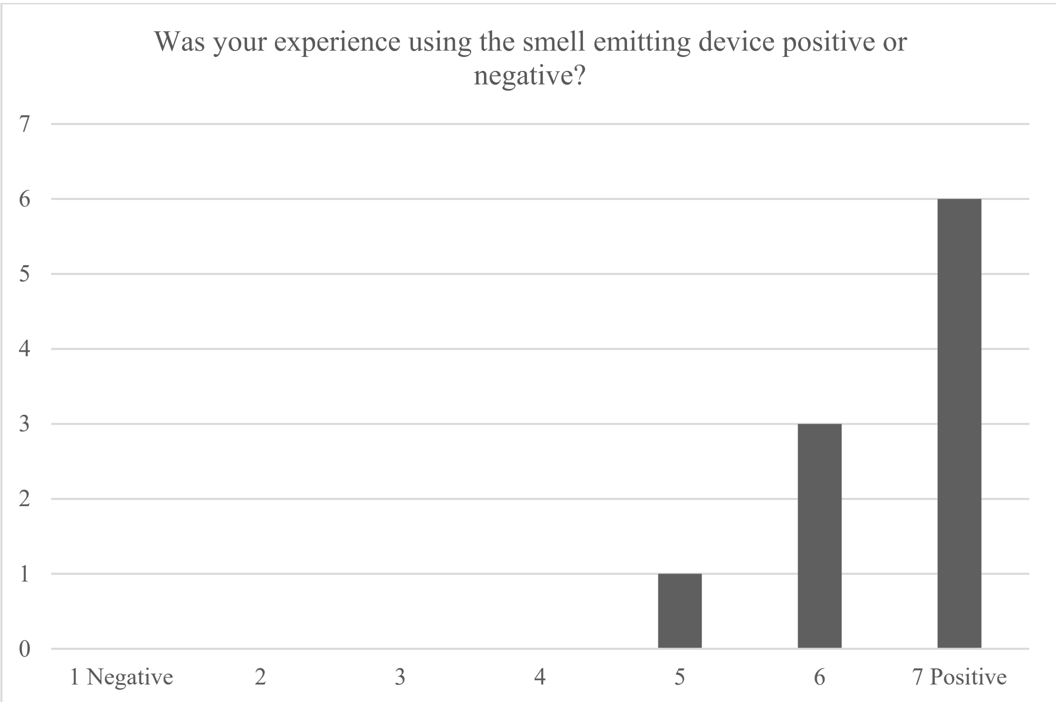

Figure 35: Was your experience using the smell emitting device positive or negative?

Did the addition of scent make the experience more or less enjoyable? (0 = Less Enjoyable, 7 = More Enjoyable): It was found that all participants found the addition of scents to provide a more enjoyable experience. (Mean = 6.5, Mode = 7, SD = 0.71) (Fig. 36).

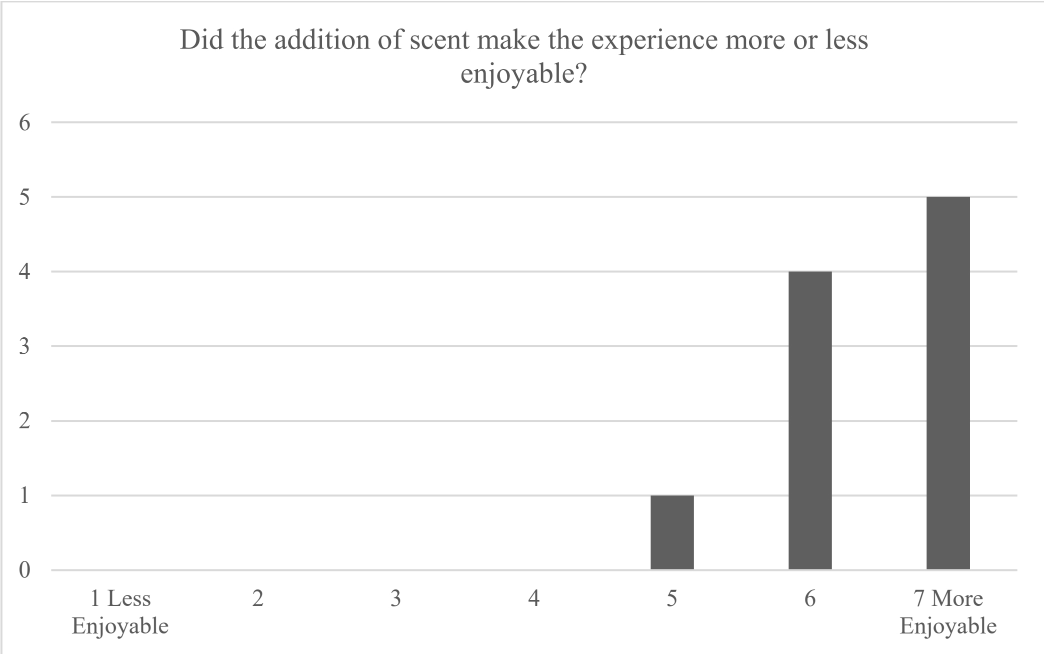

Figure 36: Did the addition of scent make the experience more or less enjoyable?

4.4.4 Thematic Analysis of Qualitative data from Think Aloud protocol and open-ended questions.

All dialogue from the think aloud protocol recordings were first transcribed along with any notable gestures the participants performed whilst undertaking the VR experience. These transcriptions were then imported into NVivo along with the corresponding responses for the open-ended questions for each participant. For the full transcriptions please see Appendices 3 and 4. A thematic analysis of this data was then carried out using a combination of both pre-defined and emergent themes to identify commonality within the responses (Fig. 37). Pre-defined themes such as the strength of olfactory stimulus, issues / limitations and comments regarding presence were created. After analysing the results, further interesting themes emerged from the data such as themes of relaxation and other psychological phenomena such as smelling scents which were not present during the study. Each of the themes will be discussed below.

Figure 37: Themes identified from a thematic analysis of 'Think-Aloud' and open-ended questions.

Identified Themes:

Presence: Responses were analysed for terms and phrases deemed to be associated with presence as defined by Lombard et al. (1997). Participants often mentioned a feeling or reality or immersion whilst discussing the experience. Participant 1, 4, 5 and 6 all used the word ‘immersed’ or ‘immersion’. Participant 1 described the experience:

> “It was very immersive; I find that VR can be immersive anyway but the smell emitting device does add an extra layer… It’s like I’m really here.” (Participant 1).

In response to the question asking how they would describe their experience using the olfactory display device, Participant 4 stated:

> “It created a more immersive experience as I felt I was walking through a forest and smelling the environment.” (Participant 4).

The term “realism” was often mentioned in responses. Participant 4, as part of the think aloud protocol described it: “It’s actually scarily realistic. I can’t believe this. So strange”. Participant 6 also stated “It makes it feel more real. Like you’re in the forest.”

Perception of Change in Strength of Scent: Participants mentioned regularly when they noticed a change in the strength of scent based on their location within the virtual space. All 10 participants acknowledged a notable presence of scent the moment they entered a scent area at least once during their experience using the olfactory display device. In response to the question asking participants to describe their experience using the olfactory display device, all 10 participants mentioned that they could notice and change in the strength of the scent when entering the patches of heather. All Participants also mentioned in either the Think-Aloud or the open-ended question that the perceived strength of scent disappeared once they left it:

> "It first seemed quite notable in the flowers and was surprised at how quickly the smell dissipated once leaving that environment" (Participant 3).

Issues, Limitations and Suggestions: A number of comments were provided that suggest limitations with the device. The current design uses a simple on/off system for the fan. Some individuals suggested that they would prefer a distance-based concentration increase.

> "I understand that the emitter will run on an on/off state but If the fan from the emitter could be programmed with distance in mind for instance as you approach a part the fan will gradually speed up emitting a stronger smell as you approach. (Participant 1) "

Participant 10 also stated in response to the request for improvements: "implement a distance-based smell strength."

7 of the 10 participants also suggested the inclusion of more scents within the experience. Participant 9 noted that the scents felt too artificial and would prefer more natural scents to be used.

Whilst the participant did not explicitly say that the following was an issue, it is suggestive of a known phenomenon known as olfactory fatigue. Upon entering a scent area, participant 9 stated:

> "I think it's like a chewing gum sort of thing. I think when I first came in it was very noticeable and now maybe I've acclimatised to the smell, so it doesn't feel very strong. It's still present. Or maybe I'm just feeling the breeze now. Yeah, the smell has gone." (Participant 9).

Interestingly, no other participants mentioned this or gave any indication through actions or phrases that this was occurring.

Residual Odour: A more noticeable issue was that of residual odour being left after the fan had been activated. The device, as built, does not have an active method of clearing the previously released stimulus. It is thought that this was found to be the case by participants:

> "Areas of bushes had a greater strength of smell, but as I continued through the map I could still smell the scent slightly in other areas." (Participant 5).
>
> "I think on the last run I felt like I was getting scents even though I wasn't in these sections (points to area before scented area) I don't know if that was because the fan was blowing before, and I was just smelling the previous one." (Participant 5).
>
> (Immediately after starting the experience) "It's weird because I don't know if the smells are meant to be coming yet but it feels like I can already smell a lot of them." (Participant 6).

Perceiving Additional Scents: Several participants stated during the first instance of the VR experience they could smell additional scents. At this point, they were not aware of the exact number of scents used and had not yet been informed of the exact number (1) by the researcher. In particular, participants often mentioned they could smell the scent of damp within a cave section of the environment:

> "Was there a smell going through there? Like a damp kind of smell? I think there was. I think I only noticed it once I left it. Maybe that's some kind of placebo effect!" (Participant 10)
>
> "I know the smell isn't turned on but I can almost smell the damp rot." (Participant 1)
>
> "Okay, I think it's myself playing tricks on me but I feel like I can smell different things. It just makes sense that there should be another smell coming next when I'm moving through it." (Participant 6).

Participant 1 also stated they felt they could smell the pine trees separately.

> "I think that even though it only emits one smell it can trick your brain into thinking other smells are present like the pine trees or even the damp." (Participant 1).

Temperature: It was found that 3 participants mentioned a feeling of temperature changes or expecting a temperature change when describing the VR experience. Participant 1 stated this when entering the cave section of the environment: "And it's cold in there too because it's not out in the sunshine…Whereas now (steps into sun lit area of VE) I'm back in the sun." Participant 9 described a disconnect because they were expecting a change in temperature but could not perceive it:

> "I was expecting that, because it feels quite warm in the room that the temperature would drop in here (points to cave)… (leaving scent area 2) That's the smell stopped now. That for me is where it's slightly counter-intuitive because as it stops that's where you get warmer but I'm in the shade (gestures to shaded area before cave.) You're expecting it to be cooler in the shade." (Participant 9).

Participant 6 noted a similar phenomenon when describing the difference between areas with scent and areas without. They described it as "It's like it's colder because there's no smell."

Wind Effects: Due to the fan system of the olfactory display device it was found that a slight breeze was emitted on the nose. It was initially expected that this would present a problem in the design. However, responses from a range of participants suggest that in the context in which the wind is produced, it is congruent to the environment and the scent. Participant 2 noted the effect as a pleasant inclusion: "And there's wind! I like that the trees rustle just a little bit because with the wind I'm feeling on my nose it's kind of proportional to the leaves.". Participant 9 also noted a pleasantness from the wind by-product of the fan: "I like the breeze from the scent machine. It feels nice to have that. I guess I think it might be the breeze that's more relaxing than the scent."

Relaxation / Calmness: Several participants described the experience of the VR environment as relaxing or calming in both the think aloud protocol as well as the open-ended questionnaire. Participant 5 stated the experience was "positive, felt more immersed and relaxed than a normal VR set-up. Felt more comfortable within the environment, and less strain when playing." Participants 7 & 9 also suggested a feeling of relaxation and calmness, stating the experience was "pleasant and relaxing" (Participant 7) and the inclusion of the scent was helped with a feeling of relaxation

(Participant 9).

4.5 Discussion

Through the design and evaluation of this olfactory display device prototype and subsequent interfacing method with the VR environment, a number of useful insights can be gained about the development of scent-based interactions. It first worth noting that this study used a limited number of participants so the results presented should not be viewed as definitive conclusions but instead present a foundation for potential further research.

4.5.1 Strengths of Prototype Design

The results presented suggest that the prototype olfactory display device functioned as intended on a fundamental level. It was clear that from the participants responses from the Think-Aloud protocol, as well as the response to the open-ended question in which participants described their experience, that the device was able to produce a noticeable and reactive scent based on the individual's location within the VR environment. Participants notably mentioned during the Think-Aloud the change in strength of scent, whether it be an increase as they entered the scent release area or when they left it. This can be reinforced by the fact that all participants were able to correctly identify the source of the scent (the heather flowers) within the environment as well as very high results for the question: To what extent, if any, did you notice a change in strength of the scent? (Mean = 6, Mode = 5 & 7, SD = 0.94). It would be expected that if the device were not capable of releasing distinct, intermittent bursts of scent throughout the experience then the results for this would have been considerably lower. The responses to the question which asked participants how many areas they thought a scent was emitted (Mean = 3.4, Mode = 4, SD = 0.97) also suggest that there is a notable difference between areas where scent is present and areas where it is not. This addressed the heuristic presented from the literature review about scent and visual latency. It was found that most participants noted the increase in strength of scent upon immediately entering a patch of heather within the virtual environment. This suggests the location of the odorant and fan system provide a suitable method of provide fast and reactive scent stimulus.

The design of the prototype and subsequent integration method to the VR environment successfully demonstrate a low cost and accessible method of producing a single scent olfactory display device. It was estimated that the device cost just under £30 to produce, including the scent cartridge used in the study and factoring in VAT. This accessibility and affordability extend into the integration of the device into the VR environment as all the software used to design and develop it is freely available. The table below further breaks down the cost of each component used:

Table 4: Cost breakdown of device and scent cartridges

Component	Cost
Prototype Device	
- Seeeduino Nano Microcontroller	£6.37
- 5V Mini Fan	£2.95
- Grove MOSFET	£4.51
- Housing materials (Foamboard, Glue, Tape)	£3 (estimated)
- 3 Metre USB – C Cable (2 Pack)	£9
- 2 mini jumper wires (for connecting the fan to the MOSFET)	£1 (estimated)
Scent Cartridges	
- 20X Mini Cylindrical Containers (5ml)	£3.99
- Cotton Wool	£1
- Heather Scented Essential Oil (10ml)	£2.50
- Jojoba Carrier Oil (10ml)	£2.50
Total	**£27.82**

It may have been possible to design the prototype using a more universal MOSFET which may reduce the cost further but would require either the use of a breadboard to connect the components or would require soldering the components together. The use of the Grove MOSFET means that the device can be built and taken apart easily with push fit connectors, this is likely to be of particular benefit to researchers that may wish to explore a range of different form factors for an olfactory display device. This device offers a more affordable option than that presented in a previous study by Herrera (2014c) which was estimated to cost roughly £40. This study made use of Unity rather than Unreal Engine 4 and the cost of the licence is not including in their costing.

4.5.2 Limitation of Design

There are several known limitations with the system that were identified before the study, however the subsequent study did reveal certain issues that had not been accounted for in the design. The prototype, by design is only able to produce a singular scent. However, it was stated as a suggestion by several participants that an improvement to the overall experience would be to include further scents. To achieve this, further considerations would need accounted for before multiple scents could be implemented. A system in which scents could be balanced, meaning the strength of one scent is not more powerful than another, would need to be developed. This may be achieved by changing the concentration of the carrier oil in each cartridge. The use of a human assessor would be required to ensure this was balanced before implementing the study. Another issue would be that the current system does not have any active method of removing a scent stimulus once it is released. This is less of an issue with the single scent but may cause issues when multiple scents begin to combine. To counter this, a filtration system would likely need to be implemented into the design. It may be possible to explore the integration of an activated carbon mesh as described by Kato (2018a). The nature of releasing more than one scent would require a method of isolating the individual scents. A potential solution may be to fit the device with a gate system to close a door in the device, stopping the airflow for all scents except for the required one. This would likely be cumbersome and difficult to implement without an additional power supply. Another method might be to use a fan for each scent, essentially keeping the design as it is in its current form but having a chamber for each scent. This too would likely make the device larger and more intrusive for use as an HMD-mounted device.

Whilst it was not explicitly stated as a problem with the design by participants, there was some suggestion that there was residual odour left from scents had been released in a prior area. This again suggests the need for some kind of odour removal or filtration system. This was one of the design heuristics presented in the literature review but due to the required compact form factor of the prototype, it was found that adding an active method of removing scent stimulus would add to the weight and intrusiveness of the design. A disadvantage of the type of fan used meant that it could not spin in the opposite direction which could potentially have been used to draw scented air back into the device when the user left an area of scent release. However, it is unlikely that the fan would have been strong enough to achieve this to a satisfactory degree. It was found that some participants stated that this residual odour added to the realism of the scene as ambient odours may be perceivable in the type of environment used. This, however, is most likely an accidental benefit of this specific environment and would likely not be a desirable trait in other environments. Another contributing factor to this issue may be that the scent was 'leaking' out of the device even when the fan was not activated. The scent is vaporised when air passes through the cartridge, this vaporisation may also be occurring when the VR user moves their head fast enough for scent to be released from the top of the device. A solution for this would perhaps be to move the chamber where the scent cartridge is kept further from the nose. This may in turn, however, increase the latency between the fan being triggered and the scent being perceived due to the greater distance from the cartridge to the nose. It would also likely be beneficial to build the housing of the prototype out of more airtight material. A future design would likely use similar dimensions but would instead be 3D-printed to prevent any scent leaking out of the connection points in the housing.

Another issue that participants suggested as a potential improvement would be to create a trigger system that allows for a variable fan speed. As the design currently exists, the fan is either in an activated state in which it rotates at its maximum speed or it is deactivated. A potential solution would be to create a distance-based trigger rather than the area trigger as is currently used in the VR environment. In this format, items and areas would be assigned a proximity distance, which would be used to ramp up or slow down the speed of the fan as the individual gets closer or further to the source of the scent. Objects could be assigned different distances so that objects that might emit a small radius of scent could have a shorter distance. A code was written for this in Unreal Engine 4, however, the current design of the prototype uses a simple on/off fan without a PWM (Pulse Wave Modulation) output which is used to control the speed of a fan. It would likely be possible to implement this system, but a more expensive fan would be required that has the required PWM output. This additional feature would likely be a priority improvement in any future iterations of the prototype. A further benefit of the variable speed fan is that it may be calibrated for accessibility purposes. As suggested in the design heuristics, olfactory detection threshold varies between individuals. A variable speed fan could be adjusted to allow for a minimum speed which would be calibrated to the individual's olfactory detection threshold. This calibration would need to be carried out as part of the setup of the study and would require further examination that the fan could even provide enough distinction between scent strength.

4.5.3 Presence Discussion

In order to discuss the role that the inclusion of the scent had on participant's sense of presence within the virtual environment it is worth noting the limitations of this study.

Due to the small number of participants that took part it was not feasible to split these into 2 groups to provide a group which experienced the VR environment with the olfactory stimulus and another group which experienced the same environment without (a control group). However, from the results of the quantitative Temple Presence Questionnaire, and when combined with the thematic analysis, there is some suggestion that undertaking the study afforded a sense of presence in the participants. During the Think Aloud and open-ended questions, the terms "realistic" and "immersive" were mentioned, unprompted several times. Whilst the quantitative data from the TPI suggests the experience had an overall very positive effect on the participants sense of presence, it would be inaccurate to state this definitively. Instead, this data opens this subject to further examination to confirm the findings. The overall experience was however, received very positively by all participants and the inclusion of the scents was stated as having made the experience more enjoyable (all 10 participants had experienced VR without the scent stimulus before undertaking the study which they were able to compare against). These positive results demonstrate the potential entertainment factor of this novel method of interaction and provides encouraging data to further examine these augmentations of virtual reality with olfaction.

4.5.4 Other Findings

An interesting phenomenon that had not been considered before starting the study was the number of scents participants expressed being able to perceive. Participants were not told the number of scents used on the first instance of the experiment and only 3 participants (4, 5 & 9) correctly stated that a single scent was used throughout. The remaining 7 suggested there were 2 or more scents used throughout. This offers an interesting insight into the psychological aspects of perceiving a scent. This phenomenon is known as phantosmia and is described as the perception of scent when there is none presented in the physical environment (Leopold et al., 2002). Although there was a singular scent presented, 3 participants suggested being able to sense a smell of 'damp' within a cave area of the virtual environment. Interestingly, during the Think-Aloud, participants acknowledged that the scent may not actually be there but suggested they could imagine it. Other participants mentioned being able to smell the pine trees. This offers a potential opportunity for designers that are developing scent-based VR. Perhaps, simply with the knowledge that a scent is present in a virtual space, our brains start to fill in the missing gaps in the scents when presented with the associated visual stimulus. Perhaps rather than designing experiences with every single scented object in the environment, the number of scents can be reduced to a selection of the most prominent within a virtual environment. This adds credence to the suggested heuristic presented in the literature review in which humans are often unable to discriminate more than 4 scents at any one time (B. A. Livermore & Laing, 1996). None of the participants actively mentioned the incongruence between the lack of deliberate scent for other visual stimulus within the environment as a noticeable issue. This could offer an exciting avenue for further research to explore this phenomenon further and whether it offers any practicality in implementing scent within VR.

Another interesting finding was that the wind effect produced by the fan was deemed to induce a pleasant feeling in most participants. Due to the design of the olfactory display device, the fan is situated roughly 5cm from the face. Preventing the individual from feeling the air it produces would be very challenging and would likely require a different form of olfactory delivery. In the case of this virtual environment, participants noted that the breeze made sense within the context and deemed it to be a desirable feature of this experience. This, similar to the issue of the residual odour from the prototype are likely to only produce this result in certain environments where it would make sense to have wind. In interior environments this may become a more problematic issue as the participant would become actively aware a scent is being released as the fan is turned on.

As previously stated, this study confirms that the prototype device functions and the integration into the virtual environment offers a viable method of creating scent-based interaction within virtual reality. The design of the prototype can be expanded further and the nature of the communication between the virtual environment and the olfactory display device means that a range of features can be added or removed based on the requirements of the researcher. The technology would allow for the addition of multiple fans, these can simply be assigned a different trigger within Unreal Engine with minimal alteration to the existing script and have them send a different numerical value to the Arduino. From here, different scents could be associated with different fans. The communication system also functions using different dispersal methods, it is possible to replace the fan for an ultrasonic atomiser, as was examined at the start of this design. With minor changes to the Arduino code, this offers a rapid method of building a modular scent delivery system, optimised for the needs of the study.

4.6 Summary

This chapter presented the design, development, and evaluation of a low-cost olfactory display device suitable for VR. Its design is based on the heuristics identified in the literature review and systematic review, namely that a VR device should be portable and be built from low cost and accessible materials, that it should receive it's trigger to release scent directly from interaction within the VR environment. To this end, this prototype was highly successful. It was also found that there is a distinct gap in the knowledge when examining the communication between an olfactory display device and the VR environment. This chapter addresses this by providing a comprehensive method of establishing this communication. The development of this prototype therefore addresses each of the heuristics as stated at the start of this chapter and provides a response to each. The prototype device was evaluated through both quantitative and qualitative means using items adapted from the Temple Presence Inventory (Lombard et al., 2009), a Think-Aloud protocol and a series of open-ended questions. It was found that the device did appear to afford a sense of presence in the participants. They found the experience overall very positive and that the inclusion of scents made the experience more enjoyable when compared to VR content they had previously experienced. A discussion on the strengths and limitations of the device was also presented.

Chapter 5: Conclusion

5.1 Introduction

This thesis examined a range of topics useful for gaining understanding and context into the use of olfaction alongside virtual reality through a comprehensive literature review. Areas addressed included the physiological aspects of perceiving a scent along with relevant phenomena such as olfactory detection thresholds and olfactory fatigue. A definition and discussion on presence was provided in relation to the use of scent for VR before examining past attempts to bring olfactory stimulus to media. This review then culminated in a series of design heuristics which were used as a foundation for both the development of the systematic review and development of the prototype olfactory display device.

A systematic review was presented in which a number of questions were defined, and when answered provide reinforcement to the presented heuristics. These included insight into the most common methods of dispersal and delivery as defined by Yanagida (Yanagida, 2012), the most common form factors: either in-environment or wearable as defined by Murray (Murray et al., 2016). Other considerations examined were whether the olfactory display device was able to communicate with the VR environment to receive triggers to release scent through the interactions of the VR user. Also presented was the number of studies that examined presence as part of the methodology. By gaining this range of information about past studies, a greater understanding of the context and background of olfactory display devices could be provided to researchers interested in developing similar technology.

It was found that there was a large gap in the knowledge when examining the methods of this communication between the olfactory display device and the VR environment. Although some of the included studies did utilise this communication. No repeatable method was provided for how it was achieved in any study. This communication was also presented as a heuristic in the literature review. As part of the development of a head-mounted prototype olfactory display device, a method of communication between the device and the VR software was outlined.

In order to evaluate the prototype display device a short study was carried out in which 10 participants were asked to undertake two instances of a VR environment using the HMD-mounted prototype device. A series of questions based on the Temple Presence Inventory (TPI) (Lombard et al., 2009) were administered to discover if the inclusion of scent afforded a sense of presence. A series of open-ended questions were also asked to help identify any issues and limitations with the design of the device. It was found that there was some evidence of a sense of presence provided by the inclusion of the olfactory stimulus from the results of the quantitative TPI as well as a thematic analysis of the Think-Aloud Protocol and the response to the open-ended questions. It was found that the prototype device functioned as intended and was able to produce a reactive release of scent based on the participants location in the virtual environment successfully.

5.2 Key Findings

The primary aim of this thesis was to examine how olfactory display technology might be used to enhance presence within virtual reality. In order to address this, the following research questions were posed:

> **RQ1:** To what extent does the inclusion of olfactory stimulus impact an individual’s sense of presence within VR?
> **RQ2:** How is olfactory display technology currently used alongside VR?
> **RQ3:** How can readily available components be used to develop an olfactory display device suitable for use with VR?

A response to each of these research questions will be provided along with a summary and discussion of the findings that led to these responses.

5.2.1 RQ1: To what extent does the inclusion of olfactory stimulus impact an individual's sense of presence within VR?

This research question was addressed by the literature review, the systematic review and the evaluation of the prototype olfactory display device. It was suggested the beneficial impact on an individual's sense of presence is one of the primary motivators for the examination and inclusion of olfactory stimulus in VR. It was found that there are overall mixed results as to the extent in which the inclusion of scent has on an individual's sense of presence. Studies ranged from those that suggest the inclusion offers little to no impact on presence, and others that present highly positive results. A categorisation of the systematic review aimed to identify the number of studies that examined presence and found that 15 of the 34 included studies had examined presence as part of the methodology. Interestingly it was found that of these 15, 7 showed that the inclusion of scent did indeed have a positive impact on an individual's sense of presence, 4 suggested that there was no discernible impact, and it was unclear in another 4 studies, the impact scent solely had on presence due to olfaction being examined alongside other stimulus such as wind and haptic effects. There did appear to be more studies that show a positive impact on presence than those that did not but there is still some uncertainty which correlates with the findings of the literature review.

Whilst it was found in the evaluation of the prototype olfactory display device, that it did appear there was some relationship between the implementation of scent and an increased sense of presence through the Temple Presence Inventory (Lombard et al., 2009) items, it is suggested that this should not be taken as conclusive evidence due to the small sample size. Instead, it offers encouragement for further study into this subject. Qualitative response from the Think-Aloud protocol and open-ended questions also suggest that participants enjoyed the novel inclusion of olfactory stimulus and that they did feel immersed in the experience whilst undertaking it which gives optimism for the future of this area of study.

Unfortunately, the answer to this research question is often not always clear. Scent studies often used different methodologies and technologies as part of their procedures which introduces a range of variables into their designs. This, coupled with the ranges of different methods of examining presence makes it difficult to compare one study, like for like against another. It does appear from the findings of this thesis that there is a relationship between the inclusion of olfactory stimulus and an increased sense of presence, but it is much harder to give a definitive answer as to the extent this is the case.

5.2.2 RQ2: How is olfactory display technology currently used alongside VR?

This research question is answered through the completion of the literature review and systematic review. It was found in the literature review that the technology used in the included literature shows a range of complexity and functionality, from the use of simple candle diffusers to present ambient odour (Serrano et al., 2016) to bespoke, complex reactive scent systems built into the physical space (Ischer et al., 2014). Yanagida (Yanagida, 2012) outlined a series of dispersal and delivery methods that olfactory display devices might utilise. The systematic review examined a corpus of 34 studies to find the most commonly used techniques within olfactory studies and found that accelerated vaporisation through wind and ultrasonic atomisation were the two most commonly used methods of vaporising scents whilst wind and natural diffusion were the two most commonly used methods of delivering the vaporised scent to the nose. The most common combination of dispersal and delivery was found to be accelerated vaporisation with wind to deliver the stimulus. It was suggested that this is likely because a fan can be used to vaporise and deliver scent whilst also having the ability to be turned on and off electronically. This means that an olfactory display device can have a smaller form factor, and be built with less components. Murray (Murray et al., 2016) suggests two form factors for olfactory display devices: In-Environment and Wearable. It was found that there were slightly more studies that used in-environment (18) than used a wearable device (12). This result was surprising as it is suggested that a wearbale device would offer a more consistent scent release as the scent stimulus could be kept at a consistent distance from the participants nose, no matter which direction they were looking. It was found that a single scent stimulus was the most common among studies. This has the benefit of not having to contend with the issue of scent mixing or developing a system of removing an existing scent stimulus before releasing a new one.

It is clear that there is a range of technology and formats of olfactory display devices and these vary from study to study to best suit the requirements of the methodologies. This variation likely also stems from the lack of any commercially available olfactory display device designed for VR. The literature review presents a discussion of the prototype devices such the FeelReal mask (*FEELREAL VR Mask*, 2019), Cilia (*Cilia Developer Kit*

(Smell Device) — HAPTIC SOLUTIONS — HAPTIC SOLUTIONS, 2019) and VAQSO (*VAQSO VR | Adding a 4th Sense to VR Worlds*, 2018). It was found that none of these devices have yet to make it to market and are currently still awaiting mass production or are still at the prototyping stage of development. Early reviews of these devices suggested that many of the issues such as scent blending, and lingering scents still remained and that this is a common issue that still needs to be addressed. This lack of commercially available device leads many researchers to develop their own devices, suited for the purposes of the study, eschewing certain functionality in favour of others. Perhaps once a device is readily available, we will see a more unified method of examining scent within VR.

Many presented olfactory display devices are encountering the same issues as some of the first attempts to implement scent with media. It was suggested in the literature review that one of the reasons for the failure of Smell-O-Vision was that scents would linger between release and blend until individual scents were no linger distinguishable (Gilbert, 2008). These inherent issues with the nature of how scent is physically delivered are apparent in recent studies (Kato & Nakamoto, 2018b) as much as they were in the 1950s. It may be impossible to entirely remove these problems from devices and it appears to often be the case that addressing one heuristic leads to a compromise on another. For example, to keep a device compact enough to be head mounted, it is unlikely there would be an active method of removing a scent stimulus after it has been released.

It is clear when answering this research question, this is a technology that is still in its infancy, that still requires further refinement and development. It is, however, an area of exciting development, with a range of different methods and technologies available to help deliver scent stimulus.

5.2.3 RQ3: How can readily available components be used to develop an olfactory display device suitable for use with VR?

This research question was answered through the development and evaluation of the prototype olfactory display device, which in turn was developed from a series of heuristics identified from the literature review. These were specifically the ability to trigger the release of scent through direct interaction of the user with the VR environment. In this case, a scent would be released when the individual was in a certain position within the virtual world. This means scent can be released in response to certain actions the VR user performs and requires no active input by them to release the scent. This heuristic was examined as part of the systematic review to understand how many studies had used a reactive system. It was found that 12 of the 34 included studies had developed a method of allowing the olfactory device to communicate with the VR software. It was found that none of the studies presented a repeatable description of how this communication was achieved. This large gap in the knowledge was also addressed through the development of the prototype device. A priority for this device was to be able to produce it with readily available components. The use of the freely available Unreal Engine 4 and open-source development platform Arduino meant that the technology that allowed the VR environment and device to communicate could be developed free of cost. The prototype device was developed from the most common combination of delivery and dispersal as found in the systematic review: Accelerated vaporisation and Airflow delivery. Scent stimulus was provided through the creation of scent cartridges: small plastic containers house a piece of cotton doused in essential oils. When air is drawn into the device by a small fan, it passes over the scent cartridge and is projected to the nose of the individual. It was decided to develop the device to be small and mountable on the HMD of the VR setup, thus keeping the delivery point consistent no matter which direction the participant faced.

It was found that the device functioned as intended and successfully presented a reactive olfactory display system using locational triggers within the VR environment. The device was evaluated to examine the impact scent has on an individual's sense of presence. As previously stated, it is suggested that the device could produce a scent stimulus so as to provide a sense of presence. When evaluating the device, it was found that all participants were able to note a perceived change in the strength of the scent based on their location within the virtual environment, this further reinforces that the method or delivery and dispersal functioned as intended and were suitable for this application. The presentation of this method also provides researchers with a guide to setup and build upon the design. The nature of the open-source Arduino format means that the device can be modified in a modular fashion if further fans were needed to emit multiple scents. It was found that the prototype could also be adapted into an in-environment form factor which might allow for the use of a larger more powerful fan if the scent needed to be delivered from a greater distance to the nose of the individual. It was found that a previously created device by Herrera & McMahan (2014c) which was also described as 'low cost' was estimated to have cost roughly £40. This device was also only designed as an in-environment format.

The device presented in this thesis is estimated to cost under £30 and, when combined with the use of freely available software, provides a strong foundation for any researchers and developers wishing to develop their own olfactory display devices. It can be said that the presented heuristics from the literature review and the development of the prototype device provide suitable answers to this research question.

5.3 Project Limitations

A number of limitations have been identified with the production of both the systematic review as well as the design and evaluation of the olfactory display device prototype.

It was found during the systematic review; a number of studies were excluded due to the lack of use alongside VR. This decision was made at an early stage in the review process and offers a comprehensive list of literature specific for VR. Several of the excluded studies did present an olfactory display device which might offer further insight into the technology of presenting scents that could be adapted to suit a VR format. It was found through examination when deciding which results to exclude that, although some devices bear a resemblance to those used with VR, many would not be able to have been adapted due to the fact they were not built with VR in mind. Therefore, this reinforces the decision to only include those studies that used a VR headset. A future literature review might examine these devices with broader inclusion data to find other potential uses of technology that might be adapted.

A known limitation with the evaluation of the olfactory display device was the small sample size of participants. Due to undertaking this study under COVID-19 restrictions, it was difficult to identify participants that had both a VR headset and a desktop PC capable of running the virtual environment. Because these studies took place in different locations, a range of external variables could not be accounted for, such as any ambient odours in the environment before the study was carried out. Based on the understanding of olfactory fatigue however, participants were acclimatised to the scents in the spaces in which the study was performed. Another limitation is that participants were not screened for their ability to smell. It may have been useful to create a calibration of scent by slowly increasing the concentration of a scent until the olfactory detection threshold for each participant could be found. This would have been complicated and imprecise through the remote method in which the studies were carried out. It was found that all participants noticed a change in scent throughout which suggests that the concentration of scent released was above the olfactory detection threshold for all participants.

When examining the impact of olfaction on presence, because of the small sample size, there was no control group in which to compare results. Instead, participants were selected based on their prior experience with VR that had used no scent stimulus which acted as a comparison point for participants when providing responses.

5.3.1 Future Work

Olfactory virtual reality is an area of study that is still in its exploratory stages and through the completion of this thesis several further areas of research have presented themselves.

5.3.2 A further study of presence with a larger sample size and use of control group

As stated above, a study using the same prototype olfactory display device would be carried out using a much larger sample size. A more controlled and consistent environment would be used to account for and minimise any variation in ambient external odours. A period of time deemed suitable to ventilate and disperse any lingering scents would be left between each participant to prevent contamination of scent between instances of the study. This time would be calculated by emitting a scent comparable to that of the prototype display device in the chosen physical space and using human assessors at 10-minute intervals to understand how long the scent might linger in the space. Extraction fans would be used to expedite this process. This study would also standardise the VR Headset, headphones and connected computer hardware to ensure a consistent visual and auditory experience through each instance.

The study would also be carried out with a control group made of the same number of participants. This group would undertake the same VR experience without the use of the olfactory display device. Both the think-aloud protocol and the questions identified from the Temple Presence Inventory (Lombard et al., 2009) would be utilised. The questions related to the effectiveness of the prototype display device would not be presented to this control group. Using this control group would offer an understanding of participant’s sense of presence within the virtual environment using only visual and auditory stimulus, thus providing a baseline comparison to help validate the impact which the inclusion of scent has on an individual’s sense of presence.

5.3.3 An examination of Phantosmia

An interesting phenomenon was discovered when examining the perceived number of scents by participants in which several suggested that multiple scents could be smelled during the study despite only a singular scent stimulus being used, a phenomenon known as phantosmia. This is likely to be a challenging and complex area to study but may offer a range of benefits to the design of olfactory display devices, potentially allowing for the reduction in the number of scents required to create immersive scent experiences in VR. A future study would be designed to show a range of distinct visual stimulus but only a singular olfactory stimulus and examine whether participants can perceive any additional scents. In this study, the visual stimulus were all relatively similar (they were all natural plants or trees) and this phenomena may not extend when the scent and visual stimulus become more and more incongruent.

5.3.4 Developing a virtual experience with scent in mind.

Another useful development would be the creation of VR content designed specifically around the findings of this thesis. The development of a narrative experience or game that is built around scent may offer useful insight into the refinement of the olfactory display prototype as well as the use of more complex interactions than simply location-based scent release. This was one of the heuristics presented in the literature review. Creating this might allow for any limitations to be factored into the design as features rather than obstacles. Although the scent display technology may function from a mechanical and technical standpoint, the results of this study suggest that a large amount of the presence felt by individuals may come from the experiences, interactions, and narratives that the device may afford. An examination of using scent as an active method of interaction might implement the scents into a narrative driven game. For example, a murder mystery in which the individual must identify the murderer using scent stimulus, similar to that of the plot of *Scent of Mystery* (Cardiff, 1960). For this to function, the issue with removing existing scent stimulus would likely need to be addressed to provide adequate distinction between the scents available.

5.4 Conclusions

This project aimed to address the impact the use of olfactory display technology has on an individual's sense of presence through the examination of available technology. It is suggested that this thesis does indeed address this and also provides a range of beneficial considerations useful to researchers and designers of olfactory display technology. The presentation of a comprehensive systematic review should provide a strong context and background to the currently available technology and how it is being utilised. A major success of this project which fills the identified gap in knowledge was the development and presentation of a low-cost, accessible olfactory display device. It was found that there was very little information on the methods used by previous studies. It is hoped that this design can be used by others in need of an olfactory display device but also that it be built upon, modified, and adapted to the needs of any future researchers and developers of olfactory display technology. In combination with the presented heuristics of the literature review it is also hoped that researchers will be well equipped to further the understanding of this exciting area of research.

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Appendix 1: Corpus of Systematic Review

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Appendix 2: Participant Consent Form and Information Sheet

The role of Olfactory Augmentation on a Virtual Reality Experience

PARTICIPANT INFORMATION

1.Aim of Study

The aim of this study is to investigate the impact the inclusion of smell (olfaction) has on a Virtual Reality experience, specifically the impact it might have on the sense of presence and perceptual realism. (Your sense of 'being within the virtual space'). This study will also be used to evaluate a prototype scent emitting device for use in Virtual Reality. This research is being undertaken as part of an MRes thesis.

2.Outline of Study

You are being invited to participate in a short Virtual Reality experience that should take no longer than 15 minutes. The VR headset is fitted with a smell emitting device which will release scent during the experience. This is released as scented air from essential oils. You will be given a very short general health questionnaire (this is related to motion sickness from VR and allergies to any odorants) before beginning the study. During the study you are encouraged to verbalise your thoughts and experience. This will be audio recorded. The audio will then be transcribed, and the original audio clips will be deleted. Your response will be completely anonymised.

Upon completion, there will be a short questionnaire of 7 questions to complete about how engaged and how present you felt whilst in the experience. A further 3 open ended questions are asked to provide evaluation on the prototype device.

3.What is Virtual Reality?

If you have never experienced Virtual Reality before, the concept is that you will embody a virtual character within a virtual environment. When you move and turn your head, the virtual character will do the same. Because of the limited space, movement within the environment uses a teleport system. This will allow you to point to a location you would like to move to and then your position will instantly move there.

In some cases, there are reports of motion sickness that come from using Virtual Reality. If you feel ill or uncomfortable at any point, you are free to stop the study and remove the VR headset.

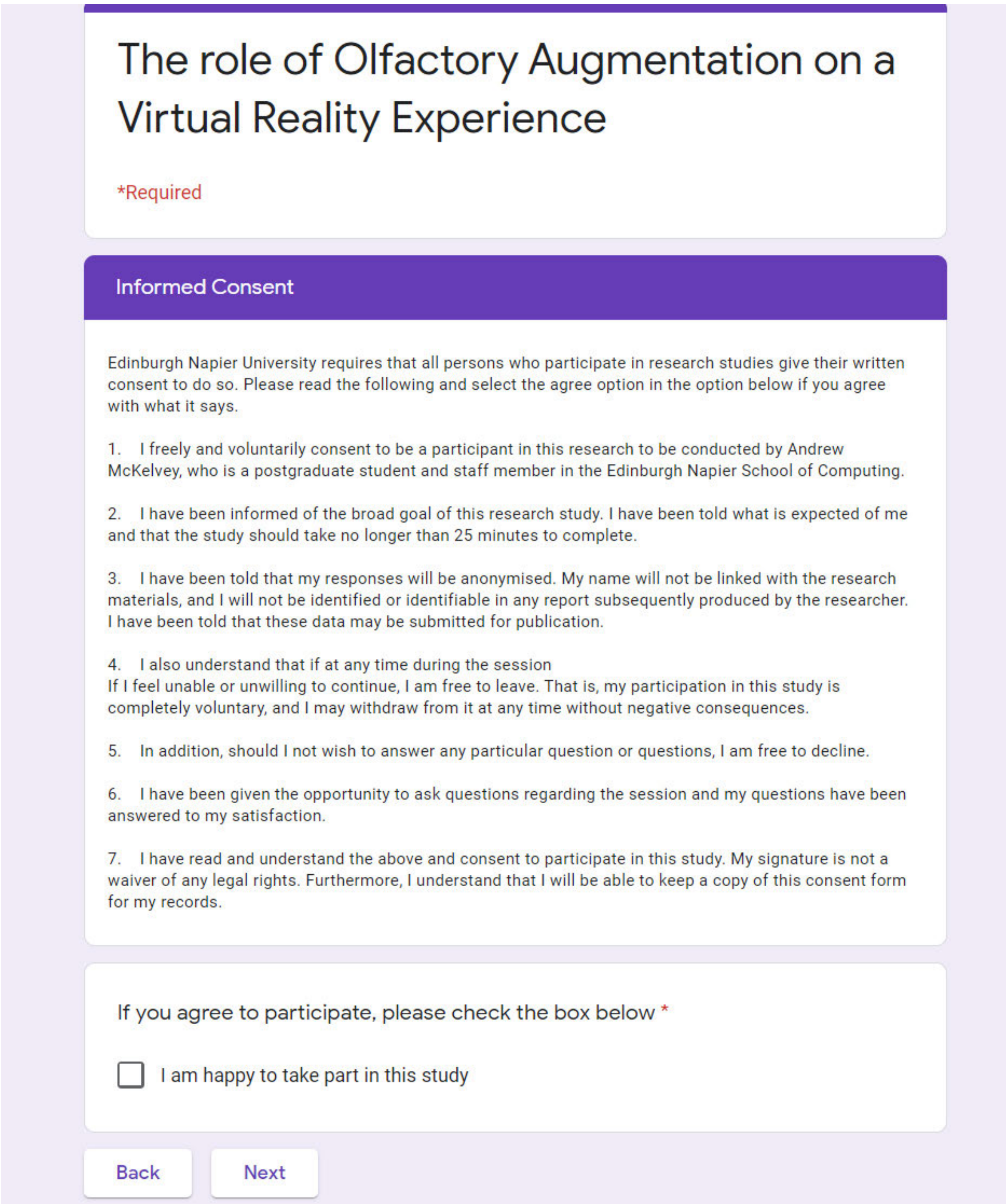
4.The VR Environment

Before beginning the study, you will be given the opportunity to get comfortable navigating and using the Virtual Reality environment. When you are comfortable and are ready to proceed, your virtual character will then be placed in a virtual environment that is an approximation of a European Pine Forest. You are asked to follow the road that you will see in front of you until you reach the designated end point (Shown as red markers). There are blue trail markers to help you follow the route and these will be shown to you before undertaking the study. You are welcome to look at any aspect of the environment you wish and are free to take a long as you like to complete the study.

5.Your Data

The data you supply when undertaking this study will be anonymised and any identifying information will be deleted. It is intended that the results from this study will be published in journal format.

Next



The role of Olfactory Augmentation on a Virtual Reality Experience

*Required

Informed Consent

Edinburgh Napier University requires that all persons who participate in research studies give their written consent to do so. Please read the following and select the agree option in the option below if you agree with what it says.

1. I freely and voluntarily consent to be a participant in this research to be conducted by Andrew McKelvey, who is a postgraduate student and staff member in the Edinburgh Napier School of Computing.

2. I have been informed of the broad goal of this research study. I have been told what is expected of me and that the study should take no longer than 25 minutes to complete.

3. I have been told that my responses will be anonymised. My name will not be linked with the research materials, and I will not be identified or identifiable in any report subsequently produced by the researcher. I have been told that these data may be submitted for publication.

4. I also understand that if at any time during the session
If I feel unable or unwilling to continue, I am free to leave. That is, my participation in this study is completely voluntary, and I may withdraw from it at any time without negative consequences.

5. In addition, should I not wish to answer any particular question or questions, I am free to decline.

6. I have been given the opportunity to ask questions regarding the session and my questions have been answered to my satisfaction.

7. I have read and understand the above and consent to participate in this study. My signature is not a waiver of any legal rights. Furthermore, I understand that I will be able to keep a copy of this consent form for my records.

If you agree to participate, please check the box below *

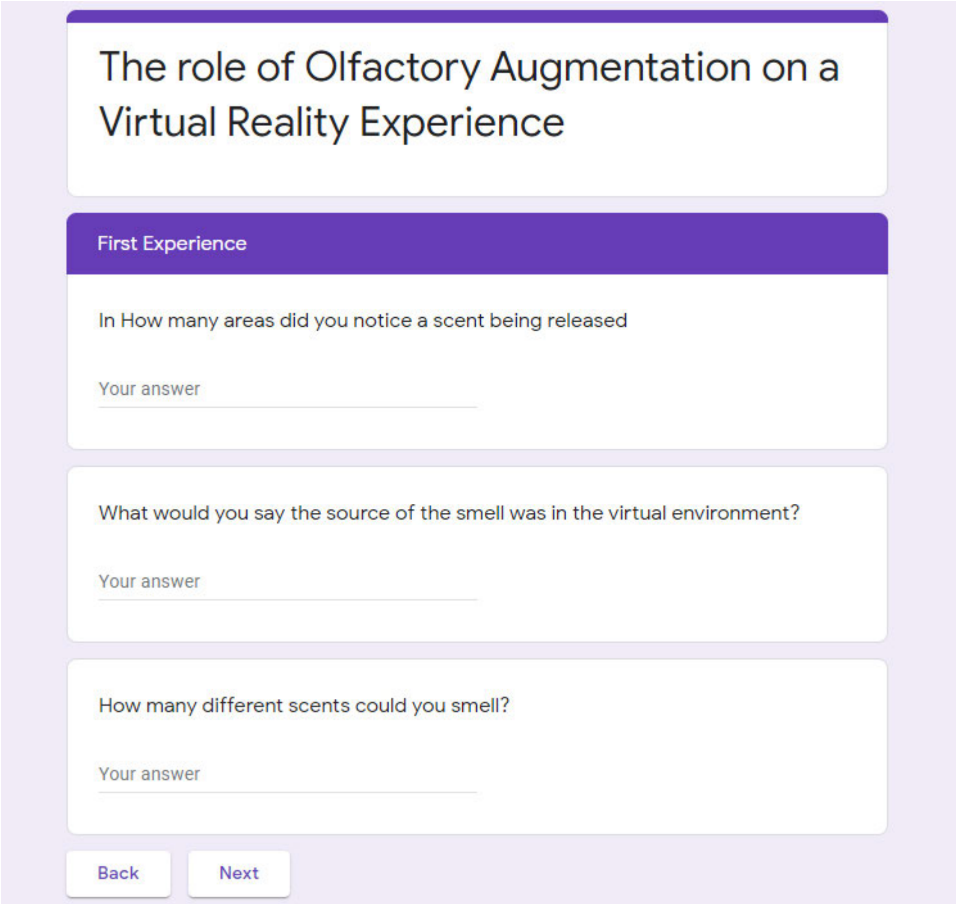
- [ ] I am happy to take part in this study

Back Next

Appendix 3: Questionnaire Items

The following questions were completed by the participants. There were questions that were completed after the first instance of the experience, then follow up questions based on the Temple Presence Inventory after the second instance:

After the First Instance:


The role of Olfactory Augmentation on a Virtual Reality Experience

First Experience

In How many areas did you notice a scent being released

Your answer

What would you say the source of the smell was in the virtual environment?

Your answer

How many different scents could you smell?

Your answer

Back Next

After the Second Instance:

Presence Questions

These questions aim to find out about your sense of presence within the virtual environment and whilst taking part in the VR experience.

To what extent did you experience a sense of being there inside the environment?

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very Much

To what extent did it seem that smells came from specific different locations?

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very Much

To what extent did the things you smelled match the things you saw in the virtual environment?

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very Much

To what extent did you feel mentally immersed in the experience?

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very Much

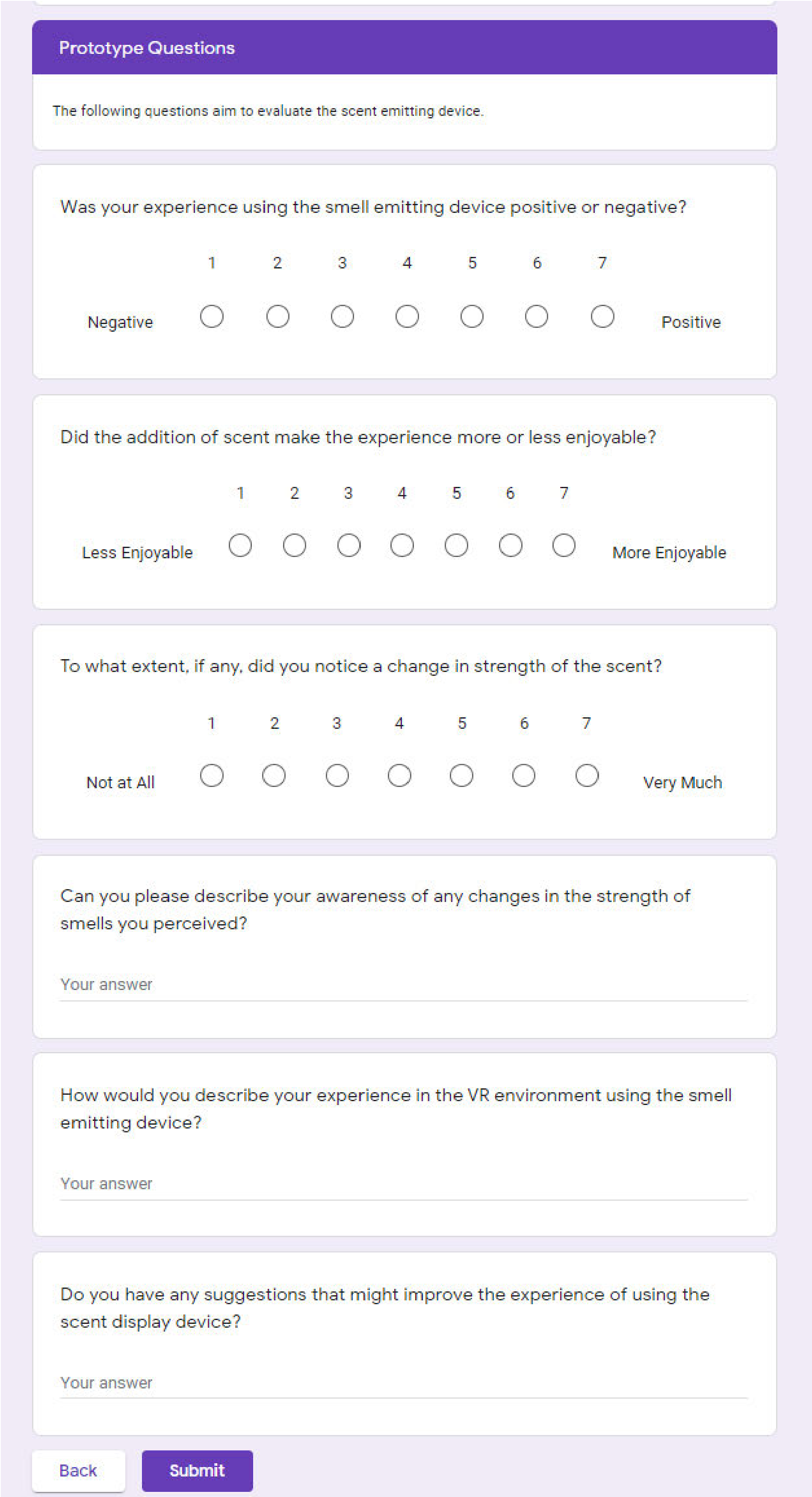
How completely were your senses engaged?

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very Much

To what extent did you experience a sensation of reality?

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very Much

Back Next



Prototype Questions

The following questions aim to evaluate the scent emitting device.

Was your experience using the smell emitting device positive or negative?

	1	2	3	4	5	6	7	
Negative	○	○	○	○	○	○	○	Positive

Did the addition of scent make the experience more or less enjoyable?

	1	2	3	4	5	6	7	
Less Enjoyable	○	○	○	○	○	○	○	More Enjoyable

To what extent, if any, did you notice a change in strength of the scent?

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Very Much

Can you please describe your awareness of any changes in the strength of smells you perceived?

Your answer

How would you describe your experience in the VR environment using the smell emitting device?

Your answer

Do you have any suggestions that might improve the experience of using the scent display device?

Your answer

Back Submit

Appendix 4: Transcriptions of Think – Aloud Protocol

Participant 1 'Think Aloud' Transcription

P1 = Participant 1

R = Researcher

First Attempt

00:02

P1: Alright amazing, so will this scent thing just activate by itself?

R : Correct

00:22

P1: This reminds me of being in the Highlands, kind of.

00:27

P1: (Looking towards flowers) That's nice.

00:28

P1: (Points towards heather) What's that? Heather?

00:30

P1: (upon entering the first area of smell source – Audible Gasp) Oh! Ah! Smells beautiful! Oh wow.

00:41

P1: (Hands gesture as if blowing scent towards nose) It's like I'm really here.

00:45

P1: (Hand gesture as if blowing scent towards nose) I don't know if you can see these robot hands, but I'm gesturing.

01:00

P1: We need more things like this because this would be good for people who maybe have disabilities or things like that and they can’t enjoy a nature walk like this.

01:20

P1: Oh man, these smells really are adding to it.

01:40

P1: (Audible gasp upon leaving source of first smell) Now they’re gone! Wow! That’s clever.

02:15

P1: (upon entering second area of smell source) It smells so good.

02:32

P1: See, I’m not talking now because I’m enjoying myself.

02:44

P1: This is going to be amazing for history for kids who have to live with COVID for the rest of their lives and can’t go outside. “Hey kids, let me show you what live used to be like” (Audible laugh).

03:02

P1: Oops (knocks scent device with motion controller) We’re good!

03:05

P1: Aw wow. Now this is nice. What this needs is a photo mode.

03:26

P1: (Upon entering the cave part of the environment) I know the smell isn’t turned on but I can almost smell the damp rot.

R: Really? That’s interesting. So what do you imagine it would smell like?

P1: So you know when it’s like that kind of wet, rocky smell, and it’s damp nearby. Actually is it making droplet noises?

R: Yep, You’re hearing some spatialised audio there.

P1: Yeah that’s cool. I can’t smell it but in my brain I feel like I can get that smell in here.

04:26

P1: And it’s cold in there too because it’s not out in the sunshine.

R: That’s interesting.

P1: Where as now (Steps into sun lit area of VE) I’m back in the sun.

04:49

P1: (Entering 3^{rd} area of smell source) This is where you’ve programmed in a jump scare right?

R: (Audible laugh)

P1: (Points to tree in distance) Behind that tree right? (Audible Laugh).

05:13

R: You’re coming towards the red end part at which you can stop.

Second Attempt

05:55

P1: Ok, so it kicked in back there (Gestures just to the area before the area of the first scent release) but however, because there’s the residual smell it’s almost like it’s already there. There’s almost like that ambient smell in the air before it comes in fully.

06:23

P1: Obviously, because I know this isn’t the real world and I can feel the fan blowing on to my nose. That’s the only thing you could say would take you out of it.

6:58

P1: So what I will say is that, because I've been in an environment like this before, it's almost like it's trying to trick my brain into smelling the pine as well.

R: That's interesting as there is only 1 smell used in the device.

08:02

R: (P1 enters cave) It was interesting you said the thing about the fan blowing on your face and you could feel it. Can you hear it? Is there anything audible from the device?

P1: No I can't, not with the headphones on. I think the audio from the environment helps too.

09:15

P1: (Upon entering 3rd source of smell) It's funny, now that I know how many patches of smell there are, and how big there environment was I was convinced there were more. Maybe it's the markers as well (Gestures to the blue way marker). I'm having a Pavlovian response to the markers.

09:52

P1: I won't know what anyone else does, but I'm be interested to see, when this is done, what other people experienced actually. (Audible laugh)

10:20

P1: (Before leaving the 3rd source of smell, gesturing to blow scent towards face) Lets get one last deep breath of it… Nice

Participant 2 'Think Aloud' Transcription

P2 = Participant 2

R = Researcher

Notes: This recording was started just before participant reached the first smell source.

First Attempt

00:02

P2: (upon entering first area of scent) Ooooh! I can smell the flowers! Oh, that's cool as (expletive)! And there's wind!

00:17

P2: Sorry. Professionally, there's a smell rising from the flowers nearby which makes me feel like I'm actually in flowers so that's cool.

00:26

P2: Oh wow.

00:35

P2: (Points towards visible root under embankment) I like that I can see that root as well.

00:49

P2: I like that the trees rustle just a little bit because with the wind I'm feeling on my nose it's kind of proportional to the leaves.

01:13

P2: (Upon entering 2^{nd} area of smell) Oh the flowers are back.

01:57

P2: (Upon entering cave area) I like the puddles. Ohh and there's a noise. They look and sound squelchy. The dripping cave is very cool.

02:28

P2: (Upon entering the 3rd smell source) I can almost tell there is flowers just by the smell without having to look down and see them there.

03:10

P2: (Entering the last part of the road) I like this bit. The birds seem like they are closer. Like they are actually right above.

03:17

P2: Oh no! Am I nearly at the end?

R: So I'm going to get you do it again in a second

P2: Yeah! Cool!

Second Attempt

03:29

P2: (A little before entering the first source of smell) Oh there's a smell maybe.

03:31

P2: Maybe not. It's not as strong though.

03:37

P2: (Upon entering the first source of smell) Woah! There is is. Yeah, they're really floral. What's there name? Erm, smells like rosemary I think.

04:26

R: (P2 in area between source 1 and 2 where no scent should be released) So, are you smelling anything just now?

P2: When I was back a step, I couldn't smell much. I don't know if it's just my brain making up that I can smell pine. But now that I've taken a step forward (Steps into 2nd area of smell source) I can start to smell the flowers which are just there.

05:30

P2: (Upon entering the cave area) That's cool. Yeah, I like the dripping and the echoing in the cave. It's very atmospheric.

05:47

P2: (Just before entering the 3^{rd} area of smell source) I'm starting to smell the flowers now.

06:20

P2: (Before leaving the 3^{rd} source of smell) Smells a bit woody towards the end of the flowers.

Participant 3 'Think Aloud' Transcription

P = Participant 3

R = Researcher

Notes: This recording was started just before participant reached the first smell source.

First Attempt

00:14

P3: (Just after starting experience) I think because I'm sitting I feel quite low to the ground.

R: You can stand if you like.

00:23

P: (Looking at trees) That's nice.

00:56

P: (Upon entering the first source of smell source) Oh that's pungent!

01:06

P: There was quite a noticeable change to the smell actually. Just a second ago

01:24

P: It's quite nice walking through the plants

01:48

P: It almost feels like there is a light breeze coming past in the environment. It's nice.

02:21

P: (Upon leaving the first source of smell) Okay, I feel like it's starting to fade now.

02:35

P: (In the area just past the first source of smell but looking back on the flowers) Yeah that's it gone now.

02:47

P: It's really odd actually because although the smell is gone I feel like there still kind of a breeziness. I don't know if there's a breeze in my flat or if the fan was still running.

03:29

P: (Gestures to a patch of nettles in the VE) Oh I like these nettles! They're nice.

03:48

P: (Upon entering second area of smell source) Oh! Yeah, that's the smell come back in again.

04:40

P: (On the cusp of leaving the second source of smell) It's still there.

04:47

P: (Upon leaving the second source of smell) okay, now it's gone.

05:48

P: (Upon entering the cave area) I love that dripping noise (Audible Laugh)

06:33

P: (Approaching a tall reed in the VE) Oh, that plant doesn't smell.

06:49

P: (Upon entering third source of smell) Oh, there's a bit of distance between me and the flowers but there's almost like a breeze just swept up. That's what it feels like right now.

07:06

P: I'm trying to recall what the smell is. I'm seeing the flowers so I know it's the flowers but I can't quite identify what the oil is. It kinda just smells like flowers. It's nice.

08:01

P: (Just before leaving the third smell source) It's still there.

08:45

P: (Upon leaving the third smell source) Okay, at this point I'd say the smell is gone. But I'm not sure.

Participant 4 'Think Aloud' Transcription

P = Participant 4

R = Researcher

First Attempt

00:17

P: (Around a second after entering first area of scent) Aww that's awesome!

00:26

R: Have you noticed something there?

P: The smell's coming through it so the fan has turned on. It smells really good.

00:41

P: (Crouching to touch the flowers) It makes you just want to smell them

01:29

P: (After leaving the second smell source) So I take it if I was to jump back and forth (Moves back into smell source 2) Does it turn back on? Yeah… That's cool.

02:27

P: (After leaving smell source 3, the participant turned round and went back into the source. They then turned back and continued on the route.)

02:48

P: (Just before reaching the end of the environment) It's actually scarily realistic. I can't believe this. So strange.

Second Attempt

03:10

P: (Within smell source 1) I think I'm more aware of it now.

R: You mean because I'd told you where the sources were?

P: Yeah, definitely.

03:22

P: I think because you're aware that it's only one scent. You're definitely more aware that it's the flowers.

R: Sure.

03:30

P: This is so cool man.

Participant 5 'Think Aloud' Transcription

P = Participant 5

R = Researcher

First Attempt

00:21

R: Are you noticing anything at this point? (participant is halfway through first scent area)

P: Yeah I am yeah, it's like a foresty kind of smell.

R: Okay.

P: It's definitely quite… calming, quite soothing.

00:53

P: The hand is going a bit weird (Vive loses tracking on hand momentarily)

P: The smell's coming through it so the fan has turned on. It smells really good.

01:25

P: So I'm guessing the smell activates at certain positions.

R: Correct, it's based on your position within the world.

P: Right, okay.

01:41

P: (In centre of second smell area) Yeah this is bizarre! (Audible laugh). That's the best way to explain it. It's kind of weird. In genuinely feels like that one sense is the one sense you don't have in normal VR.

R: Okay.

P: And now you can smell as you go round. It's quite weird. That's my initial reaction.

02:54

P: (Entering the cave area) (Audible laugh) This is really cool!

03:47

P: (Vive loses hand tracking) I've lost my hand!

04:54

P: It feels like, I dunno, like this fresh kind of feeling as I'm walking through. It's kind of…. It's really hard to explain actually. (Audible laugh) It feels like this extra sense that I didn't think would be reacting, but it is.

Second Attempt

05:37

R: (Pointing out the first scent area) So these patches of grass, the purple heather, you're coming up to, are the sources of the scent. Just so you're now aware of exactly where that's coming from.

P: I think on the last run I felt like I was getting scents even though I wasn't in these sections (Points to area before scented area) I don't know if that was because the fan was blowing before and I was just smelling the previous one.

06:13

P: (Entering first smell area) Ah yeah yeah, definitely.

R: Does it feel like there was a noticeable increase there?

P: Yeah, it's very slight, but it's enough that I can definitely smell it yeah.

06:37

P: I quite like the way it's quite subtle as well because it's not overpowering. It's a bit closer to being more realistic.

R: Sure.

07:03

R: (Participant in area between first and second scent area) So how about now in terms of the strength of the scent now that that you have left that area? How would you describe it now?

P: It went down for sure, but I can still smell a slight scent but not as powerful as it was before.

07:31

P: (Entering second scent area) Yeah yeah, as soon as I hit that bit I could feel it.

R: Sure.

09:02

P: On that last one I felt like I got a big scent here for some reason (Participant is in an area after the third scent area). I don't know if that helps.

R: Yeah of course, this is all interesting. So, of the same smell?

P: Yeah, it was around here I felt there was this last burst, but it might have just been because of the last one (Points back to the third scent area)

Participant 6 'Think Aloud' Transcription

P = Participant 6

R = Researcher

First Attempt

00:01

P: (Immediately after starting the experience) It's weird because I don't know if the smells are meant to be coming yet but it feels like I can already smell a lot of them.

P: It feels like it's more real. I don't know if it's meant to but its like there stronger smells at certain points.

00:35

P: (In centre of scent area 1) It makes it feel more real. Like you're in the forest.

P: The smell's coming through it so the fan has turned on. It smells really good.

01:24

P: I find that I'm almost subconscious that there's a smell added.

R: Do you mean you're actively thing about it?

P: Yeah a little bit. And I don't know if that's good or bad for myself. I don't know if that taking me out of it or in it more.

R: That's really interesting.

02:09

P: (In the cave area) Is there more than one smell in it?

R: I'm not going to answer that just yet, but I will give you more information at the end of this run.

P: Okay, I think it's myself playing tricks on me but I feel like I can smell different things. It just makes sense that there should be another smell coming next when I'm moving through it.

02:45

P: It was especially back in there (Turns back to the cave), it should smell damper and I don't know if I did smell that or if it's my brain going back and forth.

Second Attempt

03:46

P: (entering scent area 1) Ah right okay!

R: So would you describe a change happened there?

P: Yeah, when you know there's a trigger box, you can definitely smell that when I'm out in that part there (Points to area before scent area 1) it's a lot… er. There's not that fragrant smell. But when you come in here you do smell it. It's like it's colder because there's no smell.

04:29

P: (In first smell area) I do like the smell though, it's really nice.

R: I wasn't sure whether to do a horror game and have a really disgusting smell (Audible laugh)

P: (Audible laugh) Yeah, I don't think it'd be as nice.

04:41

R: So, what about when you're in this area now? Is there a noticeable difference in the scent?

P: I think I've still got hints of it, I guess in the air, but it is less potent because I'm not in the middle of it I'm guessing.

R: Yeah, you're now outside the trigger boxes.

P: There is a hint of it lingering about which I think works well because you've just come out of it. So perhaps there still would be that small hint but it's definitely less noticeable.

05:20

P: (Entering second scent area) And then when you step into it yeah… uh huh. (Audible sniff)

P: It went down for sure, but I can still smell a slight scent but not as powerful as it was before.

05:44

P: (Entering cave) And so is there a smell here?

R: Nope!

P: No? Is it just the flowers?

R: It's just the flowers.

P: It's weird! It smells like it should be damp.

06:17

P: (Entering third smell area) Yeah, when you know the trigger is there you can smell when it comes in.

R: Right. So, do you think it's more noticeable because you know where the triggers are?

P: Yeah, I think it's because I know where the triggers are, I can anticipate the smells coming. But when I was going through before and I didn't know I felt like I got these sudden hits of it. And I guess you wouldn't notice there's a trigger box because it's just a bunch of grass really. But then it never clicked in my mind that it would be a trigger box because I still get these small hints of it even when I'm out of it, so I wouldn't have thought it had been done with a trigger box, no.

Participant 7 'Think Aloud' Transcription

P = Participant 7

R = Researcher

First Attempt

01:01

P: (Entering cave area) Cool! (Audible laugh)

01:27

P: (Upon entering third scent area) Oh that smells nice! (Reaches down to try to touch the flowers)

Second Attempt

02:25

R: (Participant in scent area 1) So now that you're in the area that the scent's being released from is it noticeably different? Does it smell stronger? Weaker?

P: Yeah it's definitely stronger than when I started.

02:57

R: (Participant in area between 1st and 2nd scent areas) How about now? You've now left the area. How would you describe the smell?

P: It's not as strong, it's kind of disappeared but it's still there. There's a hint of it there but it's nowhere near as strong. I can't really smell it as much.

03:22

R: (Entering Scent area 2) Is there any difference now that you're in this area?

P: Yeah… I think. Yeah.

04:02

P: (Entering the cave area) I didn't notice that sound before actually.

R: Oh the dripping water?

P: Yeah I never noticed it until now.

04:29

R: (Entering the third scent area) That should be another now where smell is released.

P: Yeah, Mmhmm.

Participant 8 'Think Aloud' Transcription

P = Participant 8

R = Researcher

First Attempt

00:41

P: (Entering 1st scent area) Ahhhhh wow! (Audible sniff) Is it okay if I stay here for 5 minutes?

R: (Audible laugh) Sure!

02:02

P: (Upon entering second scent area) (Audible sniff)

02:47

P: (Upon entering third scent area) It feels like I'm here!

Second Attempt

03:47

R: (Participant in area before scent area 1) Is there anything noticeable now?

P: I don't smell anything but every 10 seconds I don't get a sense that it's working but I still get a smell of it but nothing as much as when I'm over there (Points to flowers)

04:05

P: (Entering Scent area 1) When I'm in here I can really smell it. I can't tell if it's gradual.

04:30

P: I can't really tell.

04:53

P: (Leaving Scent area 1) So now it's stopped. (Takes a step back into scent area 1) And now I can smell it.

05:10

R: (In area between scent area 1 and 2) What about now? How would you describe it?

P: Now? It's gone, I don't smell anything.

R: Okay

05:41

P: (Entering Scent area 2) Now the smell is starting to come again.

P: So what I'm guessing is that it's a cube in the area that's causing the smell so I don't think it's the individual flowers.

R: You're right.

06:08

P: (Leaving scent area 2) I notice the smell stops immediately as soon as you cross that invisible line.

06:33

P: (Entering Scent area 3) Yep, the smell starts again.

06:44

P: (Inside Scent area 3) So I'm trying to work out if it's stronger where there are more trees. Hmm, I don't know.

07:22

R: Can you hear the device when the scents are being released?

P: I cannot hear the fan but I can feel the air. So I was trying to see if the fan gets stronger in the centre of the areas to see if the smell gets bigger (Points back to scent area 3).

Participant 9 'Think Aloud' Transcription

P = Participant 9

R = Researcher

First Attempt

00:29

P: (Area before scent area 1) Mmm Lavender. (Audible sniff) Smells fresh. I'm not sure it's quite lanverdary but pleasant. Well, it smells like an air freshener smell (Audible laugh)

R: (Audible Laugh)

00:50

P: (Upon entering scent area 1) It's quite strong now. It's quite a pleasant feeling. It's certainly not unpleasant. It's also in harmony with the bird sounds. It smells a little artificial for me but the birds sound very natural. I really love being in forests and being under, especially, pine trees. Even if it's not photoreal, I still have a strong association.

01:39

P: (Inside scent area 1) I like the breeze from the scent machine. It feels nice to have that.

01:53

P: (Further inside scent area 1) Wow, we're really going into a slightly intoxicating level of lavender (Audible laugh). I'm assuming it's the same smell but I'm interested to know if the smells have changed but the visuals have stayed the same. (Audible sniff) I haven't detected a change in smell.

02:20

P: (Inside scent area 1) I like all the little details like the roots over there.

02:33

P: (Inside scent area 1) I'm getting another strong waft of being in the countryside. I think it does help in making you feel kind of relaxed. It's funny, up to that point I was conscious of the music but then it kind of went into a white noise.

03:20

P: (Entering scent area 2) Mmmm. More lavender. The landscape is very attractive.

04:34

P: (Entering cave area) I'm not feeling any sense of danger I guess because of the music. There's some water drop sounds maybe. Still feels very calm. I was expecting that, because it feels quite warm in the room that the temperature would drop in here (points to cave).

05:24

P: (Approaching scent area 3) Oh I can see some lavender ahead. (Approaches a flower not in a scent trigger) Does this flower smell as well? No.

05:34

P: (Entering scent area 3) Oh, back into lavender / forest smell. Or, is it slightly more pine like?

05:44

P: (Inside scent area 3) I'm not really paying careful attention to whether the smell changes. (Audible sniff) Does it smell different or am I just tricking myself it thinking there's a different smell? Still slightly artificial smelling as opposed to the real lavender smell. Is it more pine-like?

Second Attempt

06:37

R: (Participant in area before scent area 1) This little patch of flowers in front of you don't actually emit any scent. There isn't any trigger on these ones.

P: Did I smell something here?

R: When you first started you said you did.

P: Oh yeah, there was like a little bit of smell from when I guess, I first put the headset on. I must have imagined it more strongly.

07:10

R: (Before entering scent area 1) At this point here, how would you describe the smell?

P: (Audible sniff) Nothing.

R: Okay.

07:28

R: (Participant entering scent area 1) So this is where the first trigger is. Would you describe any change there?

P: So the smell is quite strong, but it doesn't smell like lavender to me, it smells more like an alpine-fresh toilet cleaner. (Audible laugh).

R: (Audible laugh)

07:57

P: (Inside scent area 1) I guess I think it might be the breeze that's more relaxing than the scent.

R: Okay, that's interesting. Would you say the scent has gotten stronger or weaker?

P: I think it's like a chewing gum sort of thing. I think when I first came in it was very noticeable and now maybe I've acclimatised to the smell so it doesn't feel very strong. It's still present. Or maybe I'm just feeling the breeze now. Yeah, the smell has gone.

09:06

R: (In area between scent area 1 and 2) How about now? How would you describe the scent?

P: No, I don’t notice a smell.

09:40

P: (Entering scent area 2) So now even in the proximity, its maybe making me…. Does it change my sense of direction? I’m wondering which way the wind is blowing. So is the wind blowing from that direction to here (Points towards the area past scent area 2) It could potentially give you a sense of navigation.

10:54

P: (Leaving scent area 2) That’s the smell stopped now. That for me is where it’s slightly counter-intuitive because as it stops that’s where you get warmer but I’m in the shade (Gestures to shaded area before cave.) You’re expecting it to be cooler in the shade.

Participant 10 ‘Think Aloud’ Transcription

P = Participant 10

R = Researcher

First Attempt

00:28

P: (In the area before scent area 1) I'm getting a smell now… I think. I think the thing is I'm not very confident in discerning smells. That smell has definitely changed.

01:15

P: (In area before scent area 1) Okay, so these two sides have different smells (Points to the other side of the path) I'm pretty sure.

01:29

P: (Upon entering scent area 1) Okay that's a lavender-like smell right there.

02:08

P: (Further inside scent area 1) Oh, it's getting pretty strong.

02:13

P: (upon leaving scent area 1) And now it's gone

02:40

P: (Inside area between scent areas 1 and 2, approaching some nettles) I don't think those leaves smell of anything specific.

02:47

P: (Entering scent area 2) Back to lavender.

03:47

P: (Leaving cave area) Was there a smell going through there? Like a damp kind of smell?

R: Would you describe there being a smell there?

P: I think there was. I think I only noticed it once I left it. Maybe that's some kind of placebo effect!

Second Attempt

04:59

R: (Participant entering scent area 1) As you;ve entered here you reached the trigger box to release the scent.

P: And this is just one big one?

R: Yeah, it's just one big box.

P: Oh yeah, I can smell it.

05:16

P: (Upon entering scent area 2) There it is again.

05:19

P: (Entering cave area) And there is no smell in here.

R: Correct, there is no smell in here. Knowing that, can you smell anything?

P: No, not really. The lavender smell was the only smell I could really discern; I was just assuming there was another smell. And the assumption was there must have been some other milder smell.

Appendix 5: Open-Ended Responses

P1 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: The source of the smell was coming from the patches of heather

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: When approaching and entering the patches of heather it was obvious but at the same time it didn't detract from the experience. I think after moving away from the area because the smell does linger it's almost more realistic. I could tell it was activated as I could feel the fan from the device on my face.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: It was very immersive; I find that VR can be immersive anyway but the smell emitting device does add an extra layer. I think that even though it only emits one smell it can trick your brain into thinking other smells are present like the pine trees or even the damp.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: I understand that the emitter will run on an on/off state but If the fan from the emitter could be programmed with distance in mind for instance as you approach a part the fan will gradually speed up emitting a stronger smell as you approach.

P2 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: the flowers seemed to emit a floral scent

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: I could tell I was approaching the visualisation of flowers due to the smell, without having to look at them, they smelt stronger once surrounded by them. They seemed stronger when inside the flowers as opposed to approaching them.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: I enjoyed the engagement of the extra sense. It gave an extra element of intrigue as I had another sense engaged at times.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: Maybe less of a strong air, or have the air be present at other times without the smell to make it less jarring. Or simply more smells!

P3 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: The Purple Flowers

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: It first seemed quite notable in the flowers and was surprised at how quickly the smell dissipated once leaving that environment.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: It added a bit more depth to the experience, as I felt that the smell was able to make me associate with the environment presented. The smell matched the visuals pretty quickly and so although I could not identify what the smell was other than floral, I felt I very quickly associated that smell with the flowers.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: No, it seemed pretty effective.

P4 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: The Orange flowers

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: The strength gradually changed when entering the flowers, instead of coming in fast.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: It created a more immersive experience as I felt I was walking through a forest and smelling the environment.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: Having two different smells within the forest that interact with the user.

P5 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: Yes, bushes sections.

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: Areas of bushes had a greater strength of smell, but as I continued through the map I could still smell the scent slightly in other areas.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: positive, felt more immersed and relaxed then a normal VR set-up. Felt more comfortable within the environment, and less strain when playing.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: Different scents when in the rock/cave part of the map and an easier setup/attachment to the headset.

P6 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: different plants and structures

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: During certain sections, there was an increase in smell, around the flowerbeds.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: Felt more immersed in the world.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: No Answer Provided

P7 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: the flowers

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: When coming out of flowers the scent disappeared.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: Very positive and calming.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: More scents.

P8 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: red flower trees

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: I realised that the smell was coming from the red flowers.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: It was surreal being to able something in VR for the first time. I really enjoyed it and i wonder what other smells and scenes would be like.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: It worked really good for the 1 smell, I think it would be really good if there were multiple smells that can be triggered at 1 scene.

P9 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: lavender

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: When entering space with the flowers the change in smell intensity very noticeable.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: pleasant and relaxing though would like a more natural smell.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: more natural selling smells.

P10 Qualitative Questionnaire Responses

After First Attempt

Q1: What would you say the source of the smell was in the virtual environment?

A: Proximity to certain scent objects, flowers in the path or parts of the path border

After Second Attempt

Q2: Can you please describe your awareness of any changes in the strength of smells you perceived?

A: The smell was stronger when I was in the flowers that were in the path.

Q3: How would you describe your experience in the VR environment using the smell emitting device?

A: It was interesting, the smell made the world feel more natural than a normal 3d walkthrough.

Q4: Do you have any suggestions that might improve the experience of using the scent display device?

A: Maybe more than one smell or a distance-based smell strength.