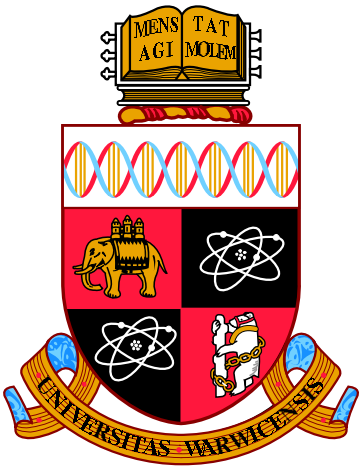

High Fidelity Olfaction Simulation for Virtual Environments

by

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Abstract

Olfaction is a key human sense due to its close connection to the brain, specifically memory and decision making, along with its effects on behaviour and emotions. Clearly, in order for virtual environments to reach perceptual equivalence with the real world, olfaction needs to be incorporated. Perceptual equivalence is defined as the same cognitive response occurring with the users whether they are exposed to real or synthesized stimuli regardless of the levels of duration, intensity or nature. While there have been previous attempts to use olfactory stimuli in virtual environments, these have been limited and not addressed some key aspects of olfaction and its corresponding stimuli, such the effects of high odour concentrations and smell habituation.

This thesis presents a framework for a physically accurate olfactory pipeline in order to help provide high fidelity perceptually equivalent virtual environments. The pipeline consists of stages for capturing, data storage, reproduction, and finally delivering stimuli to end users. In particular this thesis focuses on the final delivery stage. It presents a novel physical calibration for the olfaction delivery system and a new human perceptual calibration procedure to ensure a robust and repeatable experience.

For the first half of the delivery stage, this thesis provides the blueprint for a physically accurate smell display. This is subsequently shown be capable of reproducing smell stimuli with both accuracy, to intended real world concentrations, and precision, such that the outputted olfactory stimuli are consistently presented at the specified level. In addition, similar to other existing olfactory displays, this smell display is a low cost solution as well as a straightforward design with the intrinsic ability to provide virtually, immediate temporal displacement. The validation of the physical calibration of the display is based on fundamental laws of chemistry to provide the same result under the same specified conditions.

For the second half of the delivery stage, a perceptual calibration procedure is presented to calculate Just Noticeable Differences for olfactory stimuli. The purpose of this is to be able to create normalised stimuli levels which are perceivable by the general population but are also perceptually similar across different odours. The work provides two Just Noticeable

Difference stimuli levels for three target single molecule odours which have been calibrated on the olfactory display based on a sample population (N=10). These determined stimuli levels can subsequently be utilised as generalisable points for further experimental use with participants when investigating both olfactory phenomena and relationships between olfactory and other sensual stimuli.

A final experimental study is proposed in this thesis to clearly demonstrate the capabilities of the research and to explore the possibility of olfactory attention-masking phenomena, similar to those seen in the visual domain. Participants were asked to preferentially rank the odours presented to them based on images of the smell source. Odours were the same as those used in the perception calibration, and were presented as randomised dual conditions either in combination with the other odours or with a blank. Participants were consistently able to correctly identify the correct odours with the correct images, ranking the correct answers either primary or secondary. In addition, a number of preferences for some odours over others were identified.

In conclusion, this thesis outlines a novel framework for addressing the physical and perceptual aspects of olfaction in order to provide an accurate representation of a real world equivalent olfactory experience. Experiments show humans are readily able to distinguish between odours when presented at the same time and the evidence obtained suggests there may be attention-masking phenomena in the olfactory domain.

Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree.

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Chapter 1

Introduction

1.1 Research Motivation

Everyday the prospect of true Virtual Reality (VR) experiences grows furtherer away from the realm of science fiction and more towards close reality. VR describes a digital reconstruction of an environemnt, in which virtual representations of real objects and avatars are present for observation and interaction. While the first attempts at creating these virtual environments originate back to the 1930s, their place in the mainstream only really appeared from the late 1980s onwards with the abundance of cyberpunk science fiction in pop culture media. With the incredible pace in improvements to computational power, the point of being able to render high resolution graphics and images, generate detailed virtual 3D models, and process all of it in real time, opens the door to creating realistic VR experiences.

While the main users and early adopters have typically come from video games, recent pushes from large technology firms to implement VR into inexpensive hardware and mobile technologies has resulted in rapid mass-market adoption amongst consumers. The ubiquity of inexpensive, powerful hardware has come as a result of the recent smartphone revolution, with the majority of the parts and technologies being reimplemented for VR applications. Google VR and Apple's AR kit has allowed users to create both VR and AR (Augmented Reality) experiences using only their daily hand-held devices. Such affordable VR/AR technology has in turn driven content creation and has opened up new applications for virtual experiences from its traditional entertainment/gaming base, including fashion, construction, heritage, business, sport, greetings cards, etc [4]. With this new wave of low-cost VR and AR technologies, the future impact of VR/AR will be significant, with the global market predicted to be worth over 91 billion by 2021 [5]. In January 2016, Goldman Sachs released a report forecasting the market for VR/AR in education and training alone will be worth close to $1 billion [6].

In the visual domain, modern head-mounted displays are just one form-factor implementation of this new hardware which are proving popular with consumers and researchers, providing a immersive field of view for the wearer and allowing for full 360 movement and rotation with the help of head tracking through the use of gyroscopes and magnetometers. Notable commercial examples include: Oculus Rift (owned by Facebook), HTC Vive, Samsung Gear VR, Playstation VR and Microsoft Hololens. Support for these devices is also widening in attempt to capture this new market, with Valve adding native VR integration to their existing digital game distribution service: Steam, Oculus providing an internal ecosystem for games and application tailored to its' head-mounted display, and even Google's YouTube adding 360-degree video support to it's existing video sharing and streaming service. In the auditory domain, high definition sound is increasingly becoming the norm, and the use of head-related transfer functions to generate 3D sound profiles tailored to specific head shapes brings new levels of customised sound. There is currently significant investment into haptic-based (touch) research, largely by semiconductor manufacturers, and which has been driven by desire and need for human-computer interface devices requiring tactile and force feedback (e.g. consumer electronics, robotics including prosthetics in healthcare, and military/defence applications) [7]. This also drives improvement and miniaturisation of complementary sensor technologies.

This thesis aims to address the olfactory domain in the context of VR has largely been ignored. The research presented in this thesis naturally flows from a discussion of olfaction in general and the few current approaches taken in incorporating into virtual environments.

1.2 Research Problem and its Significance

Smell or 'olfaction' is a powerful sense and has significant effects on our memory, behaviour, and decision making abilities. Smell can also be a effective mood enhancer [8]. Olfaction provides vital information about our surroundings in way that the other senses may not. Firstly, it plays in integral part of our survival instinct, being able to alert us to possible signs of danger. Smelling smoke or mains gas can immediately evoke heightened states of awareness due to possibility of a fire/explosion. Bad smells can inform us that a particular food is unsafe to eat, even when it appears fine visually. Olfaction also makes up 80% of gustation (taste) with the perceptions of specific flavours beyond sweet, salty, bitter, sour, and umami, being reliant on what is smelled.

There is potential to create serious games with a higher level of realism which could allow for in-depth training and education remotely [9]. Olfaction has been deployed in cultural heritage sites to recreate periods in history [10]. The inclusion of odours create a visceral atmosphere and allow visitors to get a true representation of the time. Some olfactory applications within

the healthcare industry have already shown promising results, namely the use of odours during therapy sessions to help treat post-traumatic stress disorder for veterans of armed forces [11].

The world is multi-sensory so it naturally follows that, to create a perceptually equivalent virtual environment, multiple senses have to be engaged with high fidelity and accurate stimuli, including the sense of smell. Despite this, VR research tends to ignore olfaction. In contrast to vision and acoustics, olfaction research in VR is still in its infancy. This is largely due to the difficulties in recreating smell both physically and perceptually. This thesis aims to outline and address these issues.

1.3 Research Questions

The main research question that aims to be tackled in this thesis is:

- How can a generalisable approach for recreating real world olfactory conditions in virtual environments be created?

This is further optimised into the following questions:

- How can physical and perceptual olfactory accuracy be best approached?
- Can olfactory masking effects between multiple odour stimuli be quantified?

1.4 Research Objectives

The following objectives were planned in this research to answer these questions:

- outlining a framework for a standardised olfactory pipeline for virtual environments.
- creating an olfactory display which is calibrated and provides high accuracy delivery of olfactory stimuli, and validating the calibration with a set of odours.
- providing a validation method to prove the accuracy of the display is repeatable.
- outlining a procedure so that any other odours can be calibrated to give the same level of accuracy and precision.
- describing a method for creating perceptually standardised concentration thresholds across odours that are of similar intensity perceptually.

- showing an application of the work and how it can be expanded on to further optimise olfaction in virtual environments, and is one amongst many possible optimisations that can be used but is shown as an example.
- quantifying possible attention masking effects that may occur between odours in a multi-odour context.

1.5 Thesis structure

A brief overview on the rest of thesis chapters are presented as follows (Figure 1.1 also shows a schematic of the outlined structure):

- Chapter 2 gives an overview of olfaction, outlining the human olfactory system, and the many factors that affect olfaction. Molecular chemistry and characterisation is then discussed in the context of odours.
- Chapter 3 presents a literature review of olfaction in the context of virtual environments, with particular discussion on cross-modal effects between olfaction and the other senses, and olfactory stimuli delivery and simulation.
- Chapter 4 highlights the gaps in knowledge that have been observed, proposed research questions based these, and outlines the research methodology adopted in this thesis to answer them.
- Chapter 5 provides details for the construction of a calibrated, high accuracy olfactory display. A method for validation of the calibration itself along with a procedure for adapting the calibration process for other odours is also provided.
- Chapter 6 proposes a procedure for the calculation of generic, reproducible olfactory perception thresholds for odour stimuli based on just noticeable differences, and uses this to produce six thresholds for three odours.
- Chapter 7 presents a study to investigate potential attention masking effects between three when presented simultaneously. The thresholds obtained from the previous chapter are used here as high and low intensity perceptual levels.
- Chapter 8 concludes the thesis outlining contributions, limitations and future work.

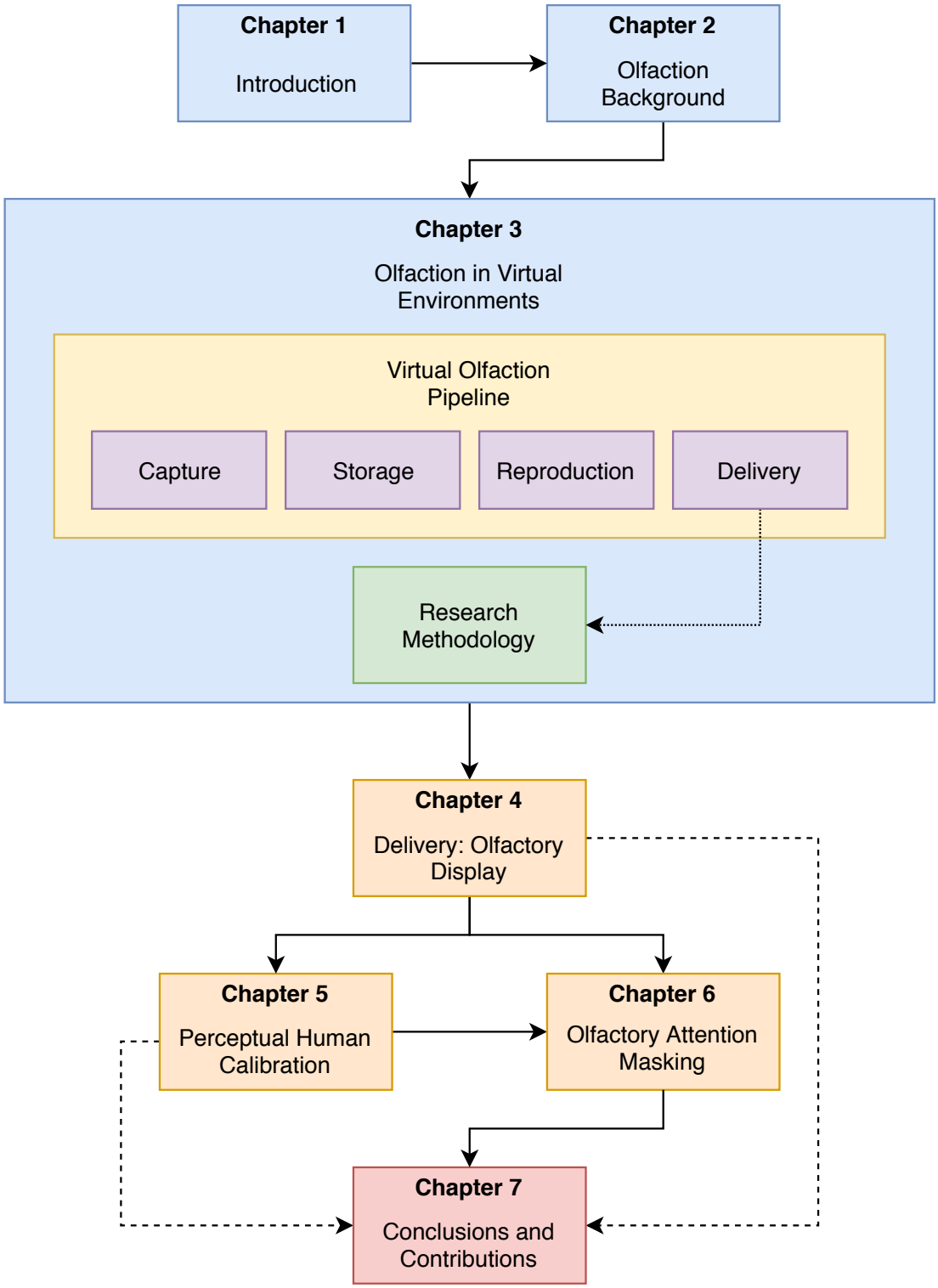


Figure 1.1: Schematic structure of the contents of this thesis.

Chapter 2

Olfaction Background

This chapter broadly covers the many facets of olfaction but mainly focuses on the relevant background of how the nose works and the associated chemical and biological properties of odour molecules. The subjective nature of its perception is also discussed through a series of studies. The underlying chemistry of molecules in the gas phase is also presented to facilitate understanding of their behaviours under expressed conditions.

2.1 The Human Olfactory System

The human olfactory system works via the nose and is closely linked to the human gustatory system (taste). It is noted that comprises up 80% of our ability to taste [12]. It was once thought that humans could distinguish around 7,000 odours [13] (later rounded to 10,000 in publications and has been widely cited as such since) odours but recent work has shown that they can discriminate more than 1 trillion different olfactory stimuli [14]. The main olfactory system deals with sensing volatile compounds which make up the majority of odours we smell. Many other mammals and reptiles also have an accessory olfactory system which is used to sense compounds in the fluid-phase.

The main olfactory system consists of three parts: the sensing of stimuli i.e. odorous molecules, the encoding of signals and the integrating of signals to be passed on to the brain via the central nervous system. See Figure 2.1.

Initially when a person breathes in through their nose, they inhale a volume of air. This air passes through the nasal cavity on the way to the lungs, and passes the olfactory epithelium which is located 7cm from the nostrils. The epithelium is around 5 cm^2 in size, (2.5cm^2 for each nostril). The olfactory epithelium has microscopic hairs called cilia which hang pendent in a mucous lining. Gaseous molecules are trapped by the cilia as they pass, diffuse into the mucous

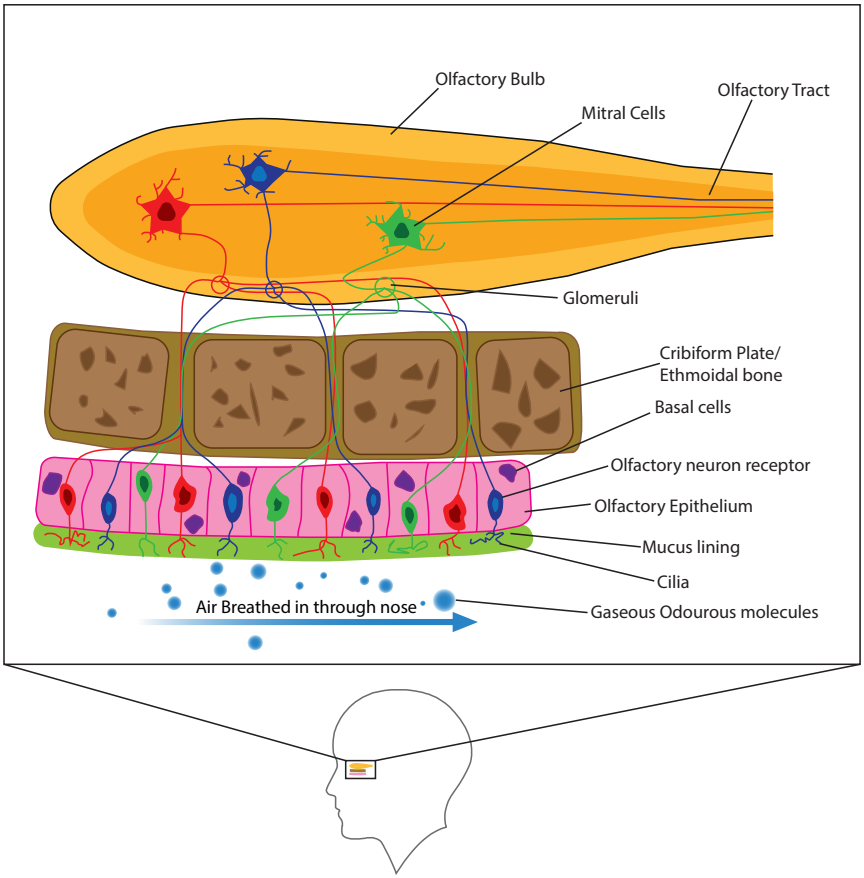


Figure 2.1: The human olfactory system

from the air, and bind to olfactory receptor neurones, a series of specialised membrane proteins. Typically there are over 40 million receptor neurones in the human nose [15].

Whilst compounds typically bind to proteins specific to the protein active site, receptor neurones have varying affinities for multiple compounds, as observed by Bieri et al. [16]. The recognition mechanism by which olfactory neuron receptor neurones encode an electrical signal is still not fully understood [17]. A nerve impulse is passed from the receptor to a series of axons and dendrite nerve cells which pass through perforations in the cribiform plate, a layer of bone, and collect together to form several glomeruli (tangles) located on the surface of the main olfactory bulb (MOB). Here these glomeruli attach to mitral cells to form the terminals of the olfactory nerve via the olfactory tract and connect to numerous areas in the brain. These areas include the preform cortex which relates to the identification of odours, the medial amygdala, which has been shown to have a role in decision-making and emotional reactions, and the Entorhinal cortex, which is associated to memory.

Due to the way the olfactory system is connected to the brain, many of the odours we smell on a daily basis form connections to certain memories and scenarios. This overlaps with the other senses and is described in further detail later in the chapter.

The accessory olfactory system typically contains a vomeronasal organ (VNO) that possesses axons (nerve cells) which extend on to a accessory olfactory bulb (AOB) and then further on to the brain. The VNO projects information on to AOB in a similar fashion to the MOB by combining signals and forming synapses from the mitral cells and glomeruli. These are then relayed onwards to the amygdala, in the brain, and then on to the hypothalamus and hippocampus via the Stria Terminalis, a bed of fibres that run along the surface of the thalamus and act as a major output pathway. The hypothalumus is responsible for body temprature control while the hippocampus associated with long-term memory and spatial navigation.

The use of the accessory olfactory system typically revolves around pheromones in the animal kingdom. Pheromones are chemical messengers passed between animals of the same species which trigger social responses. While humans possess a VNO (which can be observed in some via endoscopy), the development of the axons regresses after a critical part of the foetal development has occurred, the secretion of sex hormones. The neural connections disappear and the genes responsible for VNO receptor proteins mutate and are considered non-functional in humans [18].

2.1.1 Anosmia and loss of smell

Anosmia is a condition that affects an estimated 6,000 people in the UK [12]. The condition effectively means a loss of ability to smell, however there are several forms of anosmia which range from incorrect perception of odours to inability to recognise and smell a certain group/s of odours. This is known as parosmia. The two general terms most often used are hyposmia and hyperosmia which refer to a reduced and increased olfactory ability, respectively. Phantosmia is a unique condition in which a sufferer may smell odours that are not present, much like an olfactory hallucination. Anosmia can be caused by common colds, infections, or even obstructions in the nose, but in more severe cases may be due to underlying damage to the olfactory bulb or nervous system and/or brain. Occurences are also connected to other genetic diseases.

2.1.2 Olfactory Habituation

The nose has an innate mechanism by which the olfactory bulb can cease sending signals to the brain if it has adapted to a given odour. This adaptation effect is typically referred to as olfactory habituation. ‘Smell fatigue or habituation’ refers to when the nose has adapted to a smell. After

prolonged exposure to an odour at a similar concentration with no additional information gained about the environment, the olfactory bulb stops relaying information [19].

The mechanismbehind this is as follows. Olfactory neurons depolarise after being stimulated by odorants which causes a series of chemical responses. This results in the opening of cation channels in the cell, specifically the activation of adenylyl cyclase to create more Cyclic adenosine monophosphate (cAMP) in the cell [20] (see Figure 2.2). This causes an influx of Ca^{+2} (via the protein: calmodulin-dependent protein kinase II or CaMK) cations which desensitises olfactory receptors to prolonged odour exposure [21] via:

- the Ca^{+2} \CaMK directly repress the opening of cation channels,
- CaMK deactivates the adenylyl cyclase, stopping more cAMP being made
- activating phosphodiesterase enzyme cleaves the cAMP phosphorus-oxygen bond, producing 5'-AMP, furthur stops the opening of the channels

The effect has been observed to be counteracted by fluctuating concentrations to lower levels. This removes the nose's ability to adapt to a single given concentration. The effect was only observed over short time periods since the nose can adapt on a longer timescale to all concentrations in the experimental range [22].

2.1.3 The Nasal Cycle

The nasal cycle is a phenomena which is said to affect 80% of the population [23]. It refers to the alternating congestion and decongestion of the nasal cavities mediated by the hypothalamus. The time taken for the congestion sensation to switch between nostrils ranges from every 40 minutes to several hours. The nasal concha is a curved bone structure which houses a series of spongy bones called turbinates which form the inner air passages inside the nose. Erectile tissue then contracts and relaxes causing the inferior turbinates to block or obscure the airways. A blocked sinus is the sensation felt when the tissue contracts. When taking a deep breath through the nose in normal breathing conditions, it becomes noticeable that one is able to take in more air through one nostril than the other.

For a long time, the purpose of the cycle was unknown but recently researchers have found it plays numerous important roles. One is the inherent moderation of how much odour enters the nose. When alternating occurs, the workload is split between nostrils and allow for more effective smelling [24]. Since all odours are comprised of a variety of compounds, it seems natural that each take a different amount of time to dissolve into mucus lining of the olfactory epithelium. By channelling a fast and slow airway (slow being the congested side), odours that

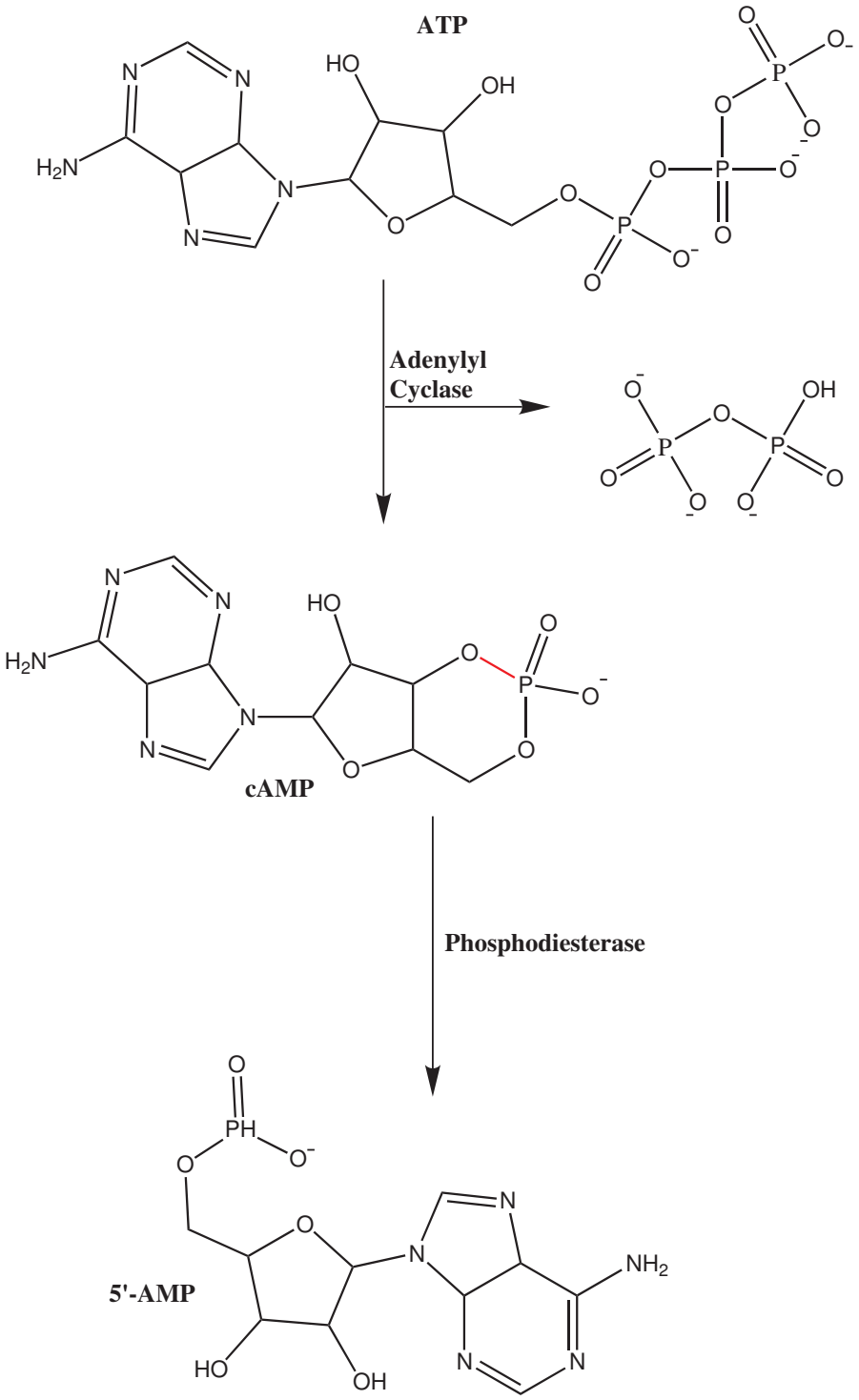


Figure 2.2: The biological mechanism for olfactory habituation

take more time to dissolve are able to be perceived via the slow airway [25]. Another role is to allow the insides of the nose to remain hydrated and moisturised since an open nostrils would mean more air passing through which in turn would quickly suck the moisture away from the epithelium.

2.1.4 Vibrational Theory

While it is generally accepted that perception of odours is based upon the shape of a molecule and the ability of receptor neurones to bind to these specific shapes, a vibrational theory to olfaction has also been proposed. This theory made a resurgence in recent years after publicity from sources such as perfumer Luca Turin's text 'The Secret of Scent' [26].

The idea behind the theory is that the smell character of a molecule lies within the vibrational frequency domain (in the infrared region of the spectrum) and that for the neurological response to be produced, which causes a particular odour to be perceived, there needs to be a closing of a gap between two energy levels within a receptor. The odorous molecule thus provides that route and allows electrons to tunnel from one level to the other causing the signal transduction pathway [27]. The theory has been shown to be mostly inconclusive, notable examples include work done by Keller and Vosshall [28] who showed that example molecules, outlined by Turin, with the same cumulative vibrational frequencies did not yield the same perceived smells.

2.2 Olfactory Characterisation

Due to lack of understanding of human olfaction, research in the field has not grown as large as other sensory counterparts. As such, there has not been much scope for classification of how and why specific odour molecules causes the brain to perceive a smell or what it is about an odour molecule that makes it odorous.

Developments in our understanding of how our sense of smell works have been made more recently. Buck and Axel [29] published their paper *A novel multigene family may encode odorant receptors: a molecular basis for odor recognition* which first described the discovery of olfactory receptors - a discovery for which they were later awarded a Nobel Prize. Their work outlined the cloning and characterising members of a large multigene family which encoded proteins specific to the olfactory epithelium, in an attempt to address olfaction at a molecular level. The experimental design used to isolate the genes was based on three main assumptions [29]:

1. "First, the odorant receptors are likely to belong to the superfamily of receptor proteins that transduce intracellular signals by coupling to GTP-binding proteins.

2. Second, the large number of structurally distinct odorous molecules suggests that the odorant receptors themselves should exhibit significant diversity and are therefore likely to be encoded by a multigene family.

3. Third, expression of the odorant receptors should be restricted to the olfactory epithelium."

Much olfactory work now revolves around the quantification of the mechanisms by which these receptors work, specifically the studying of mechanisms that transform sensory information into behaviour in both humans and animals [30, 31, 32].

Academics from as early as the 1750s have worked on the characterisation of smell. It was initially believed that the human nose worked much like the human eye in that it detected a selected number of base odour notes and that all other odours were composed of the correct combination of these notes, in the same way the eye can perceive any colour that is made up of constituent parts of red, green, and blue. Their approach involved trying to characterise classes of notes of odours [33]. Naturally, numerous classes of odours were proposed with many building on previous classifications and others proposing completely new ones.

Table 2.2 gives an overview of psychological classification studies, adapted from Kaeppler and Mueller [34], in an attempt to classify odours. Since no obvious links were found between odour perception and physiochemical features of odorants, there has been a shift in dynamic to using perception-based rating systems.

Study	No. of subjects	Knowledge status of subjects	No. of test odours	Statistical Analysis Method used	Pleasantness as Primary Dimension
Wright and Michels [35]	84	n/a	45	Exploratory Factor Analysis	No
Woskow [36]	20	Laymen	25	Multi-Dimensional Scaling	Yes
Cunningham and Crady [37]	20	n/a	14	Exploratory Factor Scaling	Yes
Yoshida [38]	20	Laymen	32	Principle Component Analysis	Yes
Coxon et al. [39]	60	Laymen	23	Multi-Dimensional Scaling	Yes
Dravnieks [2]*	507	Experts	144	Exploratory Factor Analysis	No
Jeltema and Southwick [3]	25	Laymen	35	Exploratory Factor Analysis	No
Carrasco and Ridout [40]	32	Laymen	16	Multi-Dimensional Scaling	Yes
Stevens and O'Connell [41]	104	n/a	15	Multi-Dimensional Scaling	Yes
Prost et al. [42]	240	Laymen	40	Conversation Analysis	No
Chrea et al. [43]	90	Laymen	40	Multi-Dimensional Scaling Analysis	Yes
Sugiyama et al. [44]	25	Laymen	17	Multi-Dimensional Scaling Analysis	No
Dalton et al. [45]	300	Laymen	30	Principal Components Analysis	Yes

Table 2.2: Overview of olfactory psychological classification studies. *The study and subsequent analysis for the dataset produced by Dravnieks [2] was also conducted by Jeltema and Southwick [3].

However, studies have not led to anticipated results which in turn has led to dwindling research in the field. This can be broadly attributed to four factors highlighted by Kaeppler and Mueller [34]:

1. inter individual differences in perceptual and verbal abilities of subjects,
2. stimuli characteristics,
3. approaches of data collection, and
4. methods of data analysis.

2.2.1 Odour Assessment

Odour assessment is important in areas where odour quantification and standards have to be set for health and safety and environmental reasons. In these cases it is common to use the following factors (dimensions) to characterise the perception of a given odour since the human perception of smell is a function of them (often referred to as the FIDOL factors [Nicell, 2009]):

1. Frequency
2. Intensity
3. Duration
4. Offensiveness
5. Location

Frequency typically refers to how often a person is exposed to an odour. Smell habituation occurs naturally in the nose, especially with a static odour. However if the concentration in the air fluctuates, one may be able to smell an odour for longer as the nose adapts. Quicker fluctuations will typically make it more difficult for the nose to adapt.

Intensity refers to how strong a perceived odour is. It is this aspect which is highly subjective and different for every person. Every person's nose is unique due to the number and nature of receptor neurones that are present on their respective olfactory epitheliums. The sensitivity of the human nose works on a logarithmic scale, studies have shown [46]. This correlates well with Steven's power law [47]. The concentration of an odour in the air correlates with the intensity detected and the ratio is different for every odour as well as person by person. Moskowitz et al. [48] suggested that the correlation between the pleasantness of an odour and it's intensity could be positive, negative, complex or nonexistent, depending on the odorant used.

Duration refers to the time before the nose adapts to the odour and olfactory habituation occurs.

Offensiveness refers to how offensive a person finds a odour. This is closely related to hedonistic tone of the odour i.e. how pleasant one finds an odour. As one might expect, this varies from person to person due to the associations they may have with said odours. For the majority of people, vanillin is said to have a pleasant hedonistic tone whilst hydrogen sulphide is said to have an unpleasant tone (vanillin being the smell of vanilla and hydrogen sulphide having the classic rotten egg odour).

Location refers to the source of the odour. Recycling plants and sewage treatment facilities are examples of locations where a great deal of consideration would need to be given when sourcing suitable sites in order to avoid 'smell pollution'. How close they are to e.g. schools, hospitals and residential areas all have to be taken into account (i.e. are they far enough such that the odours would be below detection thresholds in these areas?).

2.3 Olfactory Perception

What the brain perceives when an odour molecule is detected is what determines what we smell. However, it is still not known why specific compounds produce specific odours. Smell is cross-modal in nature like the other senses, in that the brain naturally combines information between them to create easily recognisable patterns and associations for future encounters, but there is a profound effect in the associations that are made.

2.3.1 Cognition and Odour Perception

A group at the Weismann Institute, Israel, has shown experimentally that the human olfactory system may have an olfactory 'white' [49], in much the same way all colours the eye perceives are substituents of white or how, when different sounds are played at once, the ear is unable to distinguish between them and 'white noise' is heard. The experiment consisted of participants smelling multiple odours in mixtures with increasing complexity. Odours were mixed together in batches with equal intensities and participants were asked to identify them. A trend showed that as the number of compounds increased, the more indistinguishable the odours became. At around 30 odours, participants could no longer identify the odours. They report that two characteristics were needed to reach this 'olfactory white': equal intensity mixtures and a wide olfactory stimulus space i.e. a wider dynamic range of smells with distinct differences between odours [49].

In a review of a number of medical studies investigating human odour perception, it was

concluded that attempts to verify exposure intensity based on the report of a perceived odour showed such reports to be unreliable with no useful application in legitimate exposure assessment paradigms [50]. It was found that subjects' responses to intensity are affected by their psychological state and are thus biased. The review then additionally states numerous factors which affect olfaction and one's ability to perceive odours [50].

Dalton [51] found that when people exhibited slower habituation when told particular odours were hazardous compared to ones that were described as 'healthy' or 'natural'. In a similar vein, Sakai et al. [52], found positive correlations between odour habituation rates when odours were presented with positive information about the odour and vice versa with negative information. Subjects evaluated odours as more intense when appropriately informed of them, that those inappropriately informed, in a study conducted by Distel and Hudson [53]. While an individual's current emotional state do not seem to affect olfactory discrimination, negative emotional states are associated with an increase in judged odor intensity [54].

2.4 Olfactory Perception Variation

As discussed, there is significant variability across populations with regard to olfactory sensory sensitivity. This can be attributed to numerous factors not limited to:

- Genetic factors i.e. inherited genes for specific olfactory receptors
- Demographical differences
- Environmental factors i.e. social preference and conditioning
- Hyposmia/ Hyperosmia (decreased and increased smell sensitivity, respectively) from lifestyle choices or health conditions
- Cross modal effects

Olfactory receptor genes make up one the largest families of the human genome, so whilst there is a large overlap across the global population in certain genes, it would not be uncommon for specific genes to become more prevalent in certain locales/regions over generations. This naturally adds to variability as this creates an acuity to certain smells compared to others across populations. Herz et al. [55] report that women show a greater sensitivity to odours compared to men and this observation matches consistently with other replications [56, 57]. These differences surface at early ages [58] and tend to apply to discrimination and identification of odours [59, 60]. Olfactory ability also decreases with age with the largest dysfunction occuring in old age. Doty

et al. [61] showed that the average ability to identify odours reaches a peak between 20 and 40 years of age and then begins to decrease after this. The study showed 65% of people between ages between 65 and 80 exhibited major olfactory impairment.

Environmental factors can play a very big part in the individual perception of odours. Perceptions can very easily guided or changed based on other information. Populations in regions of the world are more attuned to certain types of odours. One example is the Dassanetch tribe of Ethiopia where the scent of cows is associated with social status and fertility [62]. In contrast, to westerners, the odour of cow dung is generally considered foul and unpleasant. Certain odours like vanillin have shown universally positive hedonic tone.

It is well documented that certain lifestyle choices result in decreased smell sensitivity. Smokers are twice as likely to show olfactory deficit than non-smokers [63]. It has also been shown that there is a large prevalence in olfactory dysfunction in many terminal diseases. In a study, 400 sufferers of Parkinsons had their smell sensitivity tested using a psychophysical olfactory test, and it was found that over 96% exhibited some form of hyposmia i.e. a reduced smelling ability [64]. Olfactory deficit has also been used as an indicator for early diagnosis of Alzheimer's disease [65]. Similar trends have been observed in schizophrenia, anorexia and depression sufferers [66, 67, 68]. Humans show a strong hyperosmic effect with the compound isovaleric acid, a fatty acid found in essential oils and has a strong pungent cheesy odour. The compound is often a reagent/precursor to making other odorous compounds for perfumes. General cases of hyperosmia have also featured in migraine sufferers [69]. Contrary to common belief, research has shown that handicaps in one sense do not necessarily result in increased perceptual sensitivity in the other senses. Schwenn et al. [70] showed that sighted people scored better than blind counterparts in judging water quality based on odours. They concluded that smell training was the most likely factor for enhancing performance in the tasks.

Numerous examples exist of studies showing significant differences in perceptions of smell and taste based on visual cues. Morrot et al. [71] showed that by simply dying a wine red with the use of food colouring, they were able to fool more than 50 students enrolled on a university wine degree course. Similar findings showed wine experts gave more accurate descriptions of a Chardonnay which had been dyed red when it was served in an opaque glass as opposed to a transparent glass [72]. This continued to be the case even when participants were actively told to ignore what they saw. Cross modal effects are discussed in greater detail later in section 3.2.1.

2.4.1 Odour perception and Thresholds

There is a clear distinction between the concentration of odorous molecules in the air and the perceived intensity of said molecule. Whilst they are directly related to one another they vary

quite significantly in their proportionality.

Odour Intensity is found to follow Stevens' power law much like many other stimuli and phenomena. Stevens' law in the case of smell is as follows:

$$I = kCn \tag{2.1}$$

where I refers the smell intensity, C is the actual concentration present, k is an arbitrary constant and n is an exponent value. Both k and n are determined for specific odours molecules. In more general terms, I refers to the magnitude of the perceived or evoked stimulus and C refers to the physical stimulus. An important point to mention about this law is that it is true for given stimulus conditions. For example, the numbers vary for different odorous compounds and a single exponent would not hold for smell in general.

By applying a logarithm to both sides of the equation, we get:

$$LogI = logk + nlogC \tag{2.2}$$

This allows for the plotting of the independent variable against the dependant variable on a linear graph to find the exponent value. N-butanol and other volatile organic molecules such as hexane are compounds that have been used as reference standards for some time [48] and have an exponent value of 0.6. Data must be collected from willing participants in order to calculate exponent values. The smell threshold must be taken into account when doing so. A single blank forced choice method is one such way this can be done.

A person typically has two distinct smell thresholds. The first is the detection threshold which as the name suggests is the lowest concentration at which an odour is detected. The second is the recognition threshold which refers to the concentration at which the odour can be identified. Since the sensitivity between noses varies, both are crucial in being able to conduct any work as the first shows the lower point in the threshold range for a general population, whilst the second is subjective and dependent on numerous factors, and plays a more important role in the actual perception of an odour.

The standardised approach for threshold testing it outlined in CEN [73]. The procedure outlined in the standard states that there must be three containers: two containing an identical concentration odour and one containing a blank. The concentration of the odour to be presented is started at a relatively high amount such that the general population would be able to discern it from a given blank. Participants are presented with each of the three containers and must correctly identify the blank (a three alternate forced choice method). On successful identification, the odour concentration is then diluted. This is then repeated in succession in a logarithmic

scale and lowering concentrations until the odour can't be detected (i.e. dilutions could be in halves, quarters, tenths, etc). The point before participants incorrectly identify the blank on two consecutive trials is taken as the detection threshold.

When population is plotted against number of dilution steps, a normal distribution is found and in some cases a double hump is found. In the case of a double hump, it is often the case that a large proportion of the population maybe exhibit a form of hyposmia to that particular odours or set of odours [1]. This normal distribution is also helpful in determining an operating range for an odour in terms of concentration.

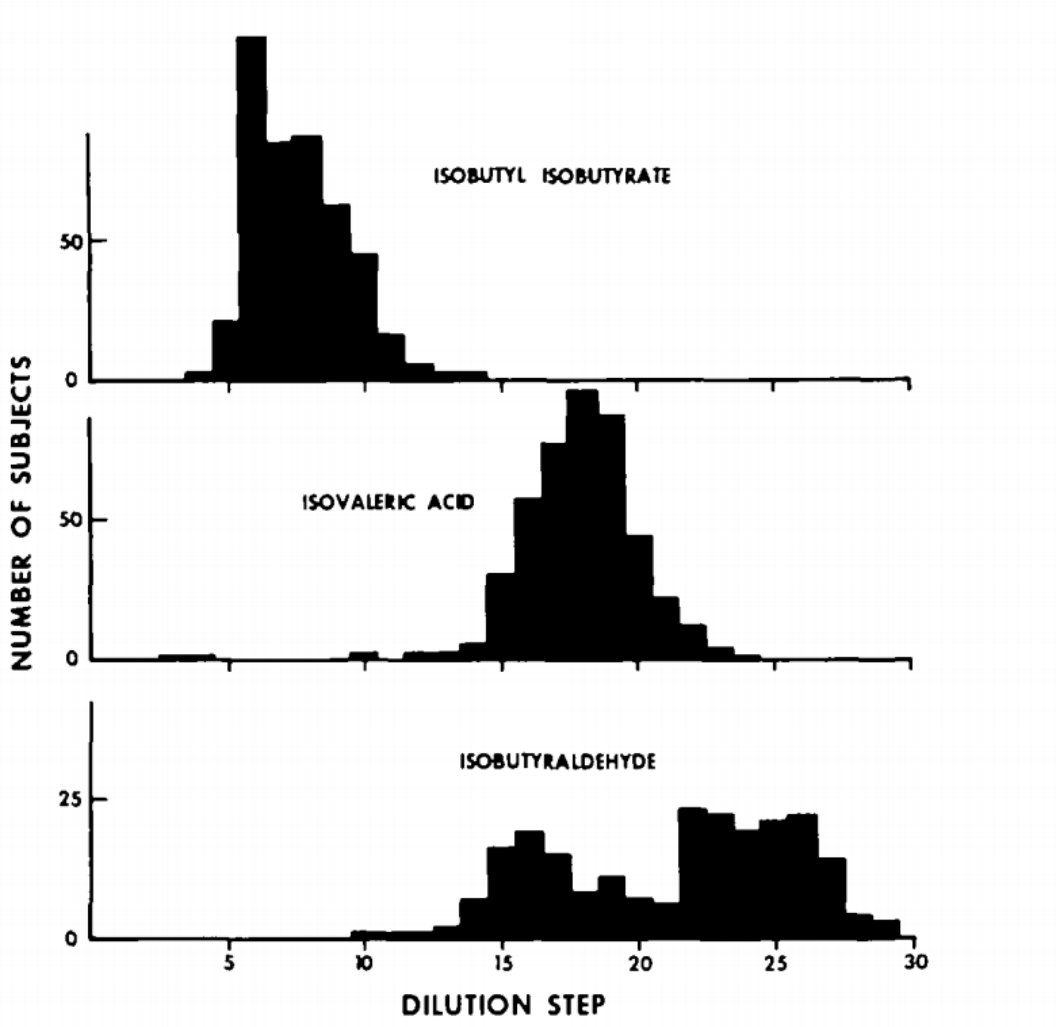


Figure 2.3: A histogram illustrating the normal distribution of ofactory thresholds for 3 compounds from [1]. The 0 point represents a pure saturated solution.

2.5 Gas Chemistry

Concentration is one of the most important factors in olfaction. It is directly proportional to the intensity perceived by the human olfactory system. Odours are volatile molecules which cause the brain to perceive a smell when an olfactory receptor binds to it. Naturally it follows that by increasing the concentration of said molecules in a given space, a person would smell a more intense odour or vice versa. The boiling point of a liquid is defined as the temperature at which the vapour pressure of the liquid equals the pressure of the environment.

2.5.1 Ideal gases

The following properties must be present in a gas for it to be considered an ideal gas. The reality is that most gases behave very close to ideal.

1. An ideal gas consists of a large number of identical molecules. This is true in the case of odours since they are either single compounds or mixtures together in a particular concoction. Thus for the mixture, this is also true by extension.

2. The volume occupied by the molecules themselves is negligible compared to the volume occupied by the gas and the molecules obey Newton's laws of motion, and they move in random motion. This is again true since the number of odorous molecules in a volume of space is very small. Smells are often measured in the parts per million or billion (ppm/ppb) scale thus they can be said to be negligible. This remains true for gases.

3. The molecules experience forces only during collisions; any collisions are completely elastic, and take a negligible amount of time. This is true when molecules are in the gas phase they have enough energy to be free of any intermolecular forces they would have bound them in liquid form e.g. hydrogen bonding or dipole-dipole interactions. Any collisions that occur will not result in a reaction unless a given activation energy between the two or more molecules is reached. Under standard conditions (298K temperature and 100kPa pressure) which is effectively the same as normal room conditions.

From the above we can establish that volatile odorous molecules behave like ideal gases. The Ideal Gas Law describes the relationship between a series of variables which shows how an ideal gas behaves:

$$pV = nRT \tag{2.3}$$

where p is pressure in pascals, V is volume in m^3, n is the number of moles of a given compound, R is the gas constant and has a value of 8.314 $J.mol^{-1}K^{-1}$ and T is temperature in kelvin.

Moles are the units used by chemists to quantify how much of a given compound is being used and is calculated using either of the two equations:

$$\text{Moles} = \text{Mass/Mr} \tag{2.4}$$

$$\text{Moles} = \text{Concentration} \times \text{Volume} \tag{2.5}$$

where Mass is the total mass in grams and Mr is the relative atomic mass of the compound. This can be calculated by summing the masses of the atoms in the molecule. Volume in this case has dm^{-3} as units and concentration is thus measured in $mol.dm^3$.

By rearranging equation (2.3), inserting it into equation (2.5) and rearranging again to make concentration the subject, we get the following equation:

$$C = p/RT \tag{2.6}$$

Where C is the concentration of the compound in mol dm-3 (the units for the volumes of the initial equations would have been converted accordingly).

From equation (6) we see that assuming environmental pressure remains constant, increasing the temperature would result in an effective decrease in concentration of the gaseous chemical. The underlying chemistry conveys a logical explanation for this despite seeming contradictory to certain experiences.

When the temperature of a system is increased, there is an increase in the amount of energy particles have on average. Figure 2 shows an example Maxwell Boltzmann distribution of a number of particles and the distribution of energy across the particles. When increasing the temperature (T2), the distribution shifts to the right so that the majority of particles have more energy. Since they are in the gaseous form they have the freedom to move around and by applying more energy to the system, they are able to move faster and thus diffuse quicker. This may mean that the particles spread out enough to the point where their effective concentration is below a given detection threshold. As such, a smell ceases to exist (not taking into account smell habituation).

First it is important to note that this applies in the case of a finite number of molecules. Day to day odours tend to have a source that constantly emits the odours. So if, for example, smelly trainers were left in a room, it is likely the odour could be smelled in the vicinity but would not be smelled on the other side of the room. Suppose there was a hot radiator next to them. It is likely in this case that after a few minutes, the odour could be smelled anywhere in the

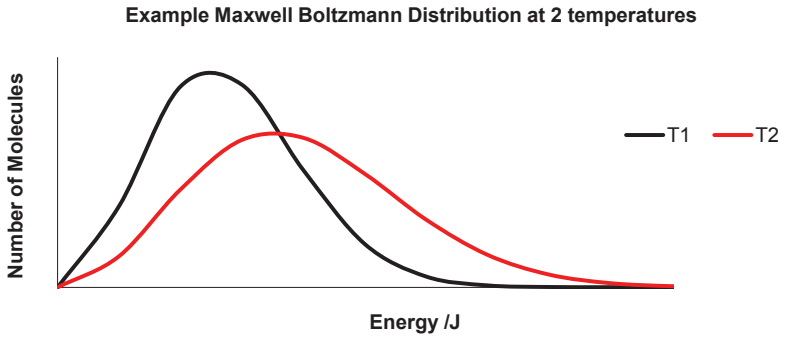


Figure 2.4: Temperature difference on a Maxwell-Boltzmann Distribution

room. This is due to the fact that particles in the vicinity have more energy (energy transfer from particles that started near the radiator) and thus diffuse faster into the room. The same effect would still occur over a longer time period at room temperature.

2.5.2 Molecule quantification

Several analytical methods can be employed for analysis of the compounds to determine their chemical structure and thus deduce any chemical and physical properties they may exhibit.

Gas chromatography-mass spectrometry (GC-MS) is a common technique which provides very detailed information about the target molecules and is very useful in odour determination. A GC-MS run involves loading the sample into a chromatography column consisting of two phases. For gases, this column resembles a coil of very thin hollow tubing several meters long. The first phase is the solid stationary phase which coats the inside of the column. The second phase is the mobile phase and is the target odour, which is loaded in with an inert mobile gas (typically helium). The particular specification of the column selected depends on the expected characteristics of the sample molecules i.e. whether the stationary phase is coated with polar or non-polar molecules, the length and width of the column, the temperature applied. As the odour passes through the column, it will temporarily adsorb to the molecules of the stationary phase for a small amount of time, then desorb. The length of time taken will depend on its relative interaction with the coating: polar to polar molecule and non-polar to non-polar interactions will result in longer adsorption times, whilst polar to non-polar will result in shorter times. This will happen many times as the target sample passes through and if a mixture is present, the different molecules will have differing affinities to the stationary phase depending on their molecular structure. The column can also be heated externally using an oven to temperatures

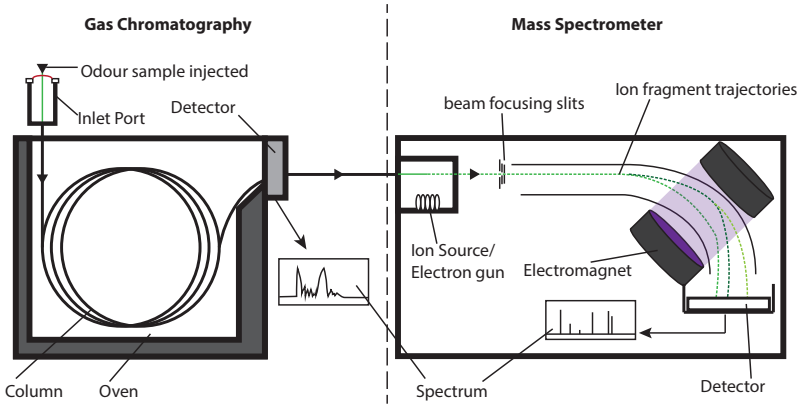


Figure 2.5: Diagram of Gas Chromatography Mass Spectrometer

over 320C, to allow for increased separation due to differing volatilities. This will cause the mixture to separate into its constituent parts. This will also produce a chromatogram showing a series of peaks (the constituent parts), as a function of time. The separated compounds are then fed into a mass spectrometer and bombarded with electrons charging the molecules into molecular ions. An electric field and then focuses the ions into a straight line and fires them past an electromagnet. This causes the ions to fall onto a detector relative to their mass-to-charge ratio. From this a spectra is produced from the ions and their respective ions fragments that hit the detector. The mass and their mass to charge ratios can then be pieced together to work out the initial molecule. This is repeated for each of the fractions from the GC. Figure 2.5 shows an illustration of a GC-MS.

Absorption spectroscopy is also a very useful analytical method for deducing molecular structure. This method relies on molecules absorbing some form of energy and the resulting effect being quantified. Molecules can be elevated to excited states via this absorption in a variety of ways, but two commonly used methods are with Infra-red and Ultraviolet/Visible Spectrum light wavelength light. Typically an instrument using these methods will have a specialised laser pointed at a substance sample, which is able to cycle through a range of wavelengths specific to that part of the electromagnetic spectrum. Bonds between atoms interact and absorb light different wavelengths and specific excitations at specific wavelengths will indicate the presence of a certain bond. The ultraviolet, visible light and infra-red spectra wavelength regions are between 10 nm (7×10^{-8}m) to 400 (4×10^{-7}m), 400 nm (4×10^{-7}m) to 700 nm (7×10^{-7}m), and 700 nm (7×10^{-7}m) to around 1 mm (10^{-3}m), respectively.

Infra-red spectroscopy excitation results in a bond vibration in organic molecules and the mid range of the infra-red spectrum (2.5-25 x 10^{-6}m) is used to study these vibrations. The

many types of bonds between carbon, oxygen, nitrogen and hydrogen can then be classified on the type of vibration and the relative intensity observed via a lookup table. These vibrations can be stretches, bends, rotations all of which can be antisymmetric or symmetric. Figure 2.6 shows just some of the types of these type of vibrations.

Ultraviolet/ visible spectrum spectroscopy can be used to find concentrations of substances within solutions via the beer-lambert law (see below) since the absorbance (%) is directly proportional to the concentration of the absorbing species. Ultraviolet light is also used in fluorescence spectroscopy, where electrons within atoms are excited above their ground states and as they return to their ground state, let off radiation which can be used to characterise the substance.

$$A = \varepsilon.b.C \tag{2.7}$$

Where A is the Absorbance (%), ε is the molar absorptivity coefficient i.e. how much a substance attenuates light, b is the path length or distance the light passes through the substance in cm, and C is the concentration of the absorbing species.

Other spectoscopy method include using ICP-AES/OES/MS (inductively coupled plasma atomic emission spectroscopy/optical emission spectroscopy/mass spectrometry) to calculate the concentration of specific elements down to the part per million/billion/trillion.

2.6 Summary

This chapter presented the relevant background knowledge on olfaction. First, the physiological aspect was described via description of the human anatomy, followed by the perception aspect which described how humans perceived smell, and concluded with the physics and chemistry of odours describing the quantification of odour molecules and their relationship to perceived intensity. The material outlined here is intended to provide an overall understanding of olfaction and aims to provide additional insight into the motivations behind the proposed research methodology.

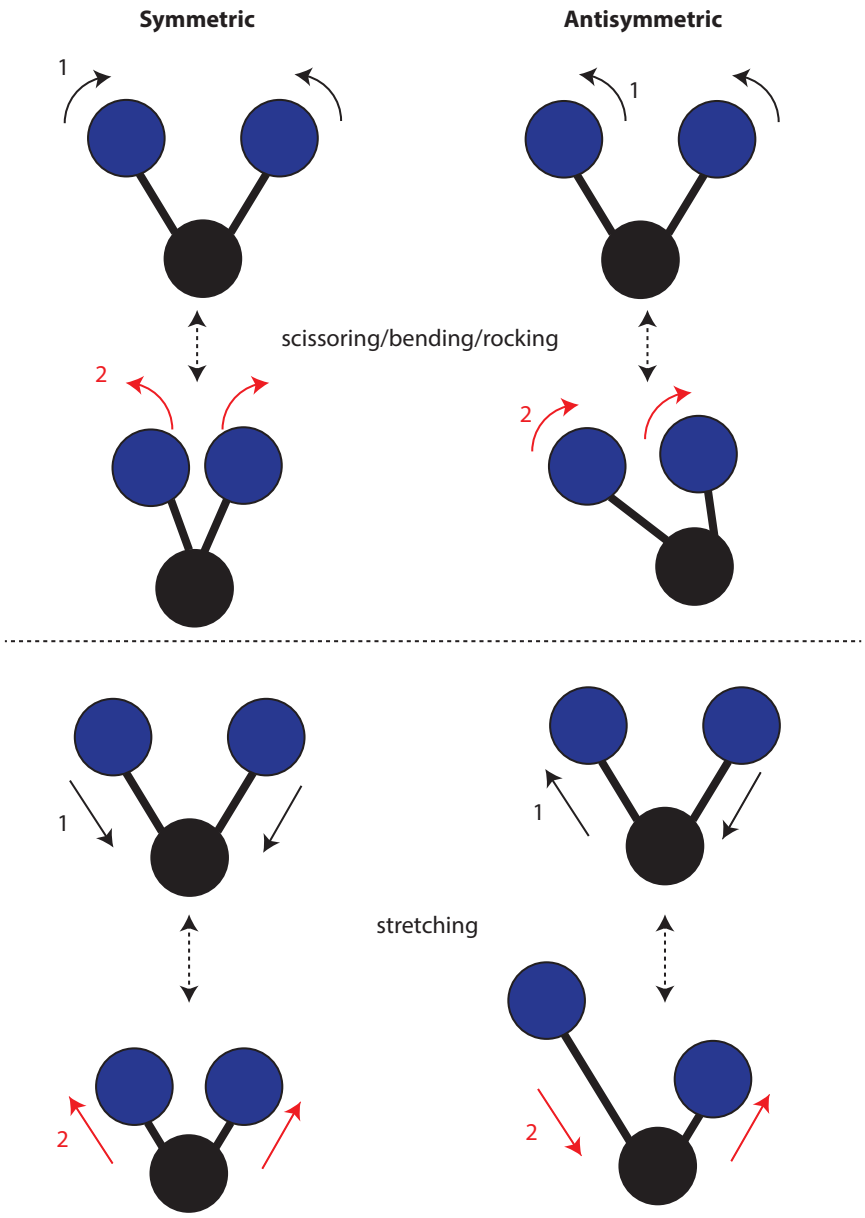


Figure 2.6: Illustrations of possible bond vibrations due to infra-red excitations

Chapter 3

Olfaction in Virtual Environments

This chapter provides a literature review of the current state of olfaction within virtual environments (VE). Olfactory applications and presence measurement are covered with work in cross-modal olfactory relationships. Olfactory displays, odour sensing, odour simulation, and the concept of a olfactory pipeline is discussed. Finally, the Research Methodology utilised in this thesis is presented with an outline of the aims and research questions this thesis sets out to address, are presented.

3.1 Virtual Reality

Virtual reality (VR) can be defined as a computer generated simulation of a three-dimensional (3D) environment which can be interacted with by a human participant. As discussed, the benefits of having VR systems become immediately apparent when thinking about potential practical applications such as commercial entertainment, training and education, healthcare, and construction. Several devices have been created in recent years that allow people to interface directly with virtual environment. These devices include head mounted displays with iteratively increasing resolutions and widening field-of-views, headphones and speakers with 3D immersive sound, haptic feedback gloves and suits which provide tactile feedback, and even olfactory and gustatory displays which emit odours and flavours.

3.1.1 Virtual olfactory applications

Novel games and applications have been created by researchers which incorporate olfaction into virtual environments all for the purposes of entertainment, training and education, and medical therapy. Examples of this include a cooking game that was devised by Nakamoto et al. [74], in which users could add ingredients to their virtual cooking pan and experience the smells

at the same time. Mochizuki et al. [75] also developed a game, Fragra, which used odours in conjunction with a visual display. Users were presented with smells of fruits via tubes connected to their hand as they picked them virtually and were asked to determine if the correct fruit was presented with the correct odour. A smelling screen has also been developed by Matsukura et al. [76]. Fans either side of a monitor and blow directed odours to a point on the screen which then collide outwards towards users. Objects can then be presented on the screen at the target point and thus the illusion of the object smelling like the odour is created.

Work has also been done in incorporating olfactory and tactile stimuli with visuals into simulations when treating post-traumatic stress disorder [11]. The virtual environment was designed to help Iraq war military personnel cope and recover from past traumatic experiences.

Dinh et al. [77] created a multi-modal virtual environment and investigated the effects of adding additional stimuli. The user was presented with a head-mounted display, headphones for audio and the odour of coffee through a mask that was connected to a canister. They found the sense of presence was increased with each added modality but not with increasing detail of the scenes. Use of the coffee odour was shown to be an effective memory enhancer: 95% of participants could recalled there being a coffee pot in the scene compared to only 59% of participants in the control group where no odours were used.

3.1.2 Presence

The use of VR environments to complete tasks emulating real world conditions requires effective ways to evaluate them. By having an environment that is perceptually equivalent to the real world, logic would dictate that any task undertaken in the virtual environment and real world would result in the same outcomes. So theoretically, by investigating the factors that contribute to what makes the human brain distinguish what is real and what is not, the difference can be minimised to the point where they are indistinguishable. At this point, tasks can be undertaken in virtual environments and data collected about behaviours and decisions can be used with confidence for prediction purposes.

This need for evaluation or virtual environments has led to a field of study known as ‘presence’. Presence describes the intangible feeling of whether a person is truly immersed into the virtual experience or not i.e. whether they are present or whether they ‘feel a sense of presence’ in that reality [78]. As one might expect, the phenomena is quite difficult to quantify which leads to several problems.

The term presence differs from terms such as level of immersion and involvement. Immersion tends to relate to the equipment used to provide the virtual experience, so having a high resolution screen with less latency would result in a greater level of immersion. Presence

refers to a more core feeling, a direct feeling in response to the immersion [79]. One could say 'this sounds like being at a theatre': it may not be particularly interesting music and somewhat immersive but a feeling of presence is invoked. The classic example of a feeling of presence is the scenario or standing on edge of a virtual cliff. Even though it's clear that it is not real, the nervous feeling of needing to stand back is sensed [80].

One typical method of measuring presence is via the use of questionnaires. Questionnaires can be taken by users in an experimental group and by answering a series of specific and targeted questions with the answers being on a numbered Likert scale (e.g. 1 to 7 with 1 being 'least' and 7 being 'most'), one can perform a statistical analysis of the numbers to arrive at certain conclusions. Typically these questionnaires will ask a mix of questions about the real and virtual world experiences in the experiment and expected scores would reflect a higher score for a real experience compared to a virtual one.

It is extremely important to ask the right questions, however, or it leads to cases where scores show the level of presence felt in the virtual world is equal to or higher than that felt in the real world in a comparative study as is shown in [81]. In this study, a comparison was done between two types of questionnaires by asking group of 10 volunteers, after a virtual and real experience involving a task of finding a red box. Simply by adding the context of an office space in one questionnaire i.e. differentiating the real world office from the virtual office space clearly and leaving less room for more open interpretation, it resulted in a higher score for real.

Ultimately it comes down to wording, which is a balancing act between giving context but not too much context as to bias the responses to the experiment. The main problem with this approach is, how participants interpret the term presence. It is for this reason that questionnaires cannot be used alone. The need for some additional metric is required. Performing wholesome statistical analysis on subjective measurements and using the trends seen as hard data is impractical. Slater [82] proved this very point by creating a made up concept of how 'colourful' someone felt. A questionnaire about daily routines was conducted with various questions posed to participants with questions revolving around colourfulness tied in with them. A likert scale was used for answers. By using these techniques alone, they were able to arrive at far-fetched conclusions such as: if you want to have a colorful day, which is something to do with having a good, pleasant, but not frustrating day, then at the very least you should accomplish what you set out to do. Getting up later than usual might also help.

There are methods that can be used in tandem with questionnaires to provide a more scientifically measured backing. The use of electrodes and skin conductance tests can help show when someone reaches this state of presence, by providing feedback to the body's current state. Excess sweating or sudden events can lead to sudden changes in the body which act as obvious indicators of a 'break in presence' [83]. It is clear that being able to measure presence is a much

needed tool for quantifying perceptual equivalence, to gauge whether a virtual environment is comparable to real ones from point of view of the human brain.

3.2 Visual Masking and Saliency

This section discusses the concept of visual attention masking and how it has been used in cognitive research for measuring consciousness, visual limits, and perception.

Visual masking occurs when the perception of a given primary stimulus (the target) is affected by the presence of another stimulus (the mask). In the temporal domain, a mask can appear before, after or at the same time as the target and are described as forward, backward, and simultaneous, respectively. In the spatial domain, the mask can either appear in the same visual location (overlapping), described as pattern masking, or it can appear in a separate location, described as metacontrast [84].

Many psychological studies have documented similar phenomena in the context of visual masking [85, 86, 87, 88]. A suppression effect exists when presentation of a pattern mask over a target are out of sync temporarily (either forward or backward) i.e. the effects of the target stimulus are hindered. Conversely the opposite effect appears to happen i.e. facilitation of the stimulus when there is metacontrast or pattern masking when there is simultaneous masking [89]. Ramanarayanan et al. [90] has shown, via a pattern masking experiment, that it is possible to recreate this effect for when varying numbers of 3D objects in rendered images.

Visual saliency is a prominent area of research within computer vision, since it can potentially be used to save on computational power when rendering high quality frames and images. Visual saliency maps highlight the areas of an image which are considered most visually salient i.e. a persons eye's are drawn more towards these area as there is more useful information. The idea is to exploit the highly salient areas by rendering these areas at higher quality and rendering everything else at lower quality, with the intention of these lower quality areas not being noticed. Typically visually salient areas of an image include areas of sharp contrast, edges, and high brightness [91].

3.2.1 Cross-modal smell perception

This section is presents a more in depth look at cross-modal relationships between senses, in order to take advantage of these cross-modal relationships in the future when implementing virtual environments incorporating multiple senses. Several cross-modal relationships showing that the olfactory system does have a deep routed and underlying presence in our consciousness and affects our decision making ability, are explored below. Similar findings have been found

with cross-modal relationships in other senses such as between audio and vision [92].

Demattè et al. [93] found that tactile perception could be modulated by odours. In an experiment, participants reported finding swatches of textiles softer in the presence of a lemon odour than with an animal like odour.

Castiello et al. [94] found that when blindfolded subjects were presented with a smell of a given fruit and asked to grasp the fruit in front of them, the size of their hand aperture would correlate to the anticipated size of the fruit that was smelt. This resulted in e.g. the smell of a strawberry resulting in a small precise hand size whereas the orange smell evoked a large open palm grasp. The crucial finding however, is a clear example of the effects of olfactory information on the process of selection for control of a goal orientated action. This suggests that olfactory stimuli that may or may not be relevant to a task can compete and in some cases override motor-related functions for the orientated task, in this case grasping the fruit. Subconsciously the brain uses previous knowledge based on current olfactory stimuli to help in the top-down, thought driven orientated task. Top-down refers to the active consciousness to focus on a given thing with the senses, as opposed to bottom-up referring to senses reacting to stimuli and giving the brain something to process [95].

In another study, the use of 'olfactory processing' from olfactory cues was shown to reduce the amount of time needed to find a related object in an image. Seigneuric et al. [96] found that when subjects were, unbeknownst to them, exposed to an odour that correlated to an object (e.g. orange smell to actual orange) and tasked with freely looking at a display image which contained an odour-related visual clue, not only was the time taken to locate the object shorter than with no odours, subjects tended to focus on it for a shorter amount of time as well. Eye tracking was used to identify the regions of the image being examined. Seo et al. [97]'s study echoed these results when subjects were presented with odours with a combination of congruent and incongruent objects in photographic slide. These collective findings suggest that olfactory processing affects the visual processing in facilitating given tasks, in this case identification of the congruent visual-odour cue.

Harvey et al. [91] found that visual attention affected the way participants looked at objects in a scene in the presence of odours. By recording eye saccades and analysing the gaze points, the length of time spent looking at particular parts of a scene was identified. This showed that smell provides an impulse on attention which could be utilised in rendering scenes using saliency maps. Brkic et al. [98] found they were able to reduce the render quality of grass without loss of fidelity in the presence of a grassy odour, saving valuable computation time.

Several papers have also studied the relationships people make between odours and the colours that are psychologically assigned to them. Zellner et al. [99] concluded from a study that, colours bias subjects towards particular colour categories, when matching them to odours,

depending on whether the deemed congruent by the subject. Increased odour identification rates would occur with cherry odours, as opposed to lemon, from a red solution. Demattè et al. [100] found that when participants were presented with odours and asked to pick the closest match from a palette of colours, results showed a positive correlation between specific colours and odours. Associations like pink to strawberry odour and turquoise to spearmint were among the results. The robustness of the associations were then tested using an implicit-association test, a test used to find automatic associations between concepts and attributes [101]. A secondary experiment involved using congruent pairs and incongruent pairs of spearmint, strawberry odours, and pink and blue colours. Findings demonstrated that participants were much quicker and accurate at assigning associative colour-odours than with incongruent matching's alone.

Similar findings have been found in gustatory perception experiments. Shankar et al. [102] found in experiments participants rated brown M&M chocolates more 'chocolately' than green coloured ones. The results show flavour perception involves the combination of chemosensory information with visual information.

3.3 Olfactory Displays

Numerous approaches from researchers in recreating olfaction have involved using predetermined and premade smells and reproducing them in select quantities in a variety of methods during experiments. These have ranged from generic approaches such as simply spraying a volatile smell into a room and measuring the perceived response of participants while performing a given task [103], to using small emission chambers which emit vaporised smells directly below the nose to more sophisticated methods such as an odour projection device which also incorporated head tracking to take into account the spatio-temporal effect of smell [104]. The device used a vortex canon which would blast smells towards users via rings of air. It went through several iterations of improvements to include chambers for multiple smells and measures to allow for controlled quantities of odours. It also incorporated head tracking of a user to ensure the air mixture was delivered to the correct space. This would mean odours could be presented to users in a non-invasive fashion. The setup for this device, however, was time-intensive since the chamber required liquid smell to be injected and allowed to vaporise, and needed cleaning between subsequent compound delivery.

Typically for the sake of storage, odours are held in capsules or vessels in liquid form and vaporised on demand. Li et al. [105] designed a number of different methods to accurately produce these test gases and included specifications, for example employing the use of polytetrafluoroethylene coatings to negate many underlying factors such as permeation into materials. Nakamoto et al. [106] demonstrates this with their airflow olfactometer with rapidly switching

solenoids and is able to switch as quick as 2 milliseconds. This is also explains the difficulties to concentrations under 1ppm. Many other displays have been designed and built, by researchers, for applications of smell within VEs. The designs of these displays are varied and there is a diversity of methods employed. For the most part, researchers have focused on being able to deliver smells to the user as quickly as possible and thus as temporally accurate as possible. The goal of these devices has been to be able to reduce the onset time (time taken to reach the user from the display) and thus be able to present odours on cue and in tandem with other visual and/or sound stimuli. A secondary goal has also been to make systems more portable and practical; systems which are easy to use such that specialists in the field are not required for their use.

Yamada et al. [107] used a portable air pump design fitted into a backpack to allow portability and movement. This design allows for different strengths of three odours which are controlled by the resistance level of a potentiometer limiting the voltage given to the air pump. Thus the main way of controlling concentration is by increasing airflow. This can mean that that as the fans increases in speed, users are likely to notice perceptual variations from the different airflows and thus experience a lack of consistency between varying trials.

Matsukura [108] used fans to present odours of different fruit teas. Open vessels containing hot tea were used and naturally emitted odours as the water evaporated. Airflows created by fans were then used to push odours to participants. They also later designed a smell display using directed airflows created by miniature fans with a computer monitor [109]. Airflows from opposite sides of the screen were directed towards each other collapsing in the middle and forced outward toward participants looking at the visual display. Howell et al. [110] also used a fan-in-a-box emission method to create ‘immersive media experiences’.

Lundström et al. [111] used both glass and polycarbonate plastic vessels containing liquid odours with an airflow produced by a centralised air compressor system in a lab. Airflow was used to push the vapourised headspace odours from the vessels through individual solenoid valves.

Nakamoto et al. [112] designed an olfactometer which used a pump to provide liquid odours to a specialised plate. This liquid would then be vaporised via high frequency sound waves applied to the plate. The high oscillation frequency excites the liquid molecules and transfers enough energy to allow them to overcome their respective enthalpy of vaporisation. This design is limited however by the need for high voltages to power and control the device.

Ischer et al. [113], similarly to Lundström et al. [111], used glass tubes with cotton swabs soaked with liquid odourants inside. Airflow was used to flush the vapourised headspace odours from the tubes via a series of solenoids. The headspace refers to the volume of air above a solid or liquid substance which becomes saturated with the gaseous form of the substance

as it vaporises over time. Whilst the design is relatively robust accounting for avenues of contamination and consistencies of the flow, they do not quantify in detail the concentrations used, but instead use generic intensity levels based on flow.

Abid et al. [114] used piezoelectric films to deliver liquid odours. Applying a voltage to the film causes the film to expand and lowering the voltage causes the film to contract back. They used this phenomena to oscillate droplets into the air, after placing the film over a small reservoir of liquid odour. This small size of the film allowed for a compact design. The main limitation of these types of devices is that the droplets produced are tiny balls of liquid and not vapour, making it difficult to measure the concentration.

3.3.1 Odour Sensing

Electronic noses (E-noses) technologies are becoming increasing prevalent in odour sensing in the medical industry. E-noses work by combining sensor arrays with pattern recognition algorithms to build blueprints of particular smells for identification. The smells detected will have a typical composite mixture which will remain in appropriately the same proportions and the sensor array can work out the odour based on its fingerprint. This can be extremely useful for healthcare professionals in diagnosing certain conditions as certain compounds expelled from the body are unique to them. For example, diabetic ketosis can occur in patients with a severe insulin deficiency which results in increased delivery of fatty acids to the liver from the breakdown of triglyceride. This generates ketone compounds, 3-hydroxybutyrate and acetoacetate, the latter of which reults in acetone being expelled through the lungs [115]. An e-nose would be able to recognise this from the breath of a patient and allow for a quick life saving diagnosis. Enoses have a wide range of applications from measuring air quality during rocket launches [116] to urban airborne pollutants monitoring [117]. However, the biggest drawback to using them, is that they must be trained to thousands of different odours profiles and iteratively learn how to identify specific patterns, which can require a lot of resources. There are a handful of simpler devices which can do gas sensing. These can be based on several different technologies namely: electrochemical sensors, infra red lasers, metal oxide semi-conductor sensors (MOS), and photoionisation detector cells (PID). Electrochemical sensors work by having a circuit between two electrodes. Gases diffuse into the cell and react with the electrodes in a series of reduction/oxidation (redox) reactions and the current produced is relative to the concentration gas that is reduced/oxidised. Infra red lasers work by having the gas pass the beam and absorb the light in a given wavelength. The energy of the light absorbed is compare to the energy not absorbed at a different non-absrobing wavelength and the ratio between the two is proportional to the concentration of gas present. These technologies are typically used in gas safety system

devices, and in breathalysers and smoke alarms. MOS sensors typically have a tin dioxide sensor in a circuit which gases react to, altering the electrical resistance. The change in resistance is proportional to the concentration of gas present. Due to their ability to detect a variety of gases, MOS sensors were the standard in gas sensing until recently whereby they have been replaced by newer PIDs. This is mainly due to MOS sensors suffering greatly from humidity drift at higher humidities while PIDs do not [118, 119]. PIDs use an ultraviolet light emitting lamp to ionise any gaseous molecules nearby. This causes the molecule to emit a negatively charged electron, creating a positively charge molecule. The charged species and move to the negative electrode and the resulting current is proportional to the concentration of gas present.

3.4 Digital Olfaction Simulation

The fact that odours cant be manipulated in the same way digital stimuli can creates a significant problem, less applicable to vision and sound. An odour is a set of real molecules in real space and the smallest changes to its physical properties can lead to the largest of changes in perceived smell and so without the ability to easily make direct changes to parameters, it becomes very difficult to quantify the variable itself.

Naturally a logical step to take to work around this problem would be to model the behaviour of molecules in a virtual environment to see their behaviour and using this in tandem with the real smell emission and potentially solve the quantification issues by somewhat digitising the odour transport. A few simulations have used computational fluid dynamic models to map particles in a room and using the mapped trajectories of target particles to estimate the concentration in a given space. Matsukura et al. [120, 121, 122] took this very approach using a basic K-epsilon turbulence model in an existing computational fluid dynamic software, CFD2000. The approach relied on generating airflows which carried smells through a virtually modelled room and particles to represent an odour. An airflow field was then generated to create a general dispersion of odour with the denser areas within the simulation in a given space corresponding to higher concentrations. The accuracy of the model was validated by measuring fluctuations in odour concentrations using metal-oxide semiconductor gas sensors in the initial environment which was modelled. In addition, they devised an experiment in which participants controlled an avatar of a small animal with a first person view whilst wearing a mask which was connected to an odour blender. The CFD simulation was run in real-time whilst the participant controlled the avatar. The location information was then relayed back to the computer which in turn told an odour blender (olfactometer) to emit odours depending on the estimated concentration determined in the simulation. Participants were given the task of working out which of three virtual teacups were the source of the odour, peach tea, in the virtual room. It was also found

that without a dominant airflow in the modelled room body heat becomes the next dominant factor for movement of particles. In a separate simulation without a simulated airflow, a model representing the human body was responsible for currents in the air and thus movement of the odour via convection of body heat.

3.5 Virtual Olfaction Pipeline

There currently lacks a unifying, generalisable approach for virtual olfaction implementation. Having a pipeline provides a sensible starting point for researchers new to the field or for those who are less familiar with this area of research. Those who have their work overlap with this field, e.g. vision VR computer scientists or behavioural psychologists, may often find themselves falling into unfamiliar territory and this creates an unnecessary obstacle for research. With a pipeline, they simply have to take it an employ it into their work, making sure to account for any limitations that are applicable to them, without having to worry about researching the entire field. Those saved resources and time can then be applied elsewhere.

When broken down, a pipeline falls into five main stages: capturing, storing, reproducing, delivery and perception. To recreate a virtual scenario, original materials are required to be replicated and an effective way to acquire olfactory information is needed. This would be addressed in the proposed capture stage. A suitable medium for this information is required for storage so that it can be called on and disseminated later, and this is addressed in the storage and reproduction stages. Finally a mechanism by which the olfactory information can be presented to the user, whilst the perception stage changes the delivery stimuli in response to the user interaction is needed which is addressed in the delivery stage. An illustration of an ideal pipeline, breaking down its' core components, is shown in Figure 3.1.

3.5.1 Capture, Storage and Reproduction

To create a perceptually equivalent virtual experience directed at any sense (or multiple) requires stimuli to be not only relevant to the given experience but also accurate such that they appear authentic to users; so naturally the start of the pipeline would involve capturing the stimuli which will be replicated later.

In the case of olfactory stimuli, as discussed earlier, this involves capturing physical molecules responsible for the smells we perceive (similar to capturing light with a camera). One such approach for accomplishing this for odours is by using an volatile molecule capture kit. A kit typically contains several smell capture tubes and work by passing air containing the odours through them via a micro air pump and some tubing. The tubes contain a 'sorbent' coil which

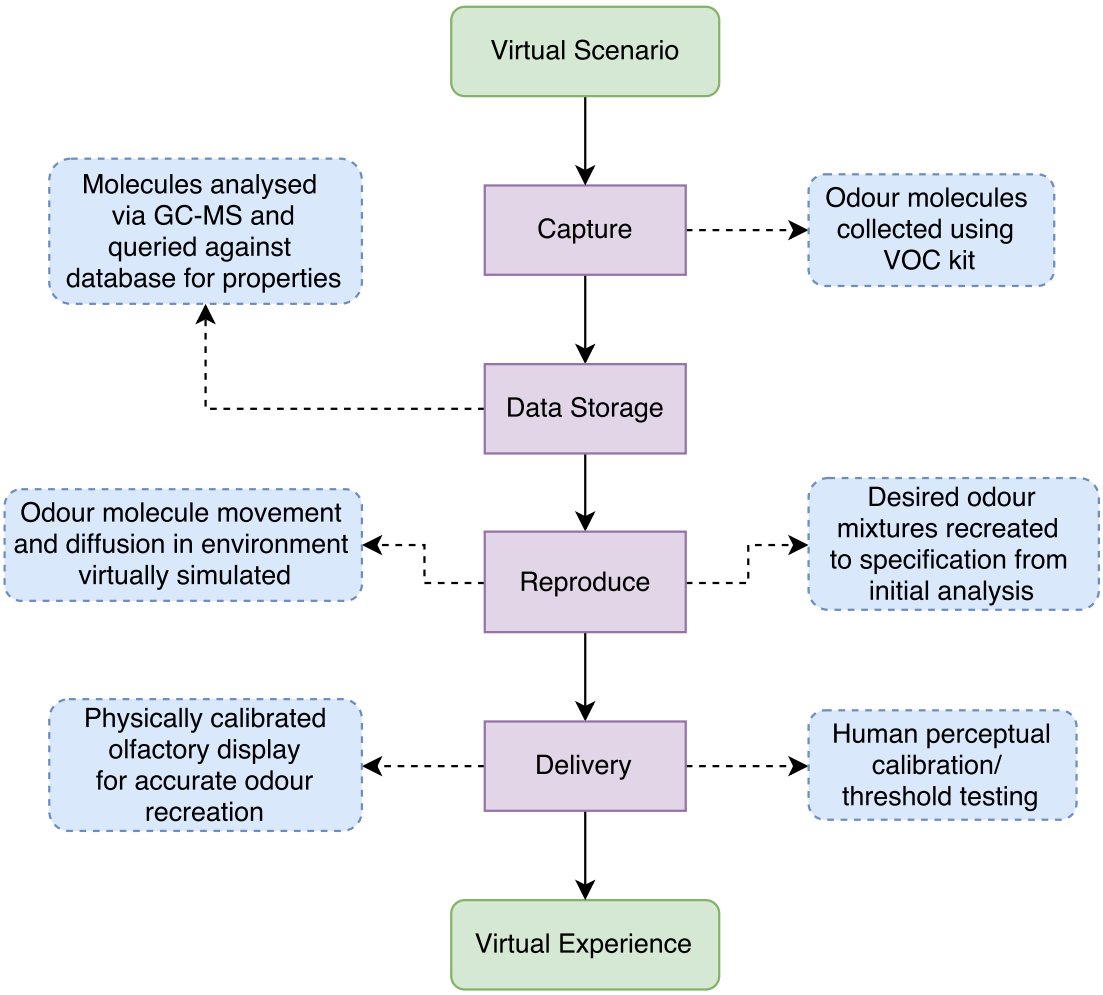


Figure 3.1: Diagram of proposed pipeline for olfaction recreation in virtual environments

has a surface area which is suited to adsorption of VOCs that pass by. The contents of the tube can later be analysed using thermal desorption (heating with enough energy to overcome the initial adsorption but not decomposing the VOCs), effectively releasing the VOCs, which are then funnelled into a Gas Chromatography-Mass Spectrometer (GC-MS). Using this method thus allows for the documentation of the molecular make-up of a particular smell and the relative quantities of certain molecules which are required to recreate the smell exactly. This information can be stored and reproduced easily.

Reproducing smells from this data involves synthesising or purchasing the specific molecules, and mixing in the correct quantities to have a virtually unlimited volumes of the given odour, assuming these component molecules can be readily sourced. Someone designing a virtual experience would be required to do this for every desired smell for use in their virtual environment. Whilst this would be time consuming and potentially costly, it would result in perceptually authentic odours with both correct intensities and smell character.

For the delivery of odours to match real world conditions, the concentrations present in a given space and time need to be known. When capturing data, only a snapshot of a given moment is captured, and can only really be representative of that moment. When recreating a perceptually accurate olfactory experience, the movement of the particles need to be modelled and simulated, and since gaseous odours move depending on their environment, the physics of that environment need to be incorporated into the simulation. This would be very expensive in computational resources since a computational fluid dynamic simulation would be needed to model aggregated flows of air and odours. This simulation would also need to take into account any other moving bodies including e.g. the participants, since they can have substantial effects creating new convections from body heat and any physical movement. The physical delivery from the olfactometer would then adapt based on what the simulation predicts, in real-time.

3.5.2 Delivery

The delivery stage in many ways is the most important and is the most complex. The presentation of the stimuli to the user occurs but for this to be physically accurate, several factors need to be accounted for and these include both the physical and chemical properties of the odours themselves and the environment the user is in.

As mentioned previously, there is a significant amount of research in this field which focuses on the delivery aspect of olfaction in VEs [112, 113, 114, 123, 124]. Additional considerations that must be incorporated into any final design of a odour delivery device, are discussed below.

Temporal Displacement

With regards to the actual presentation, a big factor that needs to be accounted for is the temporal displacement of the odour. Some researchers would argue this is the most important factor for olfactory research in virtual environments, since olfactory stimuli are rarely used by themselves, but instead used in tandem with other sensual stimuli (i.e. visual, auditory) with the intention of investigating cross-modal effects and multi-sensory immersive virtual environments. As such, the odours used in their given scenario will need to be presented at a given cue to match the presentation of the other sensual stimuli. If there is a disconnect or incongruence between the sets of stimuli, this can lead to erroneous or unusual outcomes. Typically visual stimuli are presented 60hz or above via some form of display (monitor/ head-mounted display) at a given resolution i.e. it refreshes and displays 60+ frames a second. Auditory stimuli are typically be presented in the kHz range. However, Smell stimuli would only need be presented a much slower rate: Sobel et al. [125] showed during a study that fMRI scans showed correlated activity in the piriform cortex when sniffing as frequently as every 8 seconds or 0.125Hz. It should be mentioned this was the smallest time period tested in this study, as going smaller would have caused subject exhaustion. This is, in part, due to the effects discussed earlier i.e. habituation and the way smell has to physically move slowly to the olfactory epithelium. Olfactory neurons in the nose sample the air less frequently. Naturally smelling or even forcefully sniffing falls roughly in sync with our breathing cycle since they are using the same biological mechanisms, and so even if a given odour is in the vicinity of the neurons, the sampling will still happen a far slower rate in comparison to the other senses. As discussed previously, many olfactory displays have been designed with onset time in mind [106, 104, 110], and considering it is extremely difficult to continually keep sniffing without exhaustion for extended periods of time, a one second onset time is a reasonable compromise given the other difficulties that need to be overcome.

Chemical and Physical Properties

Another big factor that has to be taken into account which is often overlooked in this field is how the odorous chemicals interact with their environmental conditions before reaching the nose. As discussed before, odours are inherently volatile since they have to travel through the air to reach the nose and as such their individual molecules need to be light in terms of relative atomic mass. Any environment, that contains air, will naturally have air flows and micro turbulences present in it. Even if there is not an intended source of convection, simply by having someone present creates this by them moving around or their body heat creating small convections which will influence the surrounding environment. This is important since, depending on the set up, it

could result in stimuli not reaching the participant at correct times or even at all, especially if the distance travelled through the air is large. This doesn't include any possible obstacles or their related surface effects (surfaces of objects could have a tendency to adsorb molecules due to intermolecular forces) either.

Room temperature, pressure and humidity are parameters which have to be taken account for accuracy and precision when considering the above case and in general. By controlling these three main conditions, once controls odour molecule movement through the air.

Heat is responsible for giving molecules energy so that they can move around faster, so naturally having a warmer room will mean faster diffusion of odours in that environment which will naturally mean distances are closed faster and overall a quicker delivery of smell. However, unless an intended air flow is present to direct an odour, the dominant direction of diffusion will be outwards from the source. This may not be ideal since a user may have to wait longer to get a given concentration of odour, but it also becomes far more difficult to clear odours or dilute them down if the environment smells the same everywhere. Atmospheric pressure is mostly negligible since it will be approximately equal to atmospheric pressure with negligible fluctuations. Increased humidity can increase the volatility of some odours since certain polar odorous molecules can dissolve in the water vapour aiding the movement of smell. Again the proposed delivery system attempts to encompass these factors in its design.

Perception

Being able to reproduce a real world scenario is possible when matching all the recorded parameters. However, this is sometimes not necessary for producing perceptually accurate olfactory experiences. As previously discussed, human perception of smell is highly variable in a population and so it can be difficult to have a series of parameters which can be applied to olfaction which will generalise for the majority of people. A generalisable approach to perception of olfactory presentations, such that everyone is able to smell at the same level, is thus needed.

3.6 Discussion of Olfaction in Virtual Environments

The complex nature of smell has led to many varied attempts to recreate it for both study in psychological studies and simulation in virtual environments. It is obvious that a human's ability to smell is crucial in everyday decisions from natural associations that are made with memory and no virtual environment could be truly perceptually equivalent without it. It is obvious that the connections to other senses which facilitate brain function in object based

tasks and decision making, as has been demonstrated by cross-modal research. Overall there still lacks a unifying approach to employing odours into virtual environments. A generalisable end-to-end pipeline needs to incorporate concepts and methods of capture, storage, reproduction and delivery into it. The most important part, however, is the delivery aspect which is why most virtual environment has put most of their efforts on it. The focus on making olfactory displays increasingly modular and mobile with faster odour onset times has meant there has been less focus on accuracy. Accuracy in this context is referring to how close the experience of the smell in the virtual environment is to a real smell experience. Odours are ultimately made up of varying concentrations of volatile molecules with small molecular masses and being able to mimic the relevant concentrations would allow researchers to provide a true high fidelity olfactory experience.

Chapter 4

Research Methodology

The previous chapters highlighted the need for perceptually accurate olfaction in VEs. However, in the field of olfaction for VEs has been largely lacking especially in comparison to research being conducted on the other senses particularly in visuals and acoustics. In terms of olfaction research, most work focused on quantifying multi-modal relationships specifically combining the visual and audio domains with smell. As has been established in previous chapters, olfaction is more complex than the other senses owing to its high variability in individual differences as was discussed in Section 2.4, but also due to the mechanisms behind its perception not fully being understood.

This research methodology highlights the gaps in knowledge that are currently missing from the smell simulation field, that need to be approached. Specific research questions are then posed based on the identified missing knowledge. These are then followed by research objectives which outline the approaches taken to answer these questions.

4.1 Discussion of Virtual Olfaction

4.1.1 Olfaction Recreation

The significant amount of research in this field focuses on the delivery aspect of olfaction when using in VEs [112, 113, 114, 123, 124]. This is logical from a researchers point of view since it is a important part when attempting to recreate virtual scenarios, since the stimuli is the principle component in eliciting perceptual responses. However, from a overall point of view, there still lacks a unifying, generalisable approach for virtual olfaction implementation. To recreate a virtual scenario, original materials are needed to be replicated. In the case of vision, real images are needed and these are then recreated by rendering scenes with models, shaders,

textures and simulated light. With audio, original sound waves need to be recorded and then digitally manipulated. However, for olfaction, there hasn't been a generalised approach for capturing and reproducing original information that has been outlined in literature. It seems counter-intuitive that something rather simple has been largely overlooked, especially when the end goal is to recreate a perceptually equivalent real world scenario. A pipeline for olfactory implementation for virtual environments needs to be outlined to standardise the approach to olfactory experimentation and research. This would also provide a sensible starting point for researchers new to the field or for those who are less familiar with this area of research.

4.1.2 Physical Presentation

It is clear that many different smell displays or olfactometers have been designed and built, by researchers, for applications of smell within VEs. The designs of these displays are varied and there is a diversity of methods employed. For the most part, researchers have focused on being able to deliver smells to the user as quickly as possible and thus as temporally accurate as possible [104, 110]. The goal of these devices has been to be able to reduce the onset time (time taken to reach the user from the display) and thus be able to present odours on cue and in tandem with other visual and/or sound stimuli. A secondary goal has also been to make systems more portable and practical; systems which are easy to use such that specialists in the field are not required for their use [107, 114].

While accuracy and precision are acknowledged in general, they aren't given much attention beyond being able to produce generic discrete levels of stimuli. Accuracy and precision here refer to the concentration, the physical amount of odour in the air. The use of complementary modes of measurement and detection are lacking from exiting methodologies. Some attempts to use e-noses, specifically gas sensors whether metal oxide or photoionisation based, have been used to quantify stimulant levels with notable examples from [113, 111], however, the level of detail doesn't expand beyond this point. There aren't any known attempts to quantify olfactory stimuli to a specific ppm level or levels which will give information to the physical accuracy of the stimuli presented to a measurable unit. It could be argued that this level of accuracy isn't needed for perceptual investigations and this may be true for the majority of work when studying generalisable cross-modal relationships, however, when it comes to the question of repeatable work, it becomes difficult to validate results since all known parameters can be replicated, if certain things weren't initially accounted for, this information is lost. If exact concentrations of a stimulant are known, these can be reproduced regardless of the conditions since this number is not subject to interpretation. Researchers would be assured that the conclusions they draw from their results are based on sound data. Thus having a capability of being able to reproduce

experiments, since everything is measured, would be a invaluable tool.

This would also allow for systematic approaches to studies, examining the affects of changing a single factor but repeating the same other conditions. To reiterate, the most important part of the olfaction recreation is the stimulus (aside from the perception of said stimuli), and when the end goal is to recreate a perceptually equivalent real world scenario, it must be logical and desirable to want to have a high level of control over stimuli and conditions.

4.1.3 Perceptual Presentation

Performing threshold testing in olfaction is a widely used technique for studying the smell sensitivity exhibited by individuals. This data can be used to estimate the concentrations for when a general population can begin to start smelling certain compounds. However, a common theme that occurs in literature is that while using custom olfactory displays, often, information is lacking with regard to the stimuli presented beyond the specific odours used and in some cases arbitrary levels, when studying the sensory modalities but also cross-modal relationships. This is a important field of research within virtual reality (VR). Methods state ways of varying amounts of stimuli, though rarely is there any approach of validating this scientifically. Olfaction differs from the other senses, in that receiving this stimuli is heavily dependent on its mode of transport to the sensory organs, and in this case travels through the air subjecting it to turbulences which can drastically affect the end result i.e. from getting all the intended odour to getting none. It is assumed that the highest care is taken when conducting olfactory experiment in stating everything that was done but the onus falls on the researcher to disclose this. Olfaction also shows high variability between people which adds to the complexity and difficulty in recreating exact olfactory stimuli. These combined effects create the need for a generalisable approach for studying olfaction in VEs, but there has yet to be a definitive approach to be proposed. Any such approach would need to incorporate high accuracy and precision of stimuli, for the sake of validation, and be able to be applied to a general population while also giving the flexibility to be applied across different odours.

4.1.4 Applied Perceptual Presentation

In the case of quantifying the olfactory modality for VEs, most recent work focuses on cross modal effects with vision and audio. This includes work from [126, 127], where the use of olfactory stimuli can be used to enhance perception of the overall quality of stimuli when presented with visuals. Other studies find similarly interesting findings congruence between visuals and olfactory stimuli facilitate presence in VEs which reduce the need to spend increased resources on the other senses [94, 96, 104]. These effects can then be used to make computational savings.

Research in the visual domain, often looks at finding optimisations to reducing computation overhead when rendering images, and one such optimisation is through the use of attention masking effects and exploitation of visual saliency. They refer stimuli having an overriding effect on one another such that only one is noticed and has the participants attention. Aggregates are an example of this and refer to having large groups of objects, in which the visual saliency of the group are more than that of individual object resulting in small differences not being noticed. [90] showed that observers didn't notice the difference between several low quality and high quality objects above certain numbers of objects. Attention masking is an established concept in the visual domain, but has to be explored in the olfactory domain. If more than one odour is present in a VE, it is currently unknown if the attention of the observer show preference for one odour over another when they are present at the same perceptual level. Other possible optimisations could include, measuring the perceptual point at which subjects feel that an olfactory stimuli is overwhelming or looking for a generic approach to tailor odours to individuals. In both these cases.

This thesis set out to answer the following research question:

How can a generalisable approach for recreating real world olfactory conditions in virtual environments be created?

This main research question was optimised into the below question based on context from literature, since it was identified that some of the biggest challenges when using olfactory stimuli in virtual environments revolved around key aspects of the delivery of said stimuli:

- How can physical and perceptual olfactory accuracy be best approached?

The primary contributions of this thesis was providing two frameworks which each allow for the physical and perceptual calibration of olfactory stimuli, respectively. The physical accuracy is achieved through the design of an olfactometer calibrated by a novel gas sensor array. The perceptual accuracy is achieved through the outlining and implementation of a framework which allows for the calculation of perceptually generalisable olfactory concentration thresholds, where perceived odour intensity is equivalent across people and can be matched to be equivalent across individual odours.

Having created a framework for producing physical and perceptually accurate olfactory stimuli, the next logical step was to use tools created to answer a crucial question for olfaction in virtual environments:

- Can olfactory masking effects between multiple odour stimuli be quantified?

This question is important since it has the potential of reducing computational cost which has big ramifications for virtual environment generation. An example could be if a computational fluid dynamic simulation was required to show the movement of odours through an environment so that the correct concentration was delivered to the user from the olfactometer to match the simulated 'expected' concentration in the simulation. If it was found a particular odour overrides another in certain contexts, the savings in computation in not having to model two smells would be significant.

An attempt is made at answering this secondary question, however, while the experimental design is robust, the number of participants required to have a far more conclusive result need to be far higher to achieve statistical significance. There is evidence, however, to suggest the existence of a masking effect in which there is a preference of certain odours over others. This could be potentially due to a olfactory saliency affect in which certain odours may be more salient than others, though more participant response data across more odours with varying smell characteristics would be needed to validate this.

The specific contributions of this thesis are outlined below:

- A novel design for olfactory display which is calibrated and provides high accuracy delivery of olfactory stimuli.
- A procedure so that any other odours can be calibrated to give the same level of accuracy and precision.
- A flexible design for a low cost gas sensor array capable of measuring volatile odours to sub-ppm level.
- A validation framework for calculating headspace recovery rates of volatile odorous compounds, which can be employed with any airflow based olfactometer to prove the accuracy of the output is repeatable.
- An outline for a framework which allows for the creation perceptually generalisable olfactory thresholds across odours, where perceived odour intensity is equivalent across people and can be matched to be equivalent across individual odours.
- An experimental procedure to quantify possible attention masking effects that may occur between odours in a multi-odour context, with evidence to suggest the existence of such an effect.

4.2 Research Questions

This thesis set out to answer the following research question:

How can a generalisable approach for recreating real world olfactory conditions in virtual environments be created?

This main research question can be optimised into the below question, based on context from literature since it has been identified that some of the biggest challenges when using olfactory stimuli in virtual environments revolved around key aspects of the delivery of said stimuli:

- How can physical and perceptual olfactory accuracy be best approached?

Looking at literature, it is clear that olfactory perception research is lacking especially with the area of olfactory saliency relatively untouched. As an initial attempt to explore this area, the following question was asked:

- Can olfactory masking effects between multiple odour stimuli be quantified?

This question is important since it has the potential of reducing computational cost which has big ramifications for virtual environment generation. An example could be if a computational fluid dynamic simulation was required to show the movement of odours through an environment so that the correct concentration was delivered to the user from the olfactometer to match the simulated 'expected' concentration in the simulation. If it was found a particular odour overrides another in certain contexts, the savings in computation in not having to model two smells would be significant.

4.3 Research Objectives

This research aims to fulfil the three research questions mentioned above by accomplishing the following objectives, based on three methods, respectively:

- The first method aims to:
  - create a calibrated olfactory display which produces a repeatable olfactory output at high accuracy and precision
  - outline a procedure that allows for the replication of both the construction of the display, and the creation of new calibrated olfactory outputs using the same validation approach

- The second method aims to:
  - create a standardised framework for producing perceptually equivalent odour intensities
  - outline a procedure for creating additional perceptually standardised concentration thresholds for any other volatile odours
- The third method aims to:
  - conduct preliminary research into the quantification olfactory saliency
  - quantify possible attention masking effects that may occur from olfactory saliency between odours in a multi-odour context

4.4 Overview

This thesis focuses around standardising processes for accurate and precise olfaction recreation in virtual environments, and using said processes to conduct further research into perception in the olfactory modality. In Chapter 5, an olfactory display design which is able to deliver olfactory stimuli to a parts per million level accuracy. All steps of calibrating for individual odours and validation of this calibration are outlined here. Three different odours are calibrated but the steps taken to do this are adaptable to any other odours too. Chapter 6, combines the use of the olfactory display design from Chapter 5 with psychophysical analysis methods to create perceptually equivalent intensity thresholds for the target odours. Chapter 7 builds on the two previous chapters by proposes a study which investigates the possible presence of olfactory masking effects during multiple odour presentation, by using the perceptual thresholds from Chapter 6 across three calibrated odours.

Chapter 5

Calibrated Olfactory Delivery

Several olfactory display designs have been presented in literature, each with various advantages and disadvantages. This chapter describes the designing and building of the olfactory display or 'olfactometer' that is used to provide the physical delivery aspect of the olfaction outlined pipeline. This is the most important step since it is the main stage at which olfactory stimuli are presented to users.

This particular olfactory display design aims to address three main requirements, the first two of which have been largely ignored:

- High Accuracy: The reproduction of real world equivalent olfactory stimuli, specifically in the context of concentration matching to ppm level.
- High precision: The repeatability of outputting said stimuli, such that the desired output is consistently and equally accurate across presentations.
- Low Cost: While other designs outlined in literature have focused on this, the combination of this requirement with the previous points is of significant importance. Having a low cost device, means it can be readily reproduced for other research and a greater adoption means more researchers can benefit from the high accuracy and precision.

Details are given on a calibration process which guarantees consistent accurate outputs under specified conditions along with a validation method as proof of this. As discussed in chapter 4, the importance lies in being able to show repeatable outputs. By being able to reproduce stimuli that are known, this removes the burden of possible unknown conditions and bypasses them by providing an exact measurement which describes the concentration of the odour. The points highlighted in 3.5 with regards to considerations for odour delivery devices are also accounted for and addressed in this chapter. Additionally a custom photoionisation gas sensor

array is built for the purpose of this calibration and details are given on its build. While the sensor cells used are commercially available, their use in the way outlined in this calibration of odour concentration output can be said to be novel, as such a methodology has yet to be seen in literature.

This chapter first gives details on the basic design of the olfactometer. A breakdown of vapour pressure theory and why it is relevant in the calibration of odours is then discussed. This is followed by a odour saturation rate measurement, for three odours, which provides the basis of the validation of the calibration approach used later in the chapter. Finally details are given of the custom gas sensor array setup along with the plotting of calibration graphs of the three odours showing the relationship between volume of odour outputted and the concentration subsequently exhibited.

5.1 Olfactory Display Design

The olfactometer was designed to allow for small concentration outputs which are more typical in nature and as such would need to be able to present stimuli in the sub-ppm region. It was also important that this be a low cost solution so that similar solutions can be deployed for other multi-sensory experience setups with ease. As such, everything used consists of off-the-shelf components. The most expensive parts in the proposed system are the digital mass flow controllers (DMFC) which retail between 300-500 GBP per unit with cheaper models from other manufacturers (at this time of writing). The remaining parts can purchased for less than 150 GBP, the bulk of which is down to the air compressor with tank bringing the total to approximately 650 GBP using only 1 DMFC. In comparison, the price of commercially available, specialised olfactometers can reach into the tens of thousands of GBP [128, 129, 130]. These olfactometers are largely less specialised and provide dilution steps of a predetermined known odour standard of a given concentration, and are suited odour threshold testing. No known olfactory displays provide a variable calibration that can be used to give desired concentrations for multiple odours.

Airflow is used as the main emission method and simplifies the whole design greatly. Notably, being able to control how odours reach the user and thus the concentration users will perceive. With the use of a closed airflow system as outlined below, there are fewer things to account for. The olfactometer was based upon an air flow method as this allowed emission of precise amounts of odour via direct displacement of air. In this particular setup, the only thing that needs to be controlled is the airflow and this is done via either limiting it to a percentage of its full amount and/or limiting the time it is permitted to output for.

An air tank with a combined compressor unit was used for the airflow with a charcoal filter attachment to provide a clean and filtered air supply, delivered at 2 Bar. This was connected

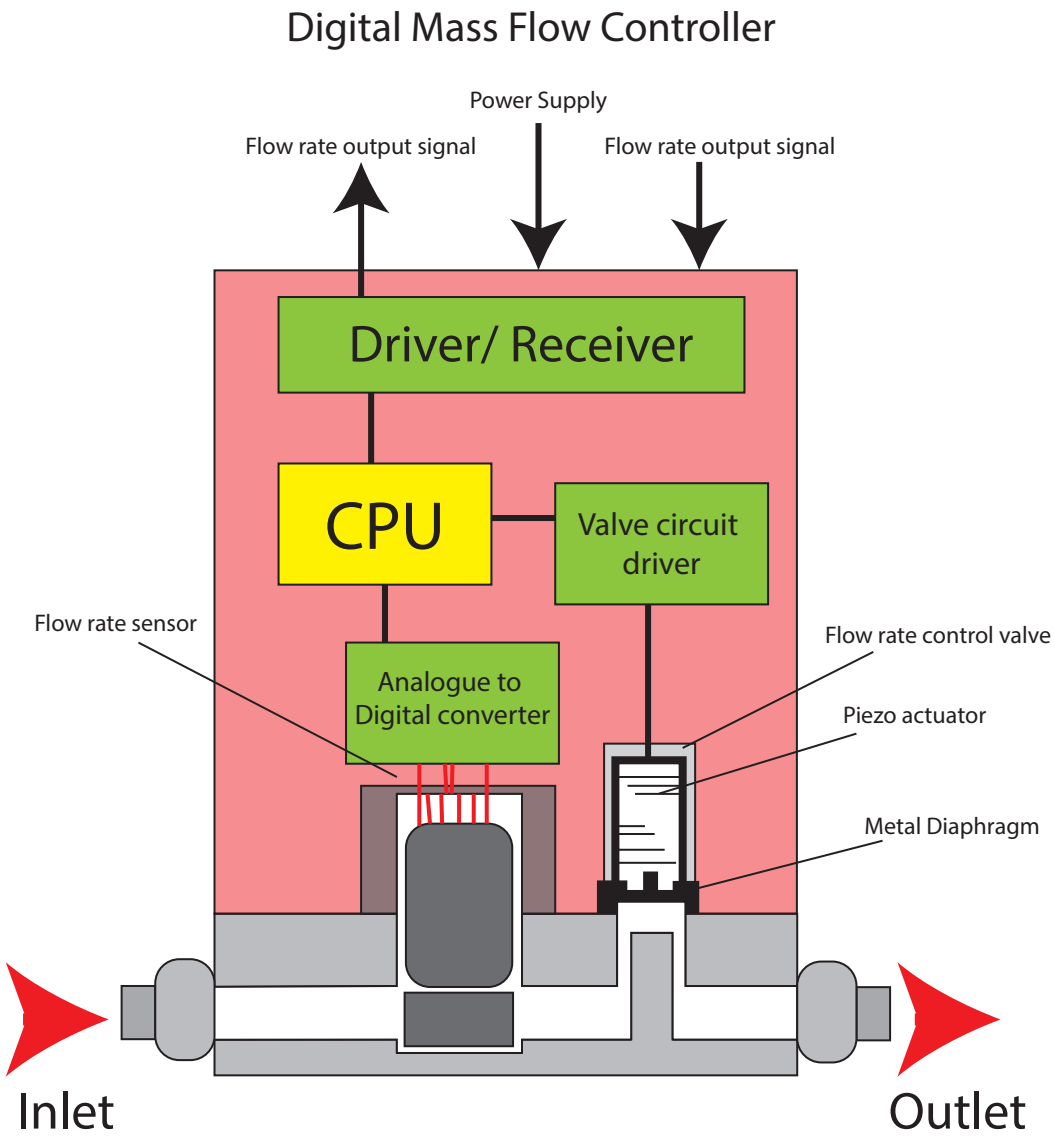


Figure 5.1: Diagram of a Digital Mass flow Controller

to a maximum 1L per second DMFC which in turn was connected to an inlet on a 100mL reservoir containing the selected odours. An outlet pipe of 50cm was connected to the reservoir. The DMFC (Horiba SEC-Z512MGX) was controlled using a RS485 serial interface to USB connection on a laptop running an application which controlled the solenoid. The DMFCs output was tested using an Ellutia 7000 flow-meter. Figure 5.1 shows a cross section of a DMFC. The DMFCs are able to adjust the flowrate using a diaphragm on the pathway to always give the close to exact specified flow rates based on readings from the sensor automatically. Several different flow rates were tested and the flowmeter showed no more than 8% variance from the expected output at flow rates lower than 100mL/min and no more than 1% variance for flow rates above 100mL/min. Additional flow controllers with reservoirs can be added easily with a splitter on the air supply. Polyfluorotetraethylene (PTFE) piping (3mm inner diameter) was used to connect all the components together due to the materials' properties, specifically its high inertness rating. This is down to the molecular structure of the polymer, in which the carbon backbone is surrounded in flourine atoms which form an unreactive and inert shield due to their fully occupied outer s and p orbitals. Other materials could potentially absorb Volatile Organic Compounds (VOC) over time and thus change both the concentration and character of the intended odour delivery, but also limit any possible contamination effects from other smells.

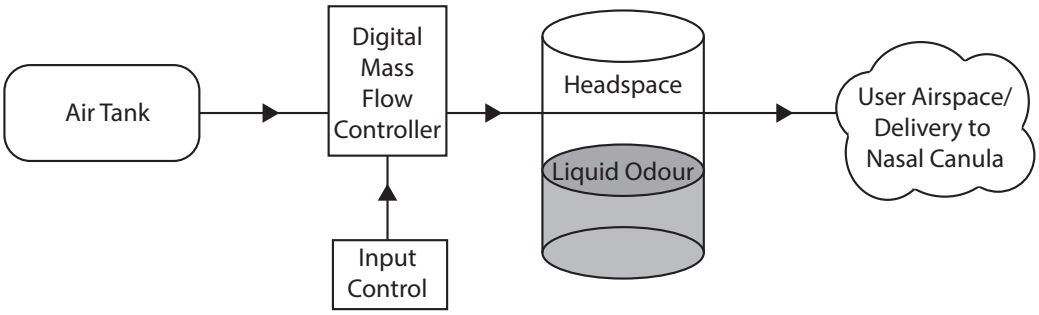


Figure 5.2: Diagram of Olfactometer design

The olfactometer had an entirely sealed system from the air tank to the final emission from the outlet. If the DMFC solenoid valve was opened for precisely timed amounts, there would be an exact displacement of air which would push an equal volume of saturated, vaporised odour out from the headspace of the reservoir and which would then presented to the user. Figure 5.2 shows a diagram of this setup while Figure 5.3 shows a picture of the real life set-up. A systematic approach for calculating the concentrations for specific volumes of displaced air was carried out for three different odours, which is discussed later in this chapter.

The single molecule odours citral, α-pinene and isoamyl acetate, which have smells of

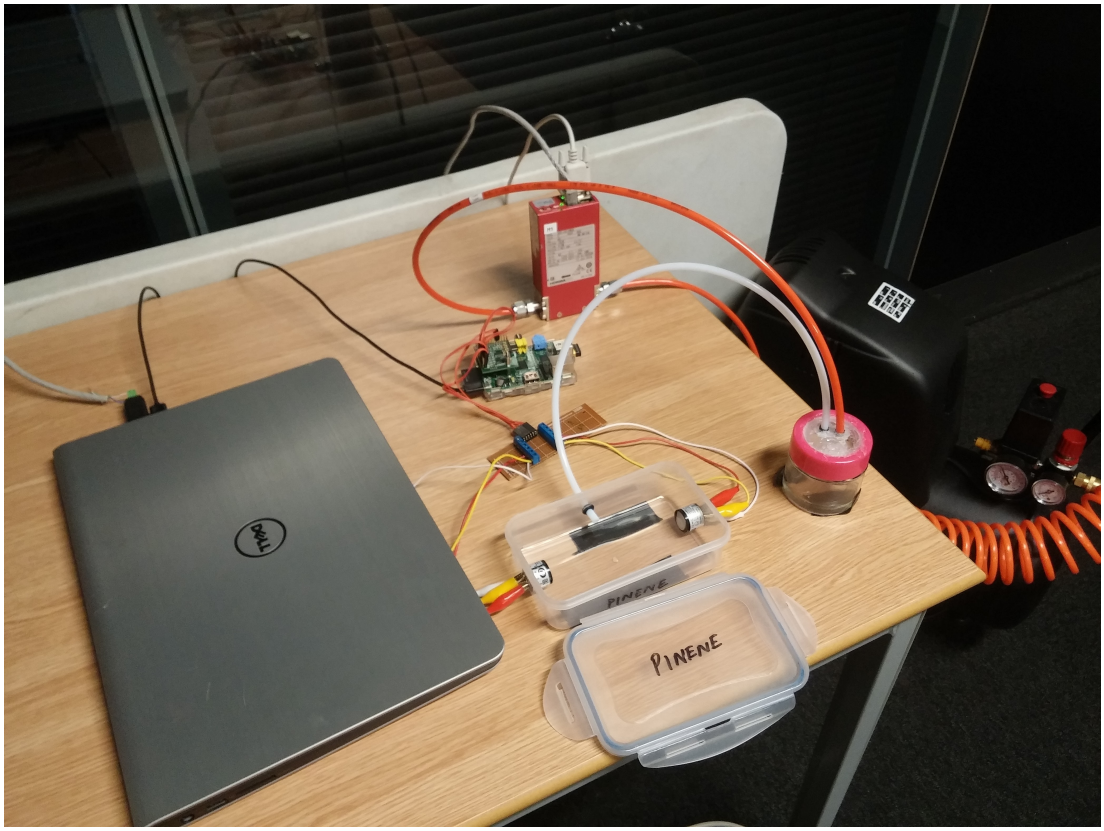


Figure 5.3: Picture of Olfactometer design also showing the gas sensor calibration set up

lemon, pine, and pear/banana respectively, were used in the olfactometer reservoirs. These substances were chosen as they each have distinctive, familiar smells and score low on their hazard profiles which make them useful for olfactory experiments. Each substance scores either a 0 or 1 for their health codes on their respective material safety data sheet where, 0 means it poses no threat and 1 means high exposure could cause minor residual irritation. As a distinction, ethanol (alcohol) scores a 2 on this code, and it is important to note the odours were being used in the gaseous state meaning the exposure is orders of magnitude lower than simple contact with the liquid. The odours are all single molecule compounds and were purchased from pharmaceutical companies at relatively low cost (approximately 35 GBP for 1 litre at 99.5% purity). The compounds were delivered and stored in brown-stained glass bottles and transferred to the olfactometer reservoirs on use.

One crucial point to using this type of set up is that it is entirely dependent on the source of the odour being the same concentration at all times. In order to maintain consistent delivery of odours, the headspace of volatile odour has to stay constant at the same concentration, since every

displacement of air that is delivered to the user will be a small proportion of this concentration. This will create a dilution effect which will then temporarily lower the concentration of the headspace. Subsequent deliveries will drop in accuracy due to this dilution if the headspace is not allowed to return to its original state. To make sure that the saturation point had been reached for later measurements, the recovery times were measured to indicate how long to wait before each new displacement.

5.2 Vapour pressure

Vapour pressures describes the pressure of the gaseous constituent of the compound (in thermodynamic equilibrium) with its condensed phase, either liquid or solid, within a closed system. Naturally the vapour pressure of a substance increases as a function of temperature since the molecules have more energy to overcome intermolecular forces present at liquid/gas phase, when heated. When a liquid is in a open system, i.e. not sealed, the molecules vaporise from the surface of the liquid layer. When the vapour pressure matches its surrounding atmospheric pressure, the bulk of molecules are able to vaporise and expand freely, and this is the point at which the substance boils. The temperature at which this happens is thus the boiling point for the given substance [131]. The vapour pressure also remains independent of the amount of liquid/solid substance present. Additionally, Raoult's law allows us to make approximations for gaseous mixture pressures or concentrations when more than one compound is in the liquid phase. It states that the vapour pressure will be the sum of the constituent compounds relative to the mole fraction i.e. the gaseous partial pressures will be proportional to the total amount in liquid/solid form:

$$p_{\text{total}} = \sum_i p_{\text{i}} x_{\text{i}} \tag{5.1}$$

where, p_{total} refers to the total vapour pressure, p_i and x_i refer to each of the partial pressures and mole fractions respectively.

When a liquid is left in a closed, rigid system, an equilibrium is formed between its liquid or solid phase and its gas phase. The rate of vaporisation (from solid/liquid to gas) reaches the rate of condensation (from gas to solid/liquid) so there is no net transfer of substance between phases. In the case of the olfactometer reservoir, it is assumed this equilibrium has been reached before each emission. When this equilibrium is reached there is a saturation of the headspace with volatile odour. Le Chatelier's principle states that when a system in equilibrium is subjected to a change in concentration, temperature, pressure or volume, the system adjusts itself to counteract the effect of the applied change, such that it is nullified [131]. The olfactometer reservoir

and its contents, are subject to the same temperature, pressure and volume conditions. The temperature remains at 20°C, the pressure of the headspace matches the standard atmospheric pressure 100kPa, and the volume remains fixed since the vessel is a rigid shape. As a result, if the concentration of the headspace is lowered via an emission of that odour air, the system equilibrium will thus shift to replace that gaseous odour. During emission the equilibrium is broken but immediately after the DMFC valve closes, a sealed system is recreated and since the initial other conditions do not change, the system will move to restore the initial conditions pre-emission thus restoring the initial headspace concentration and removing the dilution effect mentioned above. This process is described as saturation from here onwards, referring to the maximum gaseous substance concentration the system can reach under these conditions.

Knowing this, the rate of headspace saturation for can be measured and thus a general rate of saturation in a time per volume per surface area (cm.s^{-1}) can be determined (see below). This is applicable only for substances at a given vapour pressure and at a given temperature. To test for this, the procedure outlined in Section 5.3 was followed.

$$\text{Saturation} = \frac{V}{S} \times t \tag{5.2}$$

where V is the volume of the headspace, S is the surface area of exposed odourant, and t is the time in seconds for the recovery to complete, according to the spectra of timed measurement.

$$\text{Saturation} = \frac{\text{cm}^3}{\text{cm}^2 \times \text{s}} \tag{5.3}$$

Which simplifies to:

$$\text{Saturation} = \frac{\text{cm}}{\text{s}} \text{ or } \text{cm.s}^{-1} \tag{5.4}$$

5.3 Recovery Time Validation

This section describes the validation procedure used ensure the headspace of the odour vessel remains consistently saturated. Saturation rates are measured using infra red spectroscopy techniques.

5.3.1 Materials and Procedure

As discussed previously, infra-red light spectroscopy is an ideal analytical method for classifying organic compounds since molecular bonds vibrate when excited and each bond has a characteristic vibration, ie is excited at a particular wavelength. This makes it a very useful tool

for deciphering what compounds are present. However, it can also be used to tell if a substance is present or not. If a known molecule was placed into a infra-red spectrometer and scanned at known vibrational frequencies, the instrument would show that the molecule is absorbing at those frequencies. In the case of a gaseous odour, it would show that the odour is present, but if the odour was completely removed, it would also confirm this. Bearing this in mind, a vessel was designed with the intention of putting a liquid odour in, allowing it to fully saturate the headspace (since the vessel would be sealed). The headspace was then scanned initially, purged, then again continuously scanned at timed intervals until it reached its initial saturated state. This procedure was followed to measure recovery times for all 3 volatile odours. Figure 5.6 shows the characteristic bond on the respective chemical structures of the compound. These bonds were chosen since they're each unique classifiers in their respective cases (though any bonds that that absrob and vibrate would show similar intensities over time).

A vessel was built to measure the time to reach saturation within a fixed volume (see Figure 5.5). The vessel consisted of an airtight resealable polyethylene box, dimensions: 5cm x 9cm x 12cm, with 2cm x 4cm window holes cut out of parallel sides and covered with NaCl salt slides. The box was placed inside a JASCO 4200 FT-IR infra-red spectrometer such that the box slides aligned with the instrument laser 1.5cm from the base of the box. The slides created a pathway and allowed the infra-red laser to penetrate the headspace of the box and reach the instrument detector. Inlet and outlet holes were drilled in perpendicular sides to the slide sides. The holes then had PTFE tubing threaded 1cm into them. A picture of the box is shown in Figure 5.4. The same three substances were used for this procedure: citral, α-pinene and isoamyl acetate. 4cm^3 of the smell was auto-pipetted into a small tray which fit the base surface area, such that the base was completely covered. The box was sealed and left to allow the odour to vapourise and reach equilibrium for 24 hours. The FT-IR instrument was set to scan the headspace of the box at wavelengths between 650cm^{-1} to 4000cm^{-1} at every 1cm^{-1} per time period. The time period varied per substance: 15 seconds was used for isoamyl acetate and α-pinene and 60 seconds was used for citral since it had a much smaller vapour pressure and so it was expected to take much longer. The temperature and pressure conditions used for the experiments were 293K and 101kPa, respectively. After an initial baseline was recorded, the box was purged with nitrogen gas to clear the headspace, for five minutes, then allowed to re-saturate.

5.3.2 Results

Figure 5.7 show the results of three different substances that were measured over time using the IR spectrometer. For each molecule, a characteristic bond vibration, specific to the molecule, was monitored over time to see the change in transmittance (%T) of light allowed through (see

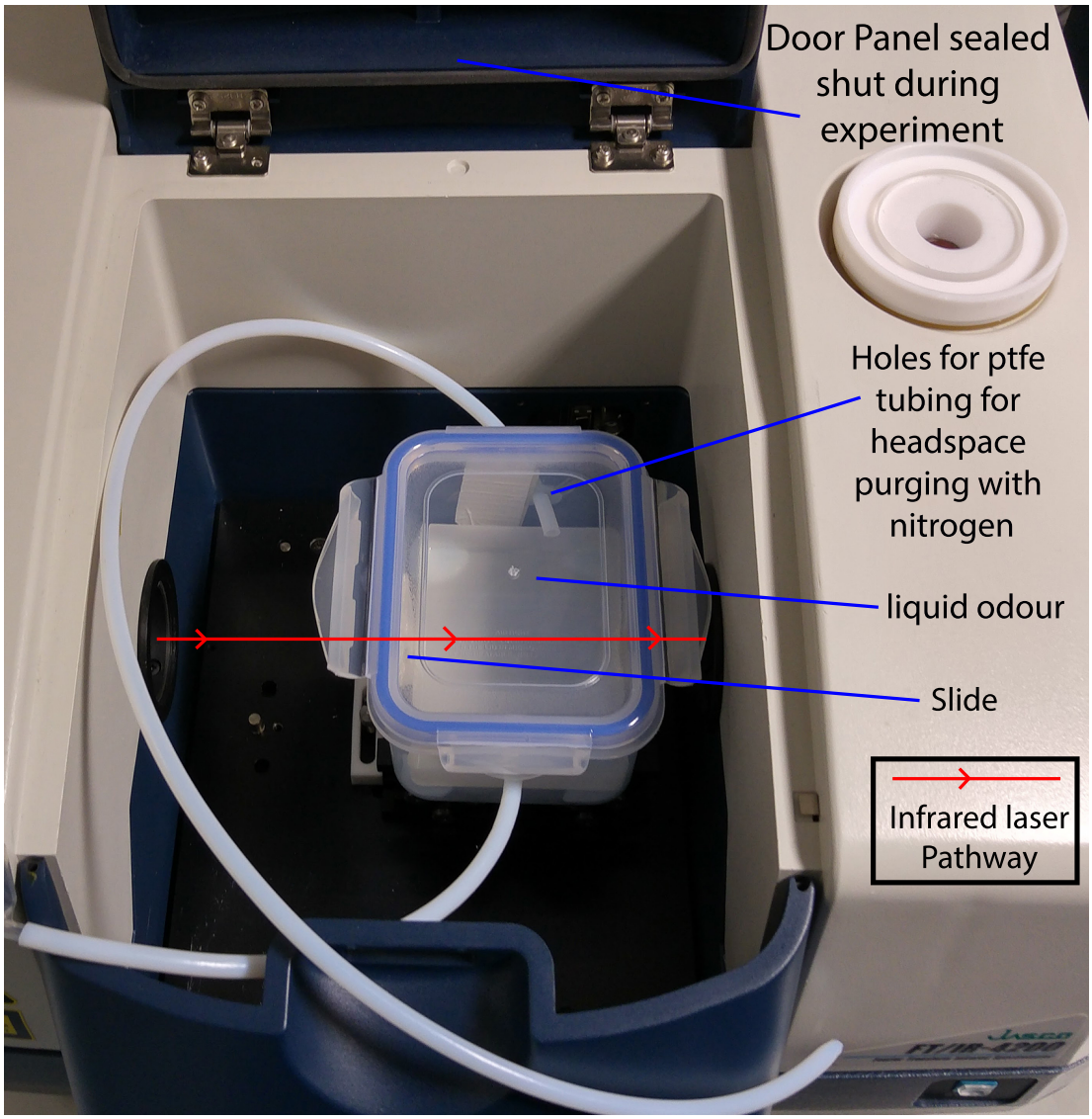


Figure 5.4: Picture of vessel for measurement of headspace saturation mounted in the infra-red spectrometer. The infra-red light is released from an emitter on the left, travels through two slides on the box sides and reaches the detector on the right as indicated by the laser pathway.

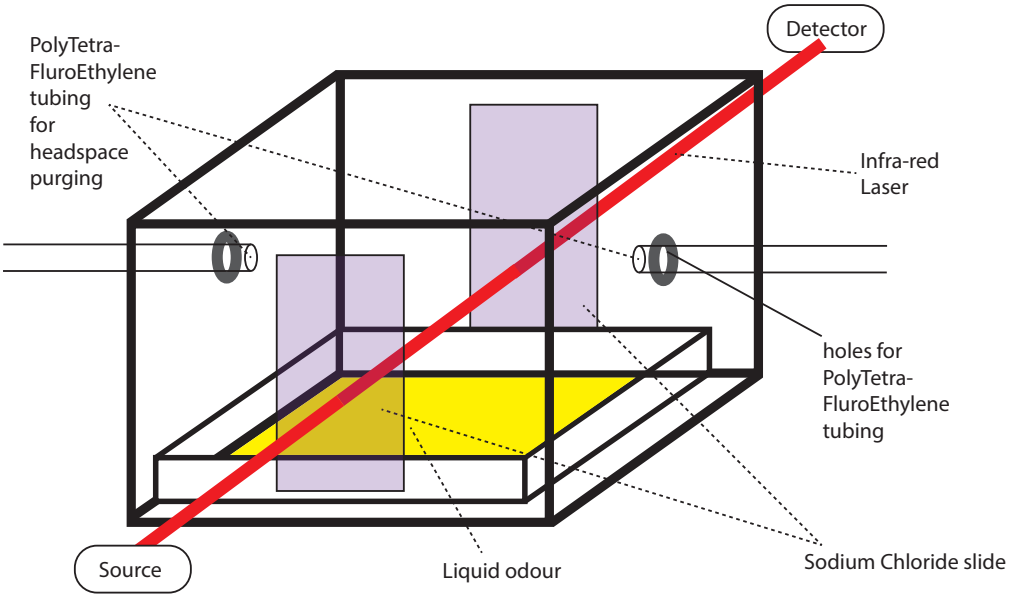


Figure 5.5: Diagram of vessel for measurement of headspace saturation mounted in the infra-red spectrometer. The infra-red light is released from an emitter on the left, travels through two slides on the box sides and reaches the detector on the right as indicated by the laser pathway.

figure 5.5). The broad troughs or peaks refer to the time where the box went from saturated with volatile compound to unsaturated after being purged with pure nitrogen gas, and then back to saturated. Figure 5.6 shows the characteristic bond on the respective chemical structures of the compound used for the plots.

5.3.3 Discussion

Figure 5.6 states the characteristic bond vibration used to characterise the compound and figure 5.7 shows the recovery time graphs. Each point is one scan of every 1cm^{-1} wavelength between 650cm^{-1} to 4000cm^{-1}. In each case we notice two distinct levels of transmittance. This illustrates the difference between the headspace in the two states: the initial and final saturation positions, and the sudden peak or trough completely purged position. In each case the purging nitrogen was left on for approximately five minutes and then turned off. We count the recovery time from the last point/scan before the subsequent drop or rise indicating the headspace refilling with volatile odour. For α-pinene, a slight discrepancy can be seen between the start and end points, with the end point being lower but also that the transmittance begins at over 100%. It is not uncommon to see a shift in transmittance over several minutes due to the fluctuations in the probe sensor temperature. For correct operation, the probe must be regularly topped up with

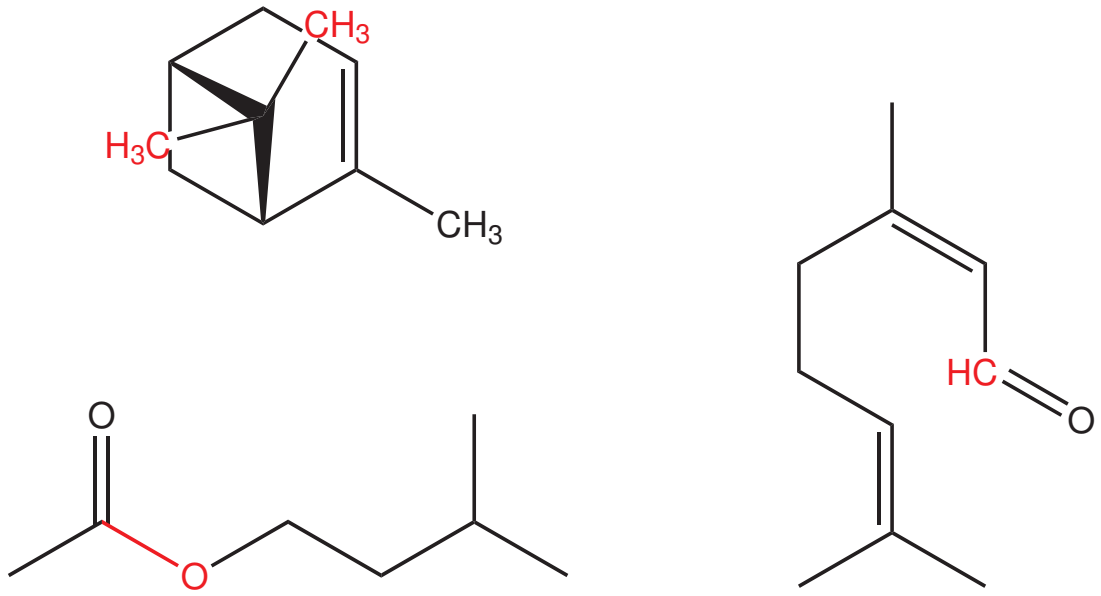
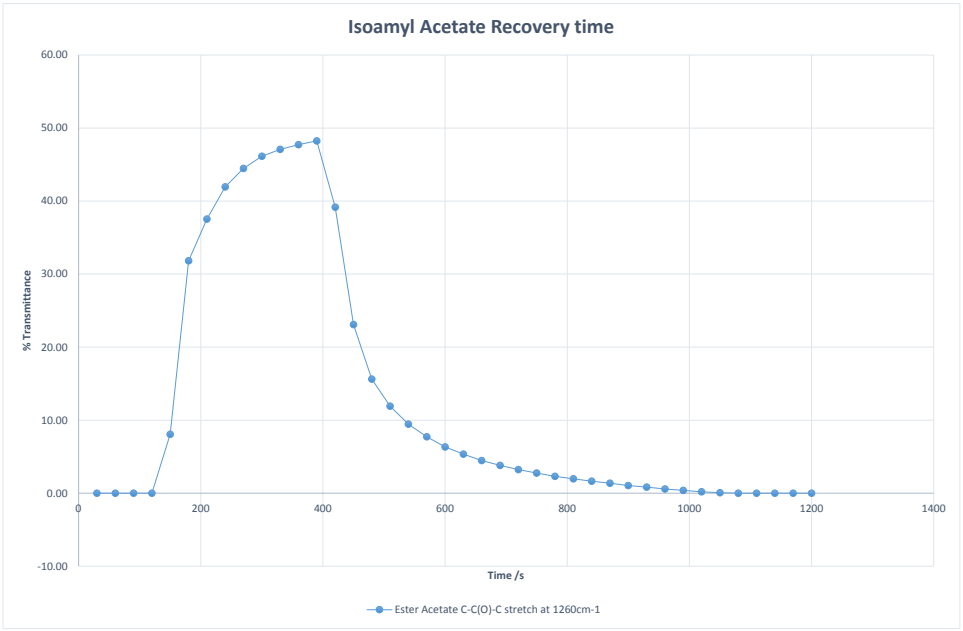
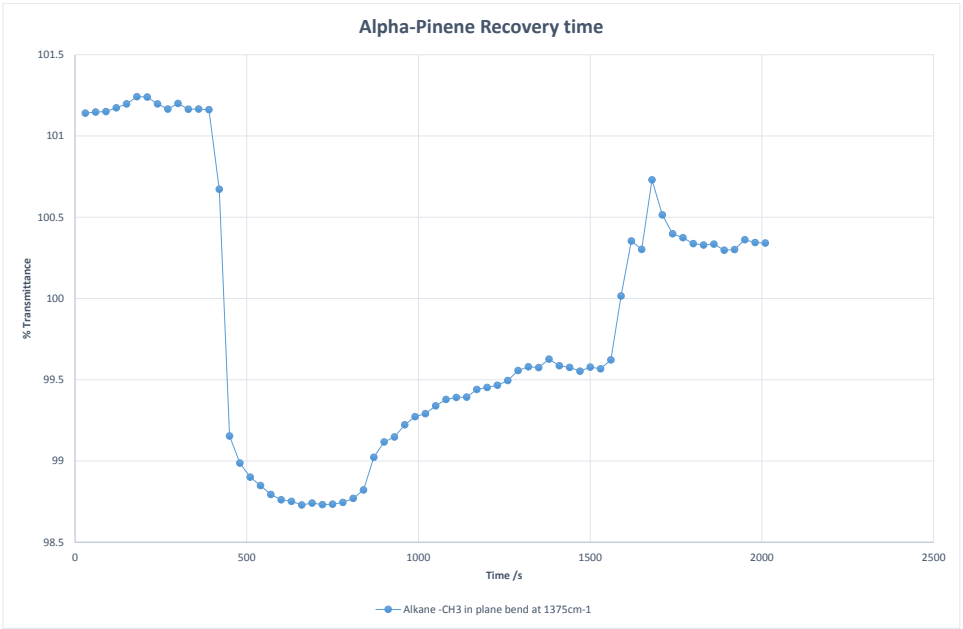


Figure 5.6: Chemical structures of the compounds used along with the respective bond tracked for the headspace measurement. On the top is α-pinene with the -CH3 bond highlighted (Alkane in plane bend at 1375 cm^{-1} bond scanned). On the bottom is isoamyl acetate with the acetate end of an Ester bond highlighted (Ester (Acetate) C-C(O)-C bend at 1260 cm^{-1} bond scanned), and the strcuture on the right is citral with the -CH in the aldehyde bond highlighted (Aldehyde -CH stretch at 2750 cm^{-1} bond scanned).

(a) IsoAmyl Acetate Recovery time



(b) α-Pinene Recovery time



(c) Citral Recovery time

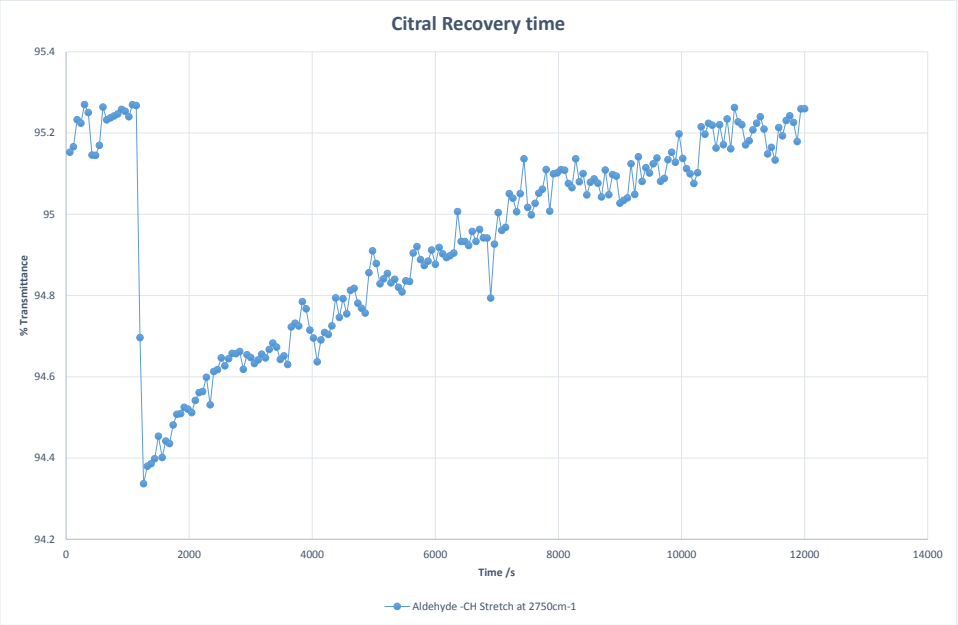


Figure 5.7: Graphs of IsoAmyl Acetate (a), α-Pinene (b) and Citral (c), over time, starting at saturation, being purged and allowed to re-saturate over time. Each of the three graphs show the measurement data obtained from the IR spectrometer instrument. In each case, an initial equilibrium transmittance level (unique to each compound) is shown followed by an increase for Isoamyl acetate and a decrease for α pinene and citral as the headspace is purged using nitrogen gas. This is followed by the refilling of the headspace of the box with vaporous odour as the liquid odour naturally vaporises, eventually reaching the initial saturation level.

liquid nitrogen to keep it cool.

Comparing the recovery times, i.e. time taken to saturate the 540mL headspace of the box to equilibrium, to the respective vapour pressures of the chemical compounds, it is clear that there is an obvious relationship. The higher the vapour pressure, the quicker the headspace saturates. This is to be expected since a higher vapour pressure means a volatile species vapourises more readily at a given temperature since, as discussed previously, the closer the vapour pressure is to the external pressure, in this case 100kPa, the closer it is to its boiling point. However, by recording the recovery times the time taken for this happen can be quantified. This in turn correlates with vapour pressures in general at this temperature and from which again a linear relationship can be seen.

From the datapoints obtained from the spectra it was deduced it takes isoamyl acetate, α-pinene, and citral 630 seconds, 870 seconds and 9060 seconds, respectively to recover 540mL of headspace (to the nearest 10 seconds). By dividing this down to find a rate and plotting against their vapour pressures (4, 3, and 0.22 mmHg respectively [132]), a positive correlation can be seen. Vapour pressures are typically described in mmHg, a imperial measurement of pressure. The conversion from mmHg to Pa is shown below. For reference atmospheric pressure is 101.325kPa or 760 mmHg.

$$\text{Pressure in Pascals} = \text{mmHg x } 133.322 \tag{5.5}$$

Using Equation (5.2), we can do this for the 3 odours:

$$\text{IsoAmyl Acetate saturation rate} = \frac{540\text{cm}^3}{108\text{cm}^2 \times 630\text{s}} = 0.00794 \text{ cm.s}^{-1} \text{ 3 s.f.} \tag{5.6}$$

$$\alpha\text{-Pinene saturation rate} = \frac{540\text{cm}^3}{108\text{cm}^2 \times 870\text{s}} = 0.00575 \text{ cm.s}^{-1} \text{ 3 s.f.} \tag{5.7}$$

$$\text{Citral saturation rate} = \frac{540\text{cm}^3}{108\text{cm}^2 \times 9060\text{s}} = 0.000552 \text{ cm.s}^{-1} \text{ 3 s.f.} \tag{5.8}$$

These rates effectively show how much volume will be replaced per second for every cm^2 of surface area is exposed in the a given vessel containing odour.

The relationship drawn between the recorded recovery time against the specific vapour pressure for the given substance is illustrated in Figure 5.8. A positive linear relationship can be seen between the recovery rate and the vapour pressure, which again, shows evidence about the fact that substances vaporise quicker as they reach the their local atmospheric pressure. This is

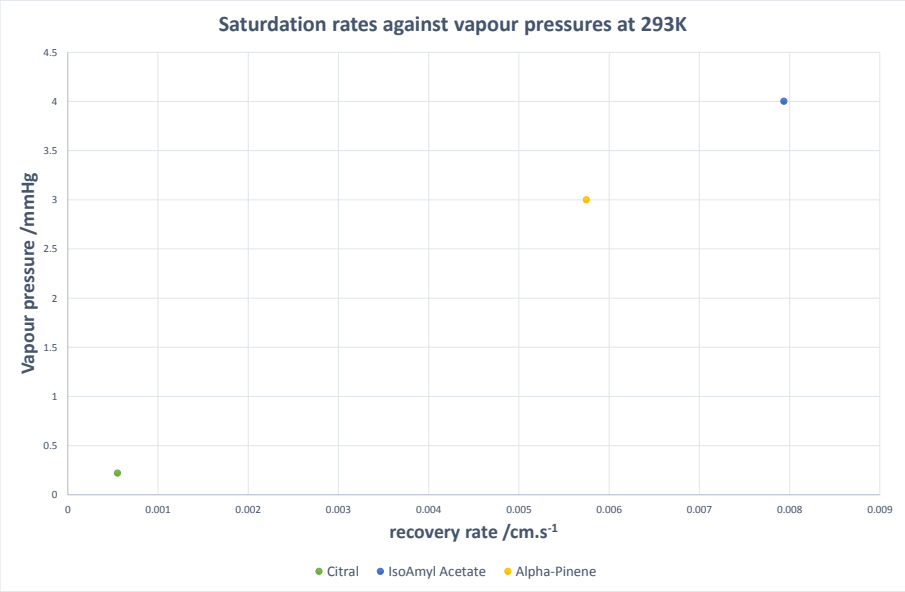


Figure 5.8: Graph showing the positive relationship between the vapour pressure of a substance against its measured saturation recovery time

important as it confirms the amount of time needed for recovery between displacements of a given volume when using the presented olfactometer setup. This will also remain true for other compounds with different vapour pressures. It should be stated that this procedure can easily be replicated for virtually any other volatile compound (odorous or not) so these rates can be applied to other smells, with specific vapour pressure values readily being available in scientific literature. As discussed in previous chapters, the human nose requires stimuli far less frequently that other senses so having a recovery time between presentations is compatible with this idea. Since the saturation recovery rate is mostly dependent on surface area of the liquid, and volume of headspace to be filled, one could easily change these parameters to maximise their utility i.e. having a very wide and long, but short vessel, speeds up the effective rate since the ratio of surface area volume is increased.

5.4 PID Sensor Array Design and Olfactometer Calibration

In order to accurately quantify the emission from the olfactometer's air flow output, it was mandatory to calibrate the emitted concentration of the odour displayed for a range of flow rates. This section discusses this process and introduces a repeatable process to calibrate ppm level coherency between target and actual output concentrations.

5.4.1 Materials and Procedure

As discussed previously, the olfactomter design was based on a sealed design meaning the only real force of displacement was via the air supply which was controlled by the DMFC. Thus a linear proportional response between the flow of air and the amount of odour emitted was expected. The experimental set up involved testing a range of flow rates at different timed intervals to produce specified volumes of air displacements.

Two photo-ionisation detector (PID) cells were mounted on opposite sides within a 500mL airtight box, facing each other. The outlet from the reservoir was mounted perpendicular and between the two sensors and protruded 2cm inside the box. A 500mL box was chosen, as the average tidal volume of a human breath is around 500mL [133] and as such any measurements in ppm could be directly applied to experiments in which the smells are presented to users either through a nasal cannula or directly around nose. Specific displacements, in mL, of odour were emitted from the outlet and into the box by varying the time of the burst and/or by adjusting the percentage opening solenoid valve in the DMFC. This gave a reading of volume in mL since it is a function of the 1L per minute output. Displacements of air were worked out systematically using either 5% or 10% increments on the DMFC, depending on the emerging trend of the data, all the way up to 100%. One second timed displacements were used, followed by 2 and 3 seconds, once a set of percentage openings was completed. This effectively doubled and tripled the volumes from the 1 second runs.

Photoionisation cells were chosen for the gas detection in this custom sensor array setup, due to the reasons discussed in 3.3.1. When compared to alternative gas sensors, photoionisation detectors show to be the most robust not suffering from humidity drift as is the case with metal oxide sensors, while providing consistently reliable readings, having a small form factor and, being relatively energy efficient. The photo-ionisation array setup consisted of using Alphasense Photo-ionisation pellistor cells, which had an isobutylene (the calibration gas for the sensor) detection range of 5ppb-50ppm. All other substances have a measurement relative to this initial calibration and are accounted for by multiplying by the relevant correction factor which can either be looked up on a data-sheet or worked out manually using known concentration

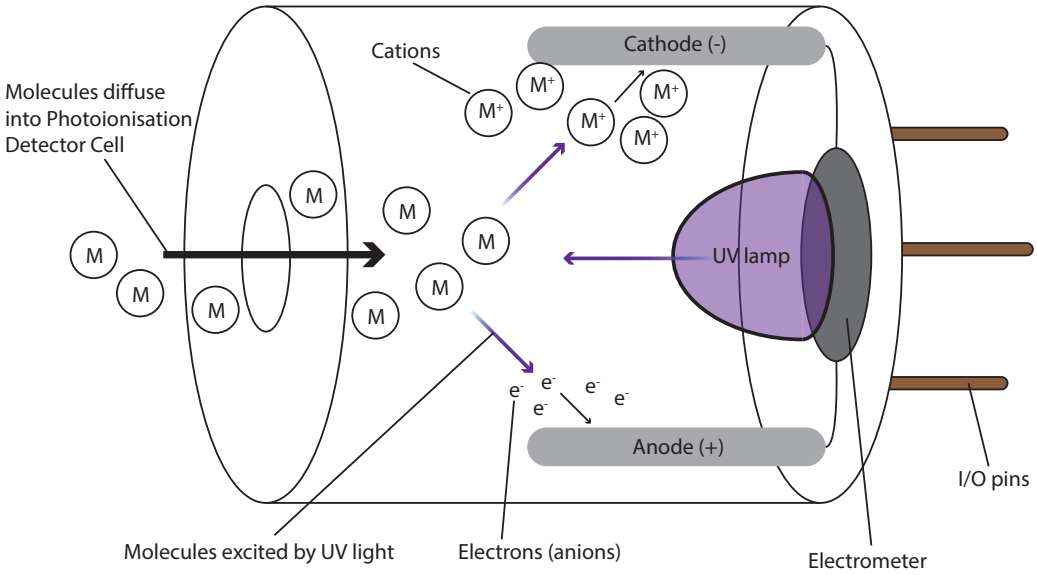


Figure 5.9: Diagram of photoionisation detector cell. Molecules diffuse through the top of the cell and absorb high energy UV light from the lamp. This results in an excitation which causes the molecule to lose it's outermost electron (specifically one of the atoms in the molecules) forming a molecular ion, a cation.

calibrants. The PID cell was wired to a Raspberry Pi Model B microcomputer with an 18-bit resolution analogue to digital converter (ADC) hat module (from ABElectronics.co.uk), and was powered by a USB 10000 mAh battery. The sensor outputted as a voltage and these were recorded using the ADC and a Python script (see Appendix).

The PID cell works by producing UV spectrum wavelength light within the space of the cell via a lamp rated at 10.6 eV which is a standard rating used in PIDs. As discussed in earlier chapters, this was chosen over higher rated lamps at 11.7eV since they result in more compounds being ionised, giving overall lower detectable results along with an increase in noise. The UV light then ionises (removes an electron from the molecule via excitation by absorbing the UV light) any airborne molecules which require 10.6 eV or less to ionise. The remaining charged particles then make contact with charged plates (anode/cathode) and produce a charge which is proportional to the concentration of molecules present, as illustrated in Figure 5.9.

The PID cell had to be initially calibrated using a 10ppm known standard of isobutylene. As per the manufacturers instructions, the isobutylene gas was vented directly on to PID cell for 10 seconds to completely saturate the sensing area with it. A reading was then taken and plotted against the known concentration to give a benchmark graph with 2 points: isobutylene at 10ppm, and background noise when nothing is present. Figure 5.10 shows the graph for the

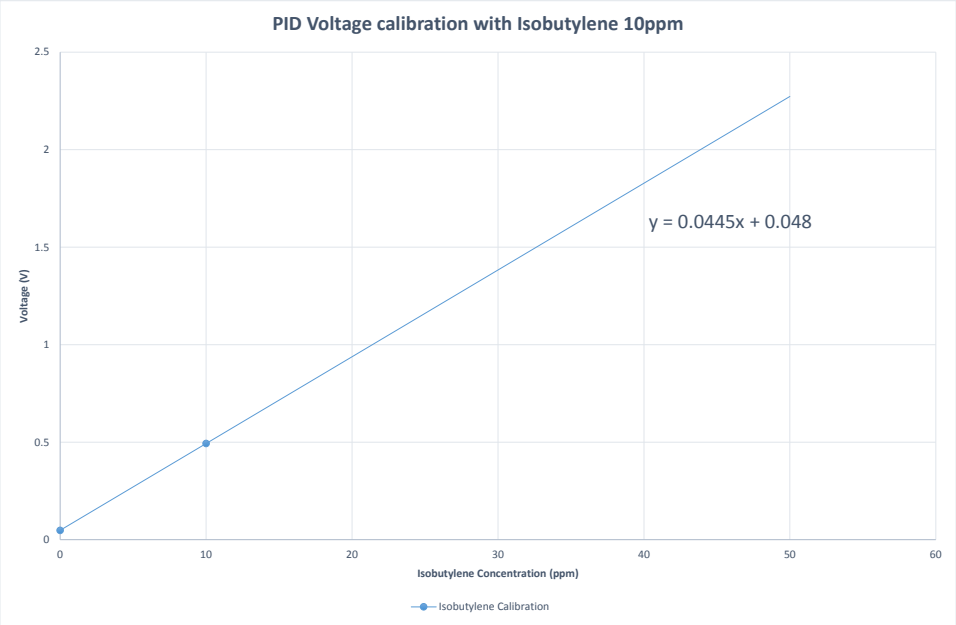


Figure 5.10: Initial calibration graph of Isobutylene 10ppm gas against measured voltage from photo ionisation detector.

initial calibration graph.

After a burst of odour was outputted to the box, time was allowed to let the two cells reach the same value (in volts later converted to ppm) to show that the smell had diffused equally in the box and that the final reading was used as the measurement for that given mL displacement. These final readings were than replicated five times, averaged and plotted against their respective mL displacements. This procedure was repeated for each of the three odours.

5.4.2 Results

Measurements for other compounds are calculated using the sensors response relative to the isobutylene calibrant. These relative sensitivity factors are either provided by manufacturers of the cell or can be manually calculated by exposing the sensor to 2+ known concentrations and extrapolating, and again comparing to calibrant values.

Figure 5.11 shows the graphs for each of the three odours with their specific airflows, in mL, plotted against their respective concentration measurements as outputted by the PIDs (after

all necessary conversions). The relative sensitivites for isoamyl acetate, α-pinene, and citral were 1.6, 0.3 and 1, respectively. This means the upper limit for the sensor for each of these compounds is 80 ppm, 50 ppm and 15 ppm, respectively, after correction. For the α-pinene only a few points could be plotted due to the high sensitivity the PID had to the substance as is indicated by the relative small airflow displacements. This effectively meant that all measurements were inflated which resulted in the upper limit of the sensor being reached far quicker than in comparison to the other substances. The opposite happens with the isoamyl acetate with deflated measurements being corrected to higher concentrations. These are still very high concentrations in terms of perception so there is more than enough range to conduct experiments with.

To plot the experimental data, the percentage points used on the DMFCs had to be converted into volumetric displacements, in mL, and the voltage outputs had to be converted into actual ppm readings:

$$\text{Airflow /mL} = \frac{1000 \text{ mL}}{60 \text{ seconds}} \times \% \text{ setting} \times \text{time /s} \tag{5.9}$$

Using the data from the isobutylene calibration:

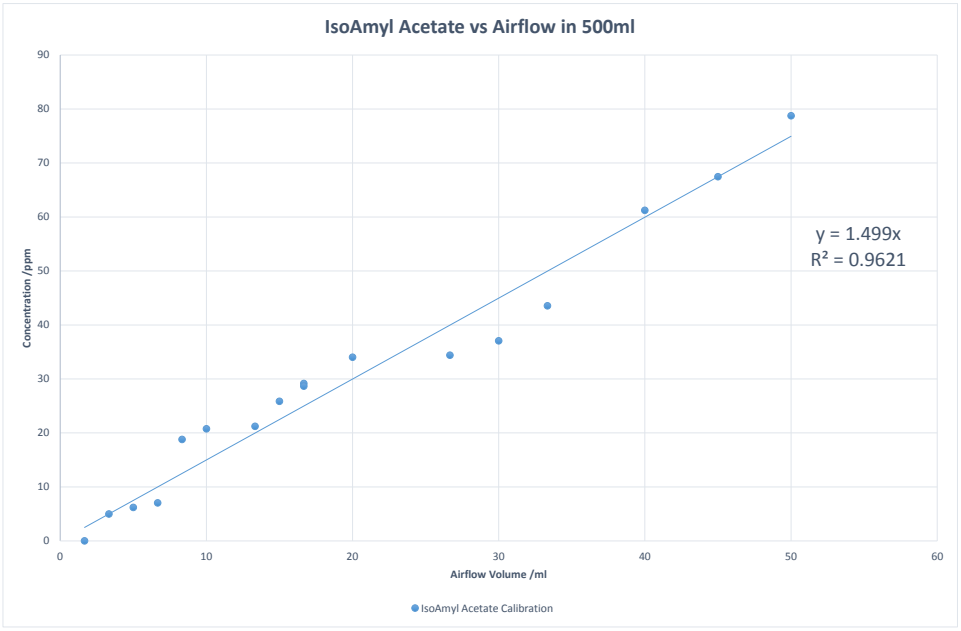
$$\text{Measured concentration /ppm} = \frac{\text{measured voltage - 0.048}}{0.0445} \tag{5.10}$$

$$\text{Corrected Concentration /ppm} = \text{Measured Concentration /ppm} \times \text{Correction factor} \tag{5.11}$$

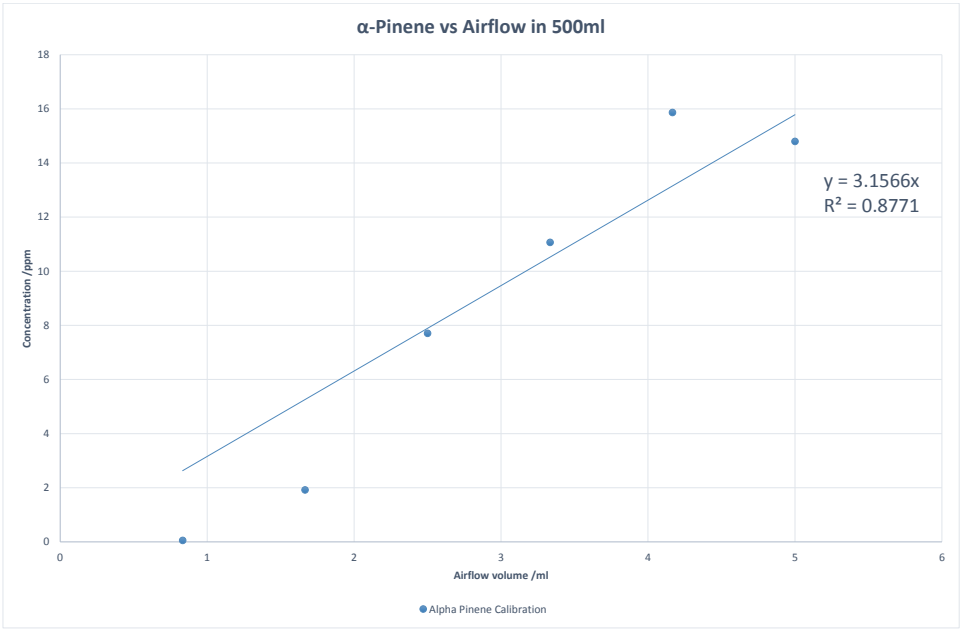
5.4.3 Discussion

These experiments were conducted based on a series of assumptions regarding our odorous compounds and the environment they would be used in. The smells would be used at around standard conditions: 293K (temperature) and 101kPa (pressure). Additionally another condition which isn't considered standard but was kept consistent across the readings was a +50% humidity. This was justified since most experiments are done at around room temperature and standard atmospheric pressure and any variations within a few degrees would most likely be negligible except for very volatile compounds. The independent variables used in this calibration were temperature, pressure, humidity, but mainly the volume of odour outputted (controlled by time and the flowrate) against the sensor array. Conversely, the main dependent variable was the measured response readings from both the PID sensor array and the IR spectrometer.

(a) IsoAmyl Acetate calibration



(b) α-Pinene calibration



(c) Citral calibration

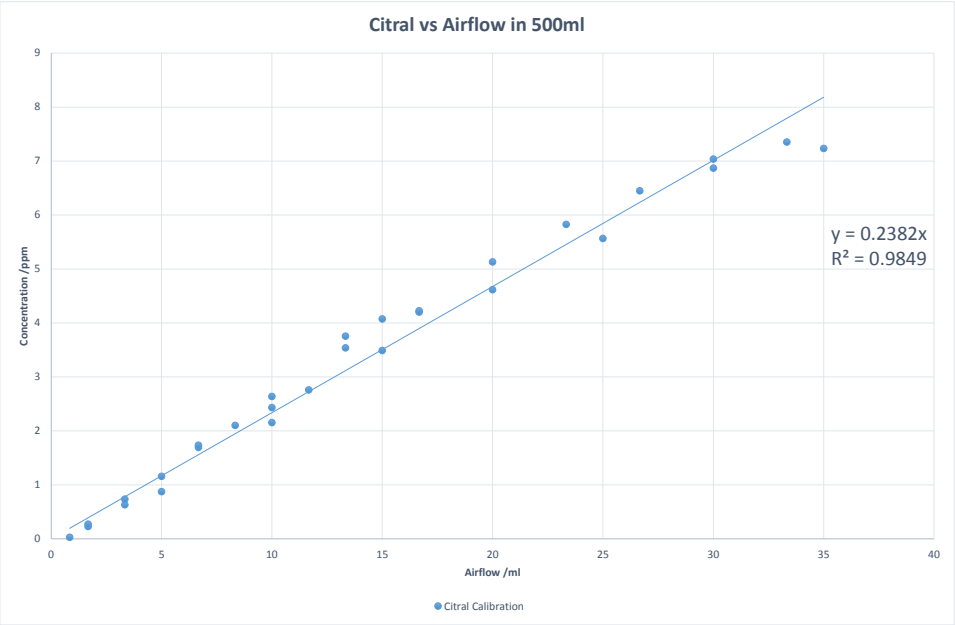


Figure 5.11: Calibration graphs of measured ppm concentrations of isoamyl acetate, α-pinene and citral against headspace volume displacements

In Figure 5.11, plotting the collected data of ppm concentration against the volume displaced shows a linear relationship, as was expected, in all three cases. Each of the graphs can be used to estimate the displacement needed for a given concentration in that range. The PID detection range is from 5ppb to 50ppm but due to the limits of the DMFC the graphs all start around 1ppm. The graphs for α-pinene and isoamyl acetate show values below and above, respectively, this standard range due to their relative sensitivity to the sensor.

The human nose is capable of smelling from the ppb (parts per billion) level upwards [134], however, it is to be noted this is the limit of detection i.e. the absolute minimum amount needed to notice there is an odour present. In typical day to day interactions and VEs, concentrations in the ppm range would typically be seen and thus this calculated range is far more practical. The onset time for the smell to reach the sensor was relatively fast taking just over a second for the smallest airflows (less than 1mL) and reducing as the volume increased. This was seen by the amount of time it took for the PIDs to have a sudden noticeable change in readings.

There are some small limitations which occur due to the limits of the instrumentation. The PID can detect down to the parts per billion level however much like our nose, that is simply the lower limit of detection. When it comes to getting usable data, the readings fluctuate too much at low concentrations (sub 1ppm) to get a discernible fixed reading. The other limitations are with DMFC valves. Whilst the output of the air is consistently at the right level, to get smaller more accurate displacement of headspace for finer concentration control, higher quality solenoids with less delay are needed which would result in increasingly costlier setups. Certain compounds may have very high sensitivities relative to isobutylene so this can make it difficult to get readings without very concentration control.

In general the three requirements specified at the beginning of the chapter are satisfied. The device created is able to reproduce olfactory stimuli to ppm level accuracy, and with high precision since the validation method proves the same result output will be obtained providing a the appropriate time has been taken for resaturation of the headspace. As stated in the display setup, the total cost of the system would be around 650 GBP, which in comparison to commercial solutions is extremely low cost, but again it should stated that these systems do not offer anywhere near the same level of control of stimuli presentation as this display.

5.4.4 Summary

This chapter outlined a novel attempt at odour delivery by detailing a design of an olfactory display which and is capable of consistently delivering sub-ppm concentrations of volatile odours, as well as incorporating the inclusion of individual properties of VOCs to improve concentration accuracy, namely vapour pressure. An analysis on the rate at which a volatile

odour is replenished from its liquid form for a given headspace volume is shown, with a methodology for generalising this result to other VOCs. A simple and repeatable experimental procedure for odour output calibrations is also shown for the device. This olfactometer is used in the next chapter to perform a perceptual calibration using this physical calibration to give discrete concentrations of stimuli.

Chapter 6

Human Olfactory Perception Calibration

This chapter outlines the methodology used to calibrate the odours, discussed in the previous chapter, to appropriate perceptual points for humans, for use in virtual environments. The work presented here produced odour concentration thresholds for the same three odours described in the previous chapter. These thresholds were then used in further work presented in the next chapter.

6.1 Smell Variability and Generalisable Odour Thresholds

As discussed in section 2.4 there are numerous factors which contribute to the high variation of smelling ability sensitivity across individuals, thus it becomes difficult to identify generalisable points, where it can be said the majority of people are able to smell something. Threshold testing allows us to find the smell thresholds for particular odours on an individual person basis and on a more general level allows categorising a person's smelling ability. While conducting this threshold testing on participants for an olfactory based experiment would give results with high accuracy due to the tests' great efficacy, it quickly becomes impractical for large sample population sizes due to its very time consuming nature and physical cost.

This then highlights the need for a standardised approach to smell presentation such that any odour perception is consistent. One method of achieving this consistently would be to normalise smell presentation to account for these differences. It would be expected that these thresholds would move towards the true threshold point as the sample population increased and the average would becomes increasingly representative of everyone's smelling ability.

When using odours in virtual environments, the goal is to be able to mimic a set of real

world scenario conditions exactly, but there is no single set of applicable parameters for this. Even when the scenario is discretised in a computational fluid dynamic simulation, it becomes increasingly complex to match exact odour concentrations due to the large amount of fluctuations caused by thermal and dynamic body convections, when mapping particles in a model. Instead it becomes far more logical to have ranges or fixed perceptual threshold concentration levels which constitute what would be considered e.g. a high or low intensity, for an average person, and applying further distinctions when necessary. These concentration ranges or thresholds could then be used as generic intensities for further study in experiments or experiences where it could be said that across a general population, a high proportion of people would universally consider the low concentration threshold, a low intensity smell, and a high concentration threshold a high intensity smell. Naturally these thresholds would need to be worked out on a per odour basis. This approach is sensible as olfactory perception variability is inherently a normal distribution as demonstrated earlier in Figure 2.3, so any threshold calculated, for a sample population for a specific smell, would essentially be a close estimate of the mean threshold i.e. the centre of a given bell curve: a perceptual point where the majority of people can smell at. It would be expected that these thresholds would move towards a true universal threshold point as the sample population increased and the average would becomes increasingly representative of everyone's smelling ability. One significant benefit of this approach provides a way of bypassing the need for vast amounts of computing power required to run a computationally expensive computational fluid dynamic simulation. Calculated thresholds could also be used in a manner which would consider them comparable across different odours, since a low/high point for two different odours would be perceived as low/high for each respective odour.

Bearing these points in mind, a procedure was designed which would allow the calculation of two generalisable odour thresholds (designated high and low) for the three odours presented in the previous chapter. While in this particular case the olfactometer built and calibrated in the previous chapter is used for this experiment, it is not strictly required to replicate the steps in this chapter. The only real requirement is having the ability to present odours consistently and accurately at specific concentrations starting at 1ppm or lower in an environment with a temperature of 293K, an atmospheric pressure 101kPa and ¿50% humidity. Providing these main conditions are met, this procedure can be translated across for any desired odour. The same three odours from the previous chapter were used since these conditions could be met for them.

6.2 Experimental Design

The following sections outlines details the experimental design, the materials and participants, but also describes the procedure in full showing the specific parameters used for presentation of the stimuli.

The method used here employed the use of a psychophysical test to calculate perceptual points. A pair of stimuli are presented to participants and one is changed over a series of trials. When the participant notices that the two are no longer perceptually, the value of the independent stimuli is noted. However this process would be repeated for several participants and in this particular method, the point where 75% of people reliably identify the change, a point of 'Just Noticeable Difference' (JND) has been identified and the value is designated JND_x.

This study used a 2 Alternate Forced Choice (2AFC) test [135] which consisted of pairwise comparisons of different concentrations of the same odour, which were presented to the user automatically.

In the context of this work, the initial Just Noticeable Difference, JND_1, expresses the first subjective point at which humans can convincingly discriminate between a starting or 'pedestal' concentration presentation and a higher concentration presentation of the same odour. The pedestal concentration is the minimum reliable that can be outputted from the olfactometer, for a given odour. This was taken as 1ppm for the three smells used.

JND_2 expresses the first subjective point at which humans can convincingly discriminate between JND_1 and a higher concentration presentation of the same odour. The previous JND step is used as the new pedestal when working out consecutive JNDs for a given odour.

6.2.1 Procedure

Before any experiments took place, participants were asked if they had normal or corrected to normal vision and smell. All twenty participants confirmed this, and were then asked to sign a consent form, after reading through a provided participant information leaflet.

Following informed consent, participants were asked to sit in a chair, wear ear defenders, place their heads on to a chin rest, and look ahead to the display in front of them. The ear defenders served the purpose of removing any external audio distractions but also blocking any audio cues potentially given from the olfactometer that may influence when odours were to be expected. They were instructed that they would be presented with two different concentrations of the same odour consecutively with two slides which would indicate when to smell/expect the odour, for several trials. The experiment then ran through the steps of Figure 6.1. During the 'Participant Response Duration' (PRD), participants marked on a form, for that trial, which of

the two stimuli they thought smelled more intense/stronger by marking a checkbox with an 'X'. A copy of the Participant sheet can be found in the Appendix. The whole procedure was then repeated for twenty trials with a three minute rest break after ten trial before continuing on to the final ten.

For every trial, an olfactory stimulus was presented, followed by a five second 'Inter-Stimulus Interval' (ISI), then followed by the second olfactory stimulus. Figure 6.1 shows a diagram of a single trial of the experiment. The 'Stimulus Exposure Duration' (SED) for both the first and second presentations were three seconds. The SED was essentially a three second window in which odour bursts of up to 3 seconds could be presented. The remaining time between after the second presentation and the next trial, the PRD, was twenty seconds. The display provided a visual cue for when odours were to be expected for both SEDs. The display was cued to show a grey slide with a '1' in tandem with the first odour presentation (SED_1) and a grey slide with a '2' with the second odour presentation (SED_2). Grey slides were used to avoid any possible colour association biases when smelling the odours. The slide changed to a black slide for five second ITI between these two slides.

[125] noticed correlated activity in the piriform cortex when sniffing as frequently as every eight seconds or 0.125Hz, during a study involving fMRI scans on peoples heads while they were presented with odours. Intervals shorter than this resulted in olfactory fatigue, in which participants would tire themselves out from constant sniffing. Bearing this in mind, the ISI time was set for five seconds, since this combined with the SED of three seconds would result in a minimum eight seconds between sniffs. This then both gave the participant enough time to recover from the first stimulus and prepare for the next one, while being short enough that the memory of the first stimulus was still present in their mind long enough for them to make a subjective choice between the two. Figure 6.1 shows a digram of a single trial in procedure.

The trials started with a pedestal concentration, C_0. For each trial, a pedestal concentration was presented with another higher concentration, C_n. As participants progressed through each trail, C would increase in concentration by a predetermined uniform amount, d. The ordering was randomised for C_0 and C_n per trial, however, the trials themselves proceeded sequentially such the in each trial the concentration of C_n was never higher on a previous trial. This was done to combat any olfactory habituation effects since being exposed to higher concentrations inhibits the noses ability to discern lower concentrations causing nasal habituation, as was described in section 2.1.2. Starting at trial one, C_0 and C_1 would both have the same concentration. For trial two, C_0 would again be the pedestal, while C_2 would be the C_{0+d}.

An initial pilot study with three participants was undertaken, using the procedure outlined above, to calculate sensible ds for the full experiment by using the results as a rough indicator of where the first JND concentration would fall. For IsoAmyl Acetate, the minimum 1% increment

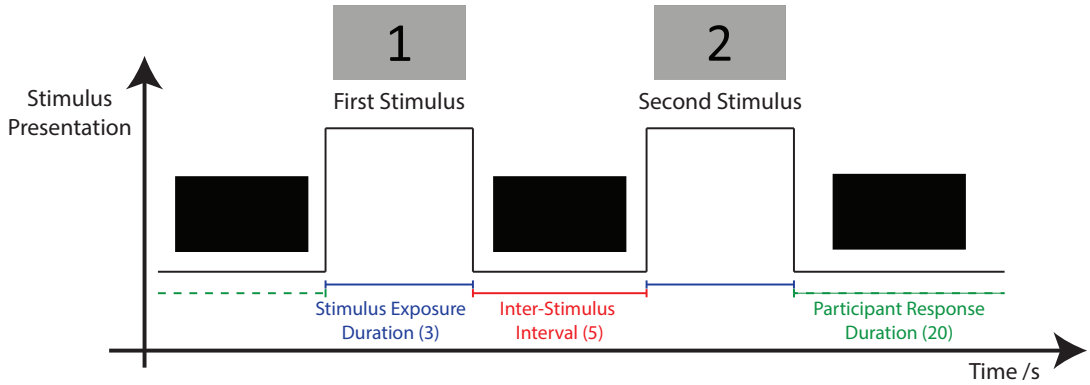


Figure 6.1: Illustration of a single trial of the experimental procedure showing each stage with their receptive visual cues. Grey slides were used to avoid any possible colour association biases when smelling the odours. The slide changed to a black slide for five second ITI between these two slides.

that could be outputted from the olfactometer, where d = 0.2ppm, was found to be sufficient and showed a primary JND relatively early in trials. For α-Pinene, initially d = 0.6ppm since this corresponded to a 1% increase in flowrate for a 1 second exposure i.e. the minimum possible increment available from the olfactometer. However, it became clear that these particular increases in concentration were insufficient to exhibit a JND even after twenty trials. The difference was thus increased based on the initial results (an approximate 3x increase), d = 2ppm, and thus a JND_1 could be calculated for this odour. For Citral, similar to α-Pinene, 1% increments were insufficient (d = 0.04ppm) so were increased by a factor of 5 based of these results such that d = 0.2ppm. It is important to remember that these d values are independent of each odour.

Participants attended experiments in sessions for each odour and JND level, resulting in total of six sessions per person. The participants were each exposed to only one smell on each occasion. The same smell was delivered on the same visit for each of the ten participants (session 1 = IsoAmyl Acetate for JND_1; session 2 = α-Pinene for JND_1 ; session 3 = Citral for JND_1, session 4 = IsoAmyl Acetate for JND_2; session 5 = α-Pinene for JND_2 ; session 6 = Citral for JND_2). Each participant was given an allotted time on a day and, on arrival, proceeded through the twenty (initial ten, three minute break, final ten) trials of odour presentation, after a brief introduction and a read through the procedure leaflet. Each session took no more than thirty minutes, and the room was left to vent for at least 30 minutes between participants. The results from the initial three sessions were used to calculate new pedestals/JND_1 values for the second round of experiments.

Participants

These ten participants were recruited as part of an 'opportunistic/convenience' sample used for this study. The number of participants (n=10), though lower than initially had been planned, was at least consistent with other similar works in this field [126, 136]. Many benefits came from using a convenience sample: it allowed for simple and quick sampling, facilitated data collection which was required for calculation of JND_1 for use in the second part of the study, and was especially helpful for pilot studies and hypothesis generation (observing and calculating out if a JND existed for an odour in a given concentration range). This sampling method can be justified since the criteria being tested (the participants' smelling ability on aggregate) is independent of individual demographic, environmental or personal factors. Overall, this experiment was a preliminary study that provided a proof of concept framework for calculating normalised points of smelling ability across a sample population, so the only real factor which would improve this would be the sample size, not any individual characteristics. The accuracy of the JND values would thus be expected to increase as a function of the sample size. Bearing this in mind, the sample size of ten can be considered relatively small, but again this was a trade-off chosen to allow for a quick validation of the framework but also in the data/result collection. It is important, however, to have a varied sample population such that the end results are more representative of a general human smelling ability as opposed to being skewed towards specific demographics. Bearing these considerations in mind, the participant recruitment was varied to try to encompass as wide a range of demographics as possible. The final participant groups' demographical breakdown can be seen in table 6.1. Participants were characterised by three main criteria: gender, age, and Ethnicity with the corresponding geographical region. These criteria were chosen since they were fixed characteristics associated with the individual participant which have have been shown to be correlated to smelling ability, as discussed in section 2.4. As can be seen from the table, a relatively varied sample of participants was used. None of the participants suffered from an olfactory impairment but if any had, hypothetically, they would not have been allowed to participate in any trials. All Participants were indirectly tested on their smelling ability for the three odours since they were all exposed to concentrated samples of odours at least one week prior to participating, as a priming exercise to make sure they understood what to expect in terms of the character of the smell. During participation, they asked to confirm whether they smelled anything after the first trial of each odour to which all confirmed they could. Participants 1, 2 and 3 were used twice, both in the pilot study and the main experiment.

The same participants were used for all three odours as a means of normalising threshold concentrations for the population across the three smells. Whilst it could be said that perception

Participant	Gender	Age range	Ethnicity/Geographical Region	Smoker?
1	M	20-29	British/Western European	N
2	F	30-39	Italian/Western European	N
3	M	20-29	British/Western European	N
4	M	30-39	Cypriot/Western European	N
5	M	30-39	Chinese/Far East Asian	N
6	M	30-39	Iranian/Middle East Asian	N
7	M	30-39	Indian/South East Asian	N
8	M	20-29	British/Western European	Y
9	M	20-29	Indian/ South East Asian	N
10	F	20-29	British/Western European	N

Table 6.1: Table showing the ten participants' demographics/criteria breakdown. These factors were recorded to make sure the sample used, had variability in it to account for any skewing of results toward specific demographics.

to some of the smells may have been stronger or weaker to the individual, this approach seemed like the most logical in terms of being able to work out comparable JND thresholds across odours.

Materials

Before any experimental work was conducted, the protocol described was formally written up and submitted to the University of Warwick Biomedical & Scientific Research Ethics Committee (BSREC) for to ensure any work would be in accordance with the university ethical guidelines. After formal approval was received, work commenced (Reference: REGO-2017-2041).

The olfactometer designed and built in chapter 5 was used for the presentation of odours in this experiment. The concentrations and respective odour volumes with corresponding olfactometer settings, used in the trials for JND_1 and JND_2 for the three odours, is shown in table 6.2. The specific starting points were based off the results from the initial pilot study.

The ear defenders served the purpose of removing any external audio distractions but also masking any noises given from the olfactometer that may influence when odours were expected.

Participants were sat 183 cm from a television display. The distance calculated using the optimal viewing conditions stated in the ITU-R BT.2022 specification [137], which states a viewing distance of 3.2H for a 1080p screen, where H is the height of the television. The dimensions of the television used here are 102.1cm x 57.2cm [138]. The edge of the table had a square plate which had a chin rest behind it and series of PTFE tubes attached to it pointing upwards in front of the chin rest. The chin rest was attached to a beam which was secured to the

floor so that a participants' nose would sit 10cm above the tubes when sat behind the table and using it.

$$\text{Optimal Viewing Distance} = 3.2 \times H = 3.2 \times 57.2cm = 183.04cm \tag{6.1}$$

In the context of this experiment the main independent variables was the concentration/volume of odour that was presented to participants and the dependent variable was the response given by participants as odours are presented to them, namely which odour presentation is deemed stronger by them, per trial. Other independent variables include all the conditions that were used in calibrating the olfactometer built in Chapter 5, which are inherent in any procedure using the calibrated output.

IsoAmyl Acetate, d = 0.2ppm, JND_1

Trial	Volume of odour /mL	Concentration 'C' /ppm	Olfactomer setting /%	Odour release duration /s
1	0.67	1.00	3.9	1
2	0.80	1.20	4.7	1
3	0.93	1.40	5.5	1
4	1.07	1.60	6.3	1
5	1.20	1.80	7.1	1
6	1.33	2.00	7.8	1
7	1.47	2.20	8.6	1
8	1.60	2.40	9.4	1
9	1.73	2.60	10.2	1
10	1.87	2.80	11.0	1
11	2.00	3.00	11.8	1
12	2.13	3.20	12.6	1
13	2.27	3.40	13.3	1
14	2.40	3.60	14.1	1
15	2.54	3.80	14.9	1
16	2.67	4.00	15.7	1
17	2.80	4.20	16.5	1
18	2.94	4.40	17.3	1
19	3.07	4.60	18.1	1
20	3.20	4.80	18.8	1

IsoAmyl Acetate, d = 0.2ppm, JND_2

Trial	Volume of odour /mL	Concentration 'C' /ppm	Olfactomer setting /%	Odour release duration /s
1	1.25	1.88	7.4	1
2	1.39	2.08	8.2	1
3	1.52	2.28	8.9	1
4	1.65	2.48	9.7	1
5	1.79	2.68	10.5	1
6	1.92	2.88	11.3	1
7	2.05	3.08	12.1	1
8	2.19	3.28	12.9	1
9	2.32	3.48	13.7	1
10	2.45	3.68	14.4	1
11	2.59	3.88	15.2	1
12	2.72	4.08	16.0	1
13	2.86	4.28	16.8	1
14	2.99	4.48	17.6	1
15	3.12	4.68	18.4	1
16	3.26	4.88	19.2	1
17	3.39	5.08	19.9	1
18	3.52	5.28	20.7	1
19	3.66	5.48	21.5	1
20	3.79	5.68	22.3	1

α-Pinene, d = 2ppm, JND_1

Trial	Volume of odour /mL	Concentration 'C' /ppm	Olfactomer setting /%	Odour release duration /s
1	0.32	1.00	1.9	1
2	0.95	3.00	5.6	1
3	1.58	5.00	9.3	1
4	2.22	7.00	13.0	1
5	2.85	9.00	16.8	1
6	3.48	11.00	20.5	1
7	4.12	13.00	24.2	1
8	4.75	15.00	28.0	1
9	5.39	17.00	31.7	1
10	6.02	19.00	35.4	1
11	6.65	21.00	39.1	1
12	7.29	23.00	42.9	1
13	7.92	25.00	46.6	1
14	8.55	27.00	50.3	1
15	9.19	29.00	54.0	1
16	9.82	31.00	57.8	1
17	10.45	33.00	61.5	1
18	11.09	35.00	65.2	1
19	11.72	37.00	68.9	1
20	12.36	39.00	72.7	1

α-Pinene, d = 2ppm, JND_2

Trial	Volume of odour /mL	Concentration 'C' /ppm	Olfactomer setting /%	Odour release duration /s
1	3.67	11.58	21.6	1
2	4.30	13.58	25.3	1
3	4.94	15.58	29.0	1
4	5.57	17.58	32.8	1
5	6.20	19.58	36.5	1
6	6.84	21.58	40.2	1
7	7.47	23.58	43.9	1
8	8.10	25.58	47.7	1
9	8.74	27.58	51.4	1
10	9.37	29.58	55.1	1
11	10.00	31.58	58.8	1
12	10.64	33.58	62.6	1
13	11.27	35.58	66.3	1
14	11.91	37.58	70.0	1
15	12.54	39.58	73.8	1
16	13.17	41.58	77.5	1
17	13.81	43.58	81.2	1
18	14.44	45.58	84.9	1
19	15.07	47.58	88.7	1
20	15.71	49.58	92.4	1

Citral, d = 0.2ppm, JND_1

Trial	Volume of odour /mL	Concentration 'C' /ppm	Olfactomer setting /%	Odour release duration /s
1	4.20	1.00	24.7	1
2	5.04	1.20	29.6	1
3	5.88	1.40	34.6	1
4	6.72	1.60	39.5	1
5	7.56	1.80	44.5	1
6	8.40	2.00	49.4	1
7	9.24	2.20	54.3	1
8	10.08	2.40	59.3	1
9	10.92	2.60	64.2	1
10	11.75	2.80	69.1	1
11	12.59	3.00	74.1	1
12	13.43	3.20	79.0	1
13	14.27	3.40	84.0	1
14	15.11	3.60	88.9	1
15	15.95	3.80	93.8	1
16	16.79	4.00	98.8	1
17	17.63	4.20	51.9	2
18	18.47	4.40	54.3	2
19	19.31	4.60	56.8	2
20	20.15	4.80	59.3	2

Citral, d = 0.2ppm, JND_2

Trial	Volume of odour /mL	Concentration 'C' /ppm	Olfactomer setting /%	Odour release duration /s
1	9.08	2.16	26.7	2
2	9.92	2.36	29.2	2
3	10.76	2.56	31.7	2
4	11.60	2.76	34.1	2
5	12.44	2.96	36.6	2
6	13.28	3.16	39.1	2
7	14.12	3.36	41.5	2
8	14.96	3.56	44.0	2
9	15.80	3.76	46.5	2
10	16.64	3.96	48.9	2
11	17.48	4.16	51.4	2
12	18.32	4.36	53.9	2
13	19.16	4.56	56.4	2
14	20.00	4.76	58.8	2
15	20.84	4.96	61.3	2
16	21.68	5.16	63.8	2
17	22.52	5.36	66.2	2
18	23.36	5.56	68.7	2
19	24.20	5.76	71.2	2
20	25.04	5.96	73.6	2

Table 6.2: Tables showing the concentrations presented during trials with their respective odour volumes, and olfactometer settings. For each of the three odours, for JND_2, the data from the first round of experiments was fitted with a logistical psychometric function, details of which described in the discussion section. These were used to calculate the JND_1 concentration which would then be used as the new pedestal for the second round.

6.3 Results

The data was fitted with the same psychometric function across all the graphs, specifically a logistic function. The data was fitted to a psychometric function to find out the concentrations at which it could be said, with a good level of certainty, that the average participant could tell there was a noticeable change in concentration, based on their perception of the odours. This was said to occur at the 75% point for correct answers. Effectively it described the point at which it can be said that the people were mostly getting answers correct and weren't simply guessing. Guessing would yield a 50% correct response rate since the only choices available would be a right or wrong answer. The 75% point is the mid way point between guessing (50%) and absolute certainty (100%). The Logistical function used for these graphs is shown here:

$$f(x) = \gamma + (1 - \gamma - \lambda) \times \frac{1}{1 + (e^{-\beta(x-\alpha)})} \tag{6.2}$$

Where γ refers to the guess rate, which is the rate at which someone can guess the right answer and is the reciprocal of the number of answers in a forced choice:

$$\gamma = \frac{1}{m} \text{ in an } M\text{-AFC task} \tag{6.3}$$

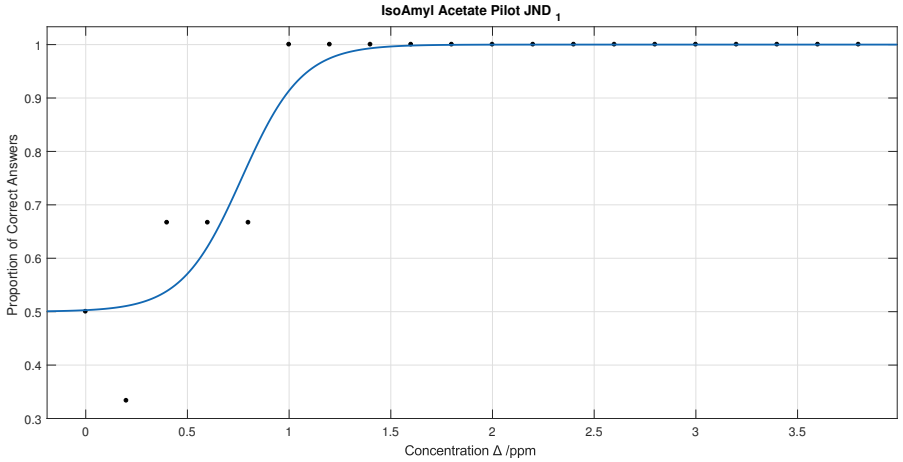
Since the experiment used a 2AFC method, $\gamma = 0.5$.λ refers to the lapse rate. This describes the rate at which participants could answer independent of the stimulus. For example, this could have happened if the participant missed the stimulus but continued to answer as if they hadn't, whether intentional or unintentional. Generally this is assumed to be zero and here it set at zero as there was no reason to think otherwise based on the experimental runs and participant feedback.

$$f(x) = 0.5 + (1 - 0.5 - 0) \times \frac{1}{1 + (e^{-\beta(x-\alpha)})} \tag{6.4}$$

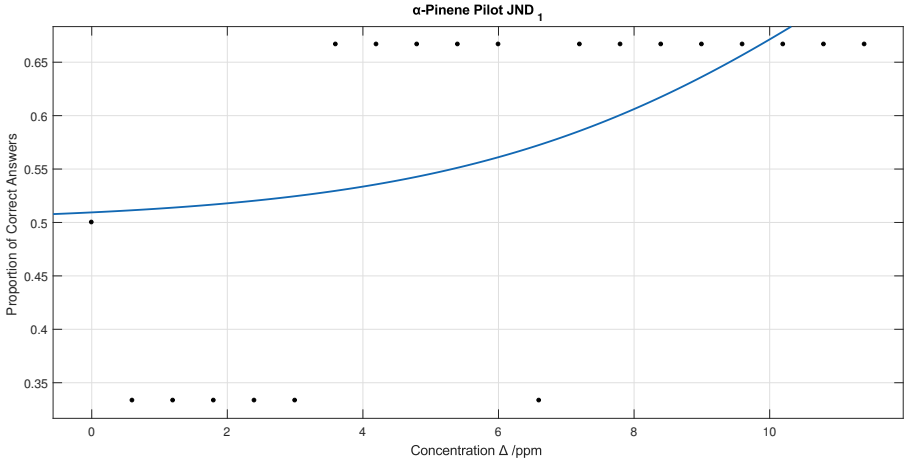
α and β are the two main parameters for the curve and change to fit depending on the data points. The α value determines the overall position of the fit and for this logistic function, also shows the JND point on the x-axis where correct responses reach 75% on the curve. β determines the gradient of the slope.

As stated before, an initial pilot study was completed prior to the main experiment to determine whether appropriate concentration ranged were used. Figure 6.2 shows the initial JND plots that resulted from the pilot study. The final concentration ranges used were simply multiplied up based on where the 75% mark was expected to fall based on these function fits.

(a) IsoAmyl Acetate Pilot JND_1



(b) α-Pinene Pilot JND_1



(c) Citral Pilot JND_1

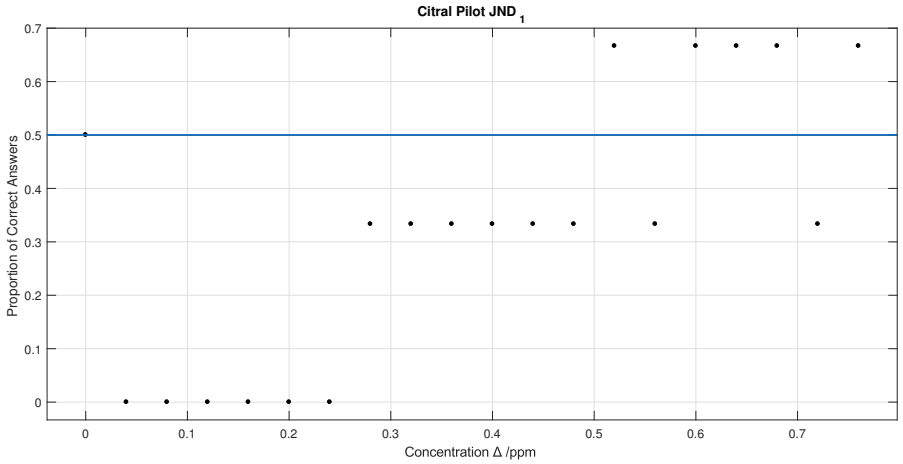
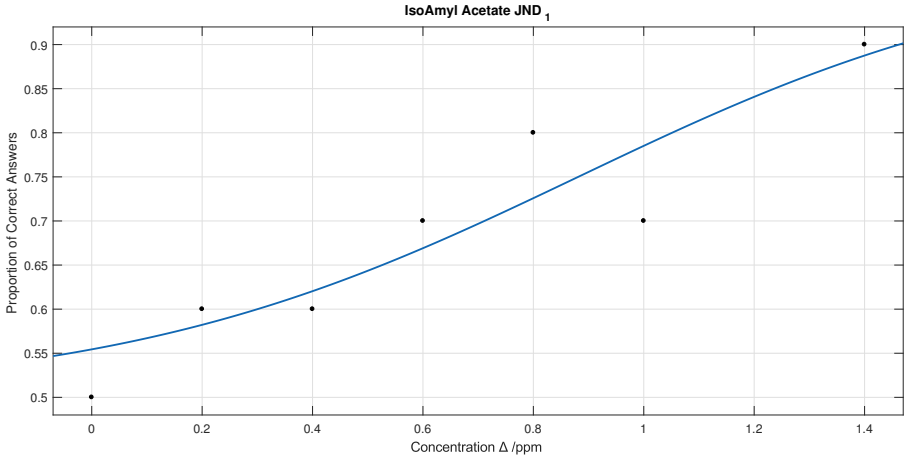


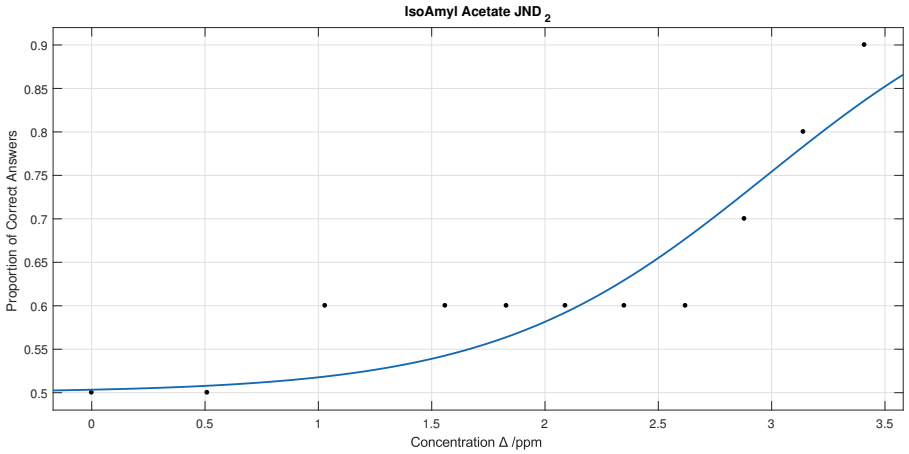
Figure 6.2: These graphs (a-c) show the psychometric functions fitted to the data obtained from the initial pilot study for JND_1 of IsoAmyl Acetate, α-Pinene and Citral, respectively.

It should be noted that some specific readings are missing from some of the graphs of the final experimental results. Concentration δs which had a correct answer rate of 40% or lower were removed. The reasoning being it was anomalous based on the fact that it is simply wrong to get below 50% since this is below the guess rate point, which invalidates the assumptions. In the case of the graphs in Figure 6.3 all the removed points were at 40%. Also trials where data points reached 90% or higher for two consecutive trials were taken as the finishing points for that respective graph and is the reason for the variable number of points per graph. This was done as, since there were only 10 participants, the weighting of a single ones answer resulted in sizeable shift in the curve fittings, and thus an incorrect answer per trial resulted in a string of 90% points This then skewed the whole fit to the right, even this may not neccesarily have been representatives of the rest of the population.

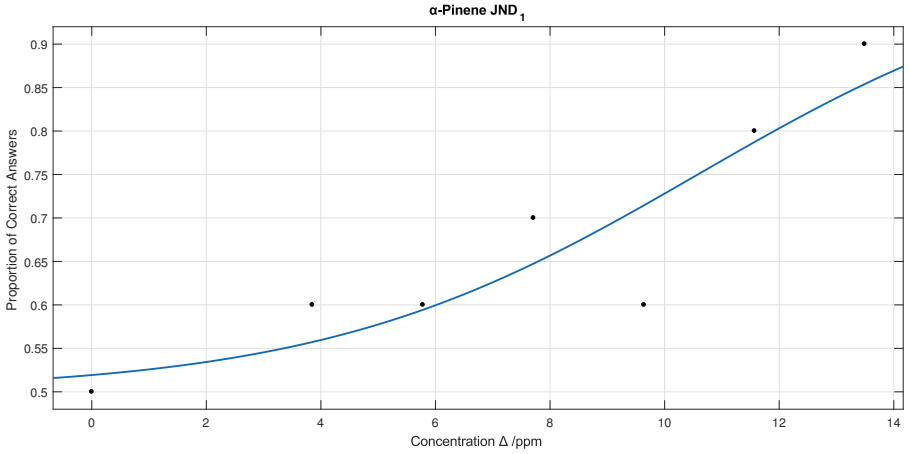
(a) IsoAmyl Acetate JND_1



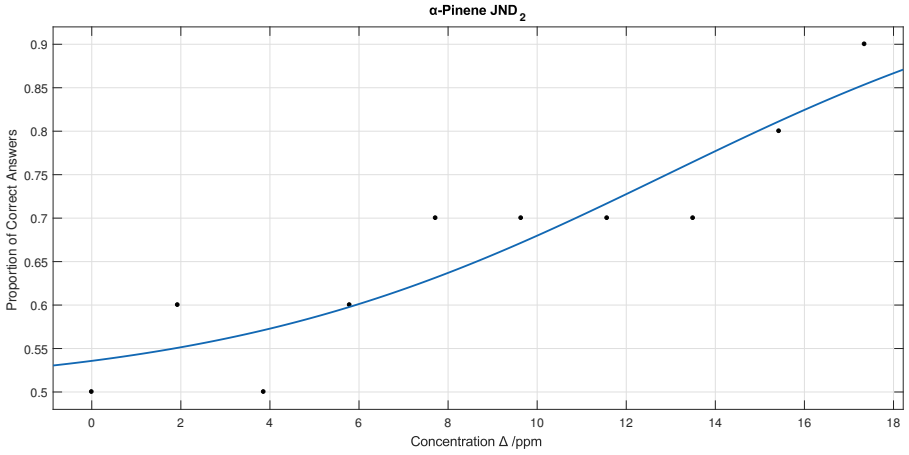
(b) IsoAmyl Acetate JND_2



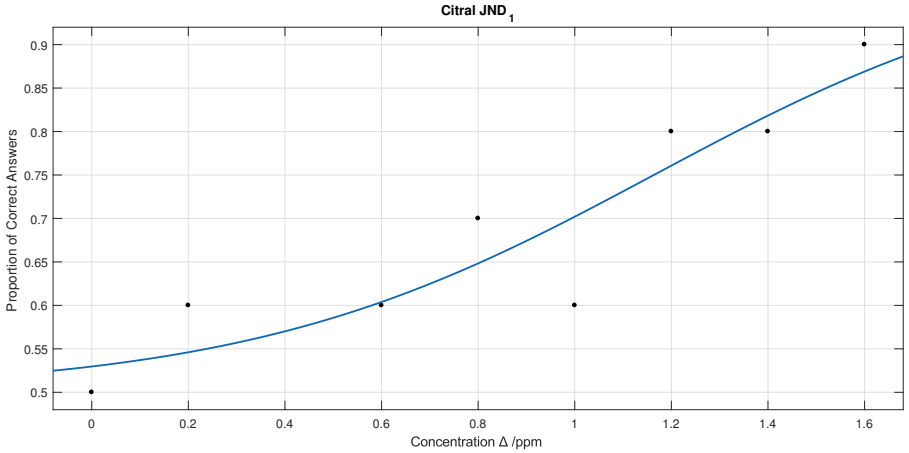
(c) α-Pinene JND_1



(d) α-Pinene JND_2



(e) Citral JND_1



(f) Citral JND_2

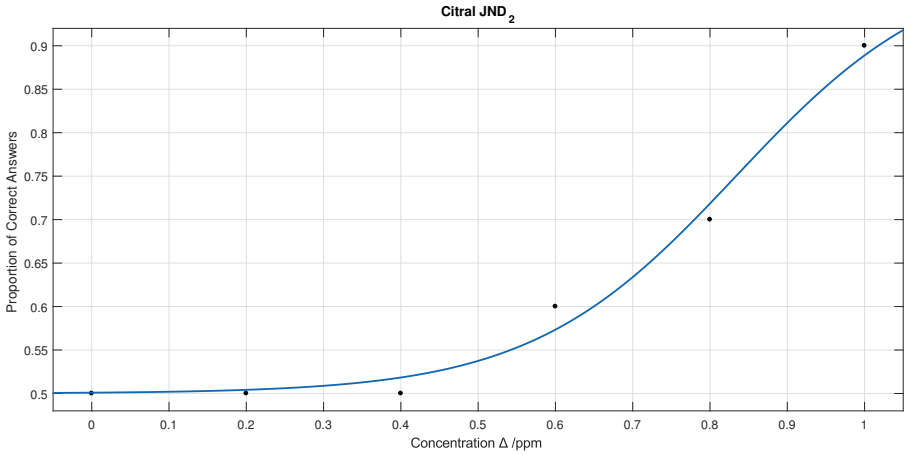


Figure 6.3: These graphs (a-f) show the psychometric functions fitted to the data obtained from the results of the JND study for both JND_1 and JND_2 for IsoAmyl Acetate, α-Pinene and Citral, respectively.

	JND_1			JND_2		
	IsoAmyl Acetate	α-Pinene	Citral	IsoAmyl Acetate	α-Pinene	Citral
α	0.8813	10.58	1.164	2.979	12.9	0.8336
β	2.386	0.3039	2.374	1.669	0.1986	7.531
R^2	0.8383	0.8215	0.8468	0.8393	0.851	0.9881
JND_{nC} /ppm	1.8813	11.58	2.164	4.8603	24.48	2.9976

Table 6.4: α, β, R^2, and JND_{nC} (final calculated JND concentration in ppm) values for each of the JND plots. The α values describe the Δ value between the pedestal and the 75% point for JND_n. Thus for the final values of JND_{nC} for a given smell and step, the α value is added to the pedestal, where the pedestal is: 1ppm for JND_1, and JND_1 for JND_2.

Table 6.4 shows the α, β, R^2, and JND_{nC} values for the fit of the respective curves, where JND_c is the actual final concentration value for a given JND step in ppm i.e. this would be the target value when wanting to use this JND for the given odour. The JND_{1C} concentrations calculated from the first round of experiments was then taken as the new pedestal values for the second round of experiments to find out JND_α values and thus the JND_{2C} concentrations. It is clear from the R^2 values that the fits for each of the curves are strong are quite strong since they values are close to 1 i.e. a perfect fit. No existing JND_{nC} values could be found for these specific compounds in literature for comparison.

6.4 Discussion

Looking at the final concentrations, in ppm, it is immediately noticeable that the values for α-Pinene are an order of magnitude bigger than the other two odours. This was to be expected, as its *d* step had to be increased by 5x after intital results from the pilot study. This does, however, illustrate the point that there can be large differences in physically measured concentrations of a substance but the perceived effect is equivalent. It is important to remember that the lower JND_{nC} values are relative to the olfactometer used to obtain them in the first place (if an olfactometer is able to produce a lower ppm pedestal value, it would be possible to get lower JND_{nC} values, assuming they are perceivable at that concentration). The DMFC of the olfactometer used limited the working range to 1ppm. This was the lowest reliable concentration output and using a back-calculated lower value would have created uncertainty in the concentrations being delivered. Thus if finer discretisations of the calibration range were possible, lower JND_{nC} values could be calculated. For higher JND points, since the calibration for the olfactometer

from 5 is a linear scale, it would be possible to continue upwards, in theory, to higher and higher JND_{nC}s assuming the headspace concentration was maintained. There quickly comes a point though, where the benefit of doing so would yield diminishing returns since the concentration would be too high for any practical use and overwhelm participants.

The JND_{1C} and JND_{2C} values calculated can be used for generic low and high thresholds for each of the three odours, respectively. Naturally these high and low designations are relative within a context i.e. if JND_{3C} were calculated using the method above (with JND_{2C} as the new pedestal), JND_{2C} would stop being the 'high' threshold and become the 'middle' threshold. As stated before, the method outlined above allows for further distinctions by calculating more JND_{nC} values for cases where a bigger scale of generalisable thresholds is required. In the context of this thesis, 2 JND_{nC} values are calculated, designated as 'high' and 'low', and are used as such in the next chapter.

6.5 Summary

The work in this chapter outlines a procedure for a perceptual calibration of three odours (IsoAmyl Acetate, α-Pinene and Citral) for humans and the calculation of generalisable odour thresholds. These thresholds provide a concentration of a given odour, where it can be said with relative certainty, not only that the population will be able to smell it, but specifically at the same perceptual intensity i.e. a high intensity smell for one person will be perceived as a high intensity smell for someone else for a given JND_{nC} value. This makes them extremely useful for carrying out olfactory research, especially for virtual environments, since it simplifies the process of recreating olfactory conditions whilst giving an assurance that participants will be able to experience similar conditions, and in general makes this area of research more accessible for researchers. There is also the possibility to calculate JND_{nC} values for different smells and link them across odours so that equivalent intensities can be matched accordingly, which again can be very useful for multi-odour studies. The procedure can be used to create new thresholds for other odours, assuming the same conditions are met (can produce an odour output at discrete concentrations with high accuracy and precision, under a temperature of 293K, atmospheric pressure 101kPA, and humidity +50%).

Chapter 7

Olfactory Masking Investigation

In this chapter an experimental study is proposed to investigate the potential for olfactory attention-masking phenomena between pairs of odours, similar to those seen in the visual domain. Both the olfactometer designed in chapter 5 and the JND concentrations from the perceptual calibration procedure in chapter 6 are used.

7.1 Olfactory Attention Masking

As discussed in section 3.2, attention masking has been examined largely in the visual domains, and the patterns identified have been exploited when used in the context of computer graphics. If similar effects can exist in the context of odours, arguably the same kinds of exploitations could be used to make computational savings with processes in line with any olfactory rendering. One such example could be if a computational fluid dynamic simulation was required to show the movement of odours through an environment so that the correct concentration was delivered to the user from the olfactometer to match the simulated 'expected' concentration in the simulation. If it was found a particular odour overrides another in certain contexts, the savings in computation in not having to model two smells would be significant. Additionally, savings could be made in time and effort if it was found that particular odours were more salient than others and so could completely mask another, there would be little point in generating the odour entirely on a physical level since lesser salient odours wouldn't be perceived at all.

Bearing this in mind, the following procedure was designed and followed in order to examine if there was evidence to suggest the existence of olfactory attention masking phenomena, on presentation of two simultaneous olfactory stimuli. Essentially, this experiment attempts to recreate a simultaneous, pattern masking effect from the visual to the olfactory domain. Participant responses were then tested for statistical significances across the specific presentation

conditions to deduce whether certain odours masked or showed signs of being more salient than others.

7.2 Experimental design

The following sections outlines details the experimental design, the materials and participants, but also describes the procedure in full showing the specific parameters used for presentation of the stimuli.

The method used for this study employed the use of both the olfactometer described in chapter 5, and the perceptual thresholds calculated in chapter 6 to create high and low intensity odours for the testing of multiple dual, single and blank olfactory conditions on participants.

7.2.1 Procedure

Before any experiments took place, participants were asked if they had normal or corrected to normal vision and smell. All twenty participants confirmed this, and were then asked to sign a consent form, after reading through a provided participant information leaflet.

Following informed consent, participants were asked to sit in a chair, wear ear defenders, place their heads on to a chin rest, and look ahead to the television in front of them. The ear defenders served the purpose of removing any external audio distractions but also blocking any audio cues potentially given from the olfactometer that may influence when odours were to be expected. Participants were presented with a score sheet, which can be found in the Appendix, and asked if they recognised the images and whether they thought they knew what each object smelled like. All twenty participants confirmed they did and were thus allowed to continue with the experiment. Participants were instructed that they would be presented with an odour while a grey slide appeared on the screen in front of them. This could have multiple smells, a single smell or no smell at all, and they would be asked to rank the four images based on what they smelled. Images were ranked from highest to lowest intensity based on the perceived smells of the odours presented. A ‘1-4’ ranking scale was used, where ‘1’ was the strongest and ‘4’ were weakest intensity smells. If participants were unsure for any of the individual rankings, they were asked to make a forced choice. This would mean each trial would always have a ‘1-4’ ranking e.g. if a participant thought they smelled a strong lemon smell and a weak pine smell, they would write a ‘1’ under the lemon image, a ‘2’ under the pine image, a ‘3’ under banana, and a ‘4’ under apple, where ‘3’ and ‘4’ are random guesses. The whole procedure was then repeated for twenty trials with a three minute rest break after ten trial before continuing on to the final ten. A ranking system was used, firstly, to allow for the collection of responses

in a standardised way. Regardless of the condition presented, the responses would follow the same system. Secondly, this approach also made it easier for participants to log their perceived responses since it removed the burden of having to select hard choices in a binary fashion: ”do you think you smelled each of these odours?”, for each of the trials. The ranking system alleviates this since they can simply rank things they are unsure of, lower, and still allows the capture of this information, that a straight ”yes” or ”no” wouldn't.

For every trial, an olfactory stimulus was presented, during the three second ‘stimulus exposure duration’ (SED), followed by a twenty second ‘ranking duration’ (RD) which gave enough time for participants to give their rankings, but also short enough that they wouldn't dwell on their answers from diminished memory of their perceptions of the odour. The remaining time between trials, the ‘inter-trial duration’ (ITD), was set at ten seconds, and gave was effectively a refresh period between smells but also prepared participants for the next odour. The television screen provided a visual cue for when odours were to be expected for the SED. The monitor was cued to show to a grey slide in tandem with the odour presentation. The slide then changed to one with four images arranged in a two by two grid. The images shown referred to the three odours sources for the three calibrated odours i.e. a lemon for Citral, a banana for IsoAmyl Acetate and a pine cone for α-Pinene, with a fourth control blank represented by a green apple. For each trial, the ordering of the images was randomised in an attempt to reduce any biases associated with image position.

The specific images chosen for the slide were tested for visual saliency to make sure each single image, out of the four, was no more visually salient (by a large margin) than another. Figure 7.1 shows an example slide with each of four individual images, along with it's counterpart grey-scale image output when processed with the visual saliency method described below. The model used was a salient object detection [139], which showed good results. There was an also implementation available, which removed potential errors in reimplementation. The algorithm picked out the most salient objects in an image, as opposed to operating only on low-level image features, which was appropriate since the four images were not shown as part of a scene. After performing the saliency detection, a random grey-scale slide was taken from the output. An average pixel brightness calculation was done on each of the four individual grey-scale images on the slide, on a scale of 0-255. This was followed by a comparison between the overall ‘brightest‘ individual image and all other images. Table 7.1 shows the results of the pixel calculation and comparison. Since the percentage difference between the ‘brightest’ and ‘dimmest’ was less than 25%, the current images were deemed acceptable in terms of no significant saliency being present between individual images.

While the SED was set for three seconds, the odour wasn't continuously presented for three seconds. The odour was provided as a burst to give a designated concentration based on

Image	Average Pixel Value (0-255)	Percentage Value vs. 'Brightest' image
Banana	201.0997	85.7623
Pine Cone	215.7778	92.0221
Lemon	234.4848	100
Apple	234.2725	99.9095

Table 7.1: Table showing the average pixel brightness values of the individual images from a slide which had a visual saliency model applied on to it. Lemon showed the highest brightness and it's value was compared to the other three images' brightnesses.

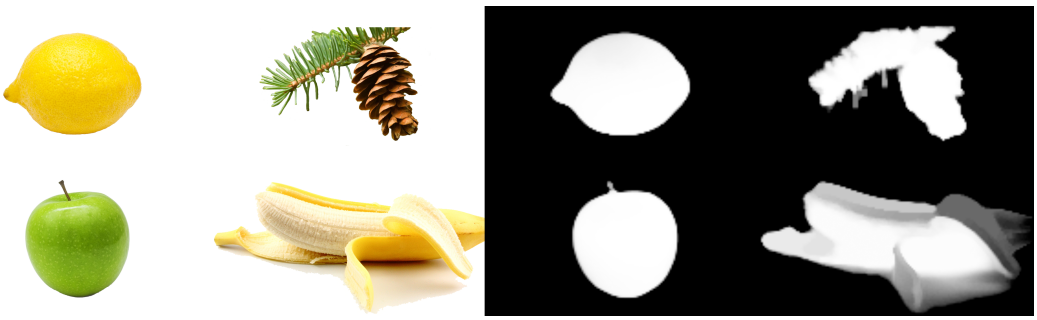


Figure 7.1: Slides showing the four images used for ranking the odours presented. The slide to the left shows the images used during the experiment and the slide to the right is the corresponding saliency map obtained from the salient object detection.

the calibration from chapter 5. During the 'ranking duration' (RD) for each trial, participants marked on a form, for that trial, a 1-4 ranking under the 4 images corresponding to the intensity they smelled of each odour. Figure 7.2 shows a digram of the procedure.

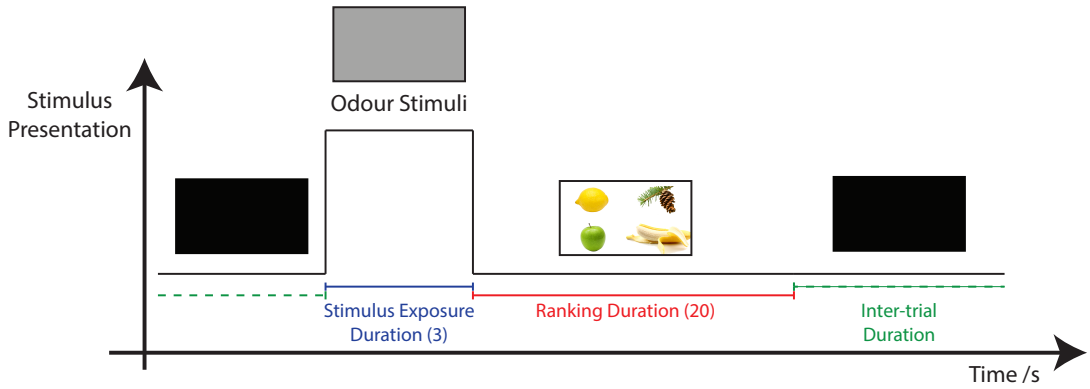


Figure 7.2: Illustration of the experimental procedure showing each stage with their respective visual cues

The actual stimulus presented to subjects for each trial was either a blank, single odour with a high or low condition, or a mixture of two different odours with a high and/or low condition. Table 7.4 shows all possible conditions. During the experiment all single and dual conditions were presented once, along with two blank trials. Table 7.5 shows the conditions for the twenty trials along with their ordering. This specific ordering was chosen so that the lower concentration trial conditions were done initially to limit any olfactory habituation effects. These effects would desensitise subjects' noses since being exposed to higher concentrations inhibits the noses ability to discern lower concentrations, as was described in section 2.1.2. Blanks were used as the fourth and final trials.

7.2.2 Participants

Ten of participants that were recruited as part of an 'opportunistic/convenience' sample used for the previous study in chapter 6, were used again. An additional ten were recruited randomly. The purpose of this was to see if any significant differences occurred between those who had been 'trained' with the odours in the previous study, and were thus familiar with them, and those who had never smelled these odours in this context. This was done to account for any bias since the 'untrained' group acted as a control group. Again, the number of participants (N=20) was consistent with other similar works in this field [126, 136]. Overall, this experiment was a preliminary study that explored the possibility of olfactory attention masking affects in the

context of two odours. The only real factor which would improve the outcome of the findings would be an increase in sample sizes.

Bearing this in mind, the sample size of twenty can be considered relatively small, but again this was a trade-off chosen to allow for a quick validation of the framework but also in the data collection. It is important, however, to have a varied sample population such that the end results are more representative of a general human smelling ability as opposed to being skewed towards specific demographics. Bearing these considerations in mind, the participant recruitment was varied to try to encompass as wide a range of demographics as possible. The final participant groups' demographical breakdown can be seen in table 7.2. Participants were characterised by three main criteria: gender, age, and Ethnicity with the corresponding geographical region. These criteria were chosen since they were fixed characteristics associated with the individual participant which have been shown to be correlated to smelling ability, as discussed in section 2.4. As can be seen from the table, a relatively varied sample of participants was used. None of the participants suffered from an olfactory impairment but hypothetically if any had, they would not have been allowed to participate in any trials. All Participants were indirectly tested on their smelling ability for the three odours since they were all exposed to concentrated samples of odours at least one week prior to participating, as a priming exercise to make sure they understood what to expect in terms of the character of the smell. During participation, they were asked to confirm whether they smelled anything after the first trial of each odour to which all confirmed they could.

7.2.3 Materials

The experimental design was based on previous works in the area, namely [126, 136]. Before any experimental work was conducted, the protocol described below was formally written up and submitted to the University of Warwick Biomedical & Scientific Research Ethics Committee (BSREC) to ensure it would be in accordance with the university ethical guidelines. After formal approval was received, work commenced (Reference: REGO-2017-2041).

The olfactometer designed and built in chapter 5 was used for the presentation of odours, along with the two JNDs calculated for each odour in chapter 6. As stated above, twenty participants (N=20) were used for this experiment and divided into two groups: ten trained (n_t=10) and ten untrained (n_u=10) individuals.

Participants were sat 183 cm from a television screen. The distance was calculated using the optimal viewing conditions stated in the ITU-R BT.2022 specification [137], which states a viewing distance of 3.2H for a 1080p screen, where H is the height of the television. The dimensions of the television used here are 102.1cm x 57.2cm [138]. The edge of the table had

Participant	Gender	Age range	Ethnicity/Geographical Region	Smoker?
1	M	20-29	British/Western European	N
2	F	30-39	Italian/Western European	N
3	M	20-29	British/Western European	N
4	M	30-39	Cypriot/Western European	N
5	M	30-39	Chinese/Far East Asian	N
6	M	30-39	Iranian/Middle East Asian	N
7	M	30-39	Indian/South East Asian	N
8	M	20-29	British/Western European	Y
9	M	20-29	Indian/ South East Asian	N
10	F	20-29	British/Western European	N
11	M	20-29	British/Western European	N
12	M	20-29	British/Western European	N
13	F	20-29	Turkish/Middle Eastern Asia	N
14	M	20-29	Turkish/Middle Eastern Asia	N
15	M	20-29	Chinese/Far East Asian	N
16	M	20-29	British/Western European	N
17	M	30-39	Indian/South East Asian	N
18	F	30-39	British/Western European	N
19	F	30-39	British/Western European	N
20	F	30-39	British/Western European	N

Table 7.2: Table showing the twenty participants' demographics/criteria breakdown. These factors were recorded to make sure the sample used, had variability in it to account for any skewing of results toward specific demographics.

		IsoAmyl Acetate			Citral			α-Pinene		
		High	Low	Zero	High	Low	Zero	High	Low	Zero
IsoAmyl Acetate	High	N/A			1	2	13	5	6	13
	Low				3	4	14	7	8	14
	Zero				17	18	Blank	15	16	Blank
Citral	High	1	3	17	N/A			9	10	17
	Low	2	4	18				11	12	18
	Zero	13	14	Blank				15	16	Blank
α-Pinene	High	5	7	15	9	11	15	N/A		
	Low	6	8	16	10	12	16			
	Zero	13	14	Blank	17	18	Blank			

Table 7.4: Pairwise table showing all the possible conditions when delivering two odours at once. The dual high-low conditions are highlighted yellow, the single conditions are highlighted lilac and the blanks are highlighted green.

a square plate which had a chin rest behind it and series of PTFE tubes attached to it pointing upwards in front of the chin rest. The chin rest was attached to a beam which was secured to the floor so that a participants' nose would sit 10cm above the tubes when sat behind the table and using it.

In the context of this study, the main independent variables were the JND_n concentrations of odours that was presented to participants and the dependent variable was the response given by participants as odours are presented to them, namely how they ranked image representations of the odour per trial. Other independent variables include all the conditions that were used in calibrating the olfactometer built in Chapter 5, which are inherent in any procedure using the calibrated output, which were also used to create the JND concentration points in Chapter 6.

Trial	Odour 1	Odour 2	Trial	Odour 1	Odour 2
1	α-Pinene$_{low}$	Blank	11	α-Pinene$_{low}$	IsoAmyl Acetate$_{high}$
2	IsoAmyl Acetate$_{low}$	Blank	12	α-Pinene$_{high}$	IsoAmyl Acetate$_{low}$
3	Citral$_{low}$	Blank	13	IsoAmyl Acetate$_{low}$	Citral$_{high}$
4	Blank	Blank	14	IsoAmyl Acetate$_{high}$	Citral$_{low}$
5	Citral$_{low}$	α-Pinene$_{low}$	15	Citral$_{high}$	α-Pinene$_{low}$
6	α-Pinene$_{low}$	IsoAmyl Acetate$_{low}$	16	Citral$_{low}$	α-Pinene$_{high}$
7	IsoAmyl Acetate$_{low}$	Citral$_{low}$	17	IsoAmyl Acetate$_{high}$	Citral$_{high}$
8	IsoAmyl Acetate$_{high}$	Blank	18	α-Pinene$_{high}$	IsoAmyl Acetate$_{high}$
9	α-Pinene$_{high}$	Blank	19	Citral$_{high}$	α-Pinene$_{high}$
10	Citral$_{high}$	Blank	20	Blank	Blank

Table 7.5: Table showing the individual 20 trials and the conditions presented for them. The low and high conditions for each odour refer to the JND_1 and JND_2 values calculated in the previous chapter, respectively.

Nineteen unique conditions result from table 7.4, and table 7.5 lists their individual trials:

1. Low singles (1, 2, 3)
2. Low-low duals (5, 6, 7)
3. High singles (8, 9, 10)
4. High-low duals (11, 12, 13, 14, 15, 16)
5. High-high duals (17, 18, 19)
6. Blanks (4, 20)

7.3 Results

The participant sheets were gathered after all participants had completed all the trials. All written rankings were digitised and aggregated together to give the twenty responses for each of the individual trials. These trials were then further grouped by the six conditions outlined above. Various statistical analyses were then carried out after sorting the rankings for each trial, to give various statistical significance values. Below outlines the results for each of the condition groupings, along with the statistical tests used and why. First the single conditions are shown, followed by the high-low condition. The high-high and low-low dual conditions are shown next followed by the blanks. In each case, results deemed to be statistically significant (values <0.05) have been highlighted in yellow. For all trials, statistical analyses were carried out on 3 different groups: the trained (n_t=10), the untrained (n_u=10), and the combined trained and untrained (N=20).

7.3.1 Single Conditions

Single condition results were processed using a Related-Samples Wilcoxon Rank Sum Test. This test was chosen since the data was rank based and thus ordinal, the independent variables were matched pairs: congruent or incongruent, and the distribution of the differences between the two related groups could be said to be symmetrical. Congruent here refers to ranks which participants chose which fell under the ”correct” answer for the trial and incongruent refers to the average of the ”incorrect” ranks. Since there was only one odour actually being presented, the answer for these trials was binary: either assigning a ”1” rank (correct) or assigning a ”2”, ”3” or ”4” rank (incorrect) to the correct odour representation image. The values for scoring each rank were taken as face value i.e. ”1” = 1, ”2” = 2, ”3” = 3, ”4” = 4. For each participant

both a congruent and incongruent value was calculated across the low and high conditions i.e. the sum of their ”correct” answers for each of the three odours, and the sum of the other ranks for each of the odours, divided by three (to give an average). For example, if a participant selected all three odours correctly in all three trials, their congruent score would be: 3 (1+1+1), and their incongruent score would be: 9 ((2+2+2+3+3+3+4+4+4)/3).

The Wilcoxon Rank Sum Test was then performed on this data across the twenty participants, and then separately for trained and untrained participant groups. In Tables 7.6 and 7.7 we see the results of these tests for both the single low and high conditions.

Low Single Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	0a	0.00	0.00
Positive Ranks	20b	10.50	210.00
Ties	0c		
	N	**Z**	**p**
Total	20	-3.951	0.000

Low Single (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	0a	0.00	0.00
Positive Ranks	10b	5.50	55.00
Ties	0c		
	N	**Z**	**p**
Total	10	-2.831	0.005

Low Single (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	0a	0.00	0.00
Positive Ranks	10b	5.50	55.00
Ties	0c		
	N	**Z**	**p**
Total	10	-2.829	0.005

a SingleLow.Incongruent <SingleLow.Congruent
b SingleLow.Incongruent >SingleLow.Congruent
c SingleLow.Incongruent = SingleLow.Congruent

Table 7.6: This table shows the results from performing a Wilcoxon Rank Sum Tests on the overall, trained, and untrained participant data for Single Low conditions (significance level p $<$0.05). The Null hypothesis assumes the median of differences between the congruent and incongruent values data is 0.

High Single Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	3a	4.00	12.00
Positive Ranks	17b	11.65	198.00
Ties	0c		
	N	**Z**	**p**
Total	20	-3.502	0.000

High Single (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	3.50	7.00
Positive Ranks	8b	6.00	48.00
Ties	0c		
	N	**Z**	**p**
Total	10	-2.099	0.036

High Single (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	1a	1.00	1.00
Positive Ranks	9b	6.00	54.00
Ties	0c		
	N	**Z**	**p**
Total	10	-2.737	0.006

a SingleHigh.Incongruent <SingleHigh.Congruent
b SingleHigh.Incongruent >SingleHigh.Congruent
c SingleHigh.Incongruent = SingleHigh.Congruent

Table 7.7: This table shows the results from performing a Wilcoxon Rank Sum Tests on the overall, trained, and untrained participant data for Single High conditions (significance level $p < 0.05$). The Null hypothesis assumes the median of differences between the congruent and incongruent values data is 0.

7.3.2 Dual Condition High-High, Low-Low

Dual condition High-High, and Low-Low results were processed using a Related-Samples Wilcoxon Rank Sum Test. This test was chosen since the data was rank based and thus ordinal, the independent variables were matched pairs: congruent or incongruent, and the distribution of the differences between the two related groups could be said to be symmetrical. Congruent here refers to ranks which participants chose as their ”correct” answer and incongruent refers to the average of the ”incorrect” answers. In these trials, there were two odours being presented simultaneously so the answer for these trials could be correct by either assigning a ”1” or ”2” rank, or incorrect by assigning a ”3” or ”4” rank to the correct odour representation image. The values for scoring each rank were taken as face value i.e. ”1” = 1, ”2” = 2, ”3” = 3, ”4” = 4. For each participant, both a congruent and incongruent value was calculated across the low and high conditions i.e. the sum of their ”correct” answers for the congruent score, and the sum of the incorrect ranks for the incongruently score. For example, if a participant selected an odour combination correctly, their congruent score would be: 3 (1+2), and their incongruent score would be: 7 (3+4).

The Wilcoxon Rank Sum Test was then performed on this data across the twenty participants, and then separately for trained and untrained participant groups. Table 7.8 show the results of these tests for the dual low conditions, and Table 7.9 show the results of these tests for the dual high conditions.

Low Dual Citral.α-Pinene Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	5.50	11.00
Positive Ranks	12b	7.83	94.00
Ties	6c		
	N	**Z**	**p**
Total	20	-2.762	0.006

Low Dual Citral.α-Pinene (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	3.50	7.00
Positive Ranks	6b	4.83	29.00
Ties	2c		
	N	**Z**	**p**
Total	10	-1.613	0.107

Low Dual Citral.α-Pinene (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	0.00	0.00
Positive Ranks	6b	3.50	21.00
Ties	2c		
	N	**Z**	**p**
Total	10	-2.333	0.020

a DualLowIncongruent <DualLowCongruent
b DualLowIncongruent >DualLowCongruent
c DualLowIncongruent = DualLowCongruent

Low Dual IsoAmyl Acetate.α-Pinene Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	1a	10.50	10.50
Positive Ranks	11b	6.14	67.50
Ties	8c		

	N	**Z**	**p**
Total	20	-2.321	0.020

Low Dual IsoAmyl Acetate.α-Pinene (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	0a	0.00	0.00
Positive Ranks	5b	3.00	15.00
Ties	5c		

	N	**Z**	**p**
Total	10	-2.070	0.038

Low Dual IsoAmyl Acetate.α-Pinene (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	1a	7.00	7.00
Positive Ranks	6b	3.50	21.00
Ties	3c		

	N	**Z**	**p**
Total	10	-1.265	0.206

a DualLowIncongruent <DualLowCongruent
b DualLowIncongruent >DualLowCongruent
c DualLowIncongruent = DualLowCongruent

Low Dual IsoAmyl Acetate.Citral Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	3a	5.83	17.50
Positive Ranks	14b	9.68	135.50
Ties	3c		
	N	**Z**	**p**
Total	20	-2.921	0.003

Low Dual IsoAmyl Acetate.Citral (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	1a	1.50	1.50
Positive Ranks	7b	4.93	34.50
Ties	2c		
	N	**Z**	**p**
Total	10	-2.420	0.016

Low Dual IsoAmyl Acetate.Citral (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	4.25	8.50
Positive Ranks	7b	5.21	36.50
Ties	1c		
	N	**Z**	**p**
Total	10	-1.718	0.086

a DualLowIncongruent <DualLowCongruent
b DualLowIncongruent >DualLowCongruent
c DualLowIncongruent = DualLowCongruent

Table 7.8: This table shows the results from performing a Wilcoxon Rank Sum Tests on the overall, trained, and untrained participant data for the three Dual Low conditions (significance level $p < 0.05$).

High Dual Citral.α-Pinene Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	10.50	21.00
Positive Ranks	14b	8.21	115.00
Ties	4c		
	N	**Z**	**p**
Total	20	-2.560	0.010

High Dual Citral.α-Pinene (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	7.00	14.00
Positive Ranks	7b	4.43	31.00
Ties	1c		
	N	**Z**	**p**
Total	10	-1.035	0.301

High Dual Citral.α-Pinene (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	0a	0.00	00.00
Positive Ranks	7b	4.00	28.00
Ties	3c		
	N	**Z**	**p**
Total	10	-2.646	0.008

a DualHighIncongruent <DualHighCongruent
b DualHighIncongruent >DualHighCongruent
c DualHighIncongruent = DualHighCongruent

High Dual IsoAmyl Acetate.α-Pinene Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	5.00	10.00
Positive Ranks	14b	9.00	126.00
Ties	4c		

	N	**Z**	**p**
Total	20	-3.091	0.002

High Dual IsoAmyl Acetate.α-Pinene (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	2.50	5.00
Positive Ranks	5b	4.60	23.00
Ties	3c		

	N	**Z**	**p**
Total	10	-1.561	0.119

High Dual IsoAmyl Acetate.α-Pinene (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	0a	0	0
Positive Ranks	9b	5.00	45.00
Ties	1c		

	N	**Z**	**p**
Total	10	-2.739	0.006

a DualHighIncongruent <DualHighCongruent
b DualHighIncongruent >DualHighCongruent
c DualHighIncongruent = DualHighCongruent

High Dual IsoAmyl Acetate.Citral Overall	N	Mean Rank	Sum of Ranks
Negative Ranks	4a	6.88	27.50
Positive Ranks	15b	10.83	162.50
Ties	1c		
	N	**Z**	**p**
Total	20	-2.804	0.005

High Dual IsoAmyl Acetate.Citral (t)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	2.50	5.00
Positive Ranks	7b	5.71	40.00
Ties	1c		
	N	**Z**	**p**
Total	10	-2.130	0.033

High Dual IsoAmyl Acetate.Citral (u)	N	Mean Rank	Sum of Ranks
Negative Ranks	2a	5.00	10.00
Positive Ranks	8b	5.63	45.00
Ties	0c		
	N	**Z**	**p**
Total	10	-1.838	0.066

a DualHighIncongruent <DualHighCongruent
b DualHighIncongruent >DualHighCongruent
c DualHighIncongruent = DualHighCongruent

Table 7.9: This table shows the results from performing a Wilcoxon Rank Sum Tests on the overall, trained, and untrained participant data for the three Dual High conditions (significance level $p < 0.05$). The Null hypothesis assumes the median of differences between the congruent and incongruent values data is 0.

7.3.3 High-Low Dual Conditions

Dual condition High-Low results were processed using a Related-Samples Friedman's Two-Way Analysis of Variance by Ranks. This test was chosen since the data was rank based and thus ordinal, the sample population was random (in the context of this experiment), and the responses were measured under three different criteria: their ability to identify strong, weak and incongruent odours. Incongruent here refers to any incorrect answers. While the perception of the odour is dependent on the participant, the results were designated on the basis that an odour ranked with a "1" would be considered the strong odour and an oour ranked with "2" would be considered the weak odour. In these trials, there were two odours being presented simultaneously so the answer for these trials could be correct by either assigning a "1" or "2" rank, or incorrect by assigning a "3" or "4" rank to the correct odour representation image, though the 'strong' odour would be considered 'more' correct. For each participant, a strong, weak, and incongruent value was taken using the rank assigned by the participant. The values for scoring each rank were taken as face value with the exception of the two lower ranks which were both given a value of 3 i.e. "1" = 1, "2" = 2, "3" = 3, "4" = 3. The 'strong' and 'weak' scores took a value of 1, 2 or 3, dependent of the ranking assigned by the participant and the incongruent took the average of the values derived from the two 'incorrect' rankings from the participant data. For example, if a participant correctly identified the strong, weak, and incongruent, in that order, their strong score would be: 1, their weak score would be 2, and their incongruent score would be 3 ((3+3)/2).

A Related-Samples Friedman's Two-Way Analysis of Variance by Ranks Test was then performed on this data across the twenty participants, and then separately for trained and untrained participant groups. Table 7.10 shows the results of these tests for the dual high-low conditions.

Overall

High: IsoAmyl Acetate Low: α-Pinene Overall	
N	20
Chi-Square	12.342
Asymp. Sig.	0.002

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.I.Low.P.Strong High.I.Low.P.Incongruent	-0.650	0.316	-2.055	0.040	0.119
High.I.Low.P.Strong High.I.Low.P.Weak	-1.075	0.316	-3.399	0.001	0.002
High.I.Low.P.Incongruent High.I.Low.P.Weak	0.425	0.316	1.344	0.179	0.537

Trained

High: IsoAmyl Acetate Low: α-Pinene	
N	10
Chi-Square	5.421
Asymp. Sig.	0.067

Untrained	
High: IsoAmyl Acetate Low: α-Pinene	
N	10
Chi-Square	7.000
Asymp. Sig.	0.030

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.I.Low.P.Strong High.I.Low.P.Incongruent	-0.650	0.447	-1.453	0.146	0.438
High.I.Low.P.Strong High.I.Low.P.Weak	-1.150	0.447	-2.571	0.010	0.030
High.I.Low.P.Incongruent High.I.Low.P.Weak	0.500	0.447	1.118	0.264	0.791

Overall	
High: α-Pinene **Low: IsoAmyl Acetate**	
N	20
Chi-Square	2.395
Asymp. Sig.	0.302

Trained	
High: α-Pinene **Low: IsoAmyl Acetate**	
N	10
Chi-Square	1.474
Asymp. Sig.	0.479

Untrained	
High: α-Pinene **Low: IsoAmyl Acetate**	
N	10
Chi-Square	2.579
Asymp. Sig.	0.275

Overall

High: Citral Low: IsoAmyl Acetate	
N	20
Chi-Square	12.182
Asymp. Sig.	0.002

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.C.Low.I.Strong High.C.Low.I.Weak	-0.650	0.316	-2.055	0.040	0.119
High.C.Low.I.Strong High.C.Low.I.Incongruent	-1.075	0.316	-3.399	0.001	0.002
High.C.Low.I.Weak High.C.Low.I.Incongruent	-0.425	0.316	-1.344	0.179	0.537

Trained

High: Citral Low: IsoAmyl Acetate	
N	10
Chi-Square	3.368
Asymp. Sig.	0.186

Untrained	
High: Citral Low: IsoAmyl Acetate	
N	10
Chi-Square	9.692
Asymp. Sig.	0.008

Pairwise Comparisons (Sample 1 - Sample 2)	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adjusted Sig.
High.C.Low.I.Strong High.C.Low.I.Weak	-0.900	0.447	-2.012	0.044	0.133
High.C.Low.I.Strong High.C.Low.I.Incongruent	-1.350	0.447	-3.019	0.003	0.008
High.C.Low.I.Weak High.C.Low.I.Incongruent	-0.450	0.447	-1.006	0.314	0.943

Overall

High: IsoAmyl Acetate Low: Citral	
N	20
Chi-Square	11.091
Asymp. Sig.	0.004

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.I.Low.C.Weak High.I.Low.C.Strong	0.625	0.316	1.976	0.048	0.144
High.I.Low.C.Weak High.I.Low.C.Incongruent	-1.025	0.316	-3.241	0.001	0.004
High.I.Low.C.Strong High.I.Low.C.Incongruent	-0.400	0.316	-1.265	0.206	0.618

Trained

High: IsoAmyl Acetate Low: Citral	
N	10
Chi-Square	9.897
Asymp. Sig.	0.007

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.I.Low.C.Weak High.I.Low.C.Strong	1.150	0.447	2.571	0.010	0.030
High.I.Low.C.Weak High.I.Low.C.Incongruent	-1.250	0.447	-2.795	0.005	0.016
High.I.Low.C.Strong High.I.Low.C.Incongruent	-0.100	0.447	-0.224	0.823	1.000

Untrained	
High: IsoAmyl Acetate **Low: Citral**	
N	10
Chi-Square	4.000
Asymp. Sig.	0.135

Overall	
High: Citral Low: α-Pinene	
N	20
Chi-Square	16.231
Asymp. Sig.	0.000

Pairwise Comparisons (Sample 1 - Sample 2)	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adjusted Sig.
High.C.Low.P.Strong High.C.Low.P.Weak	-1.050	0.316	-3.320	0.001	0.003
High.C.Low.P.Strong High.C.Low.P.Incongruent	-1.125	0.316	-3.558	0.000	0.001
High.C.Low.P.Weak High.C.Low.P.Incongruent	-0.075	0.316	-0.237	0.813	1.000

Trained	
High: Citral Low: α-Pinene	
N	10
Chi-Square	10.400
Asymp. Sig.	0.006

Pairwise Comparisons (Sample 1 - Sample 2)	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adjusted Sig.
High.C.Low.P.Strong High.C.Low.P.Weak	-1.000	0.447	-2.236	0.025	0.076
High.C.Low.P.Strong High.C.Low.P.Incongruent	-1.400	0.447	-3.130	0.002	0.005
High.C.Low.P.Weak High.C.Low.P.Incongruent	-0.400	0.447	-0.894	0.371	1.000

Untrained	
High: Citral Low: α-Pinene	
N	10
Chi-Square	7.000
Asymp. Sig.	0.030

Pairwise Comparisons (Sample 1 - Sample 2)	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adjusted Sig.
High.C.Low.P.Strong High.C.Low.P.Weak	-0.850	0.447	-1.901	0.057	0.172
High.C.Low.P.Strong High.C.Low.P.Incongruent	-1.100	0.447	-2.460	0.014	0.042
High.C.Low.P.Weak High.C.Low.P.Incongruent	0.250	0.447	0.559	0.576	1.000

Overall	
High: α-Pinene Low: Citral	
N	20
Chi-Square	9.658
Asymp. Sig.	0.008

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.P.Low.C.Weak High.P.Low.C.Strong	0.775	0.316	2.451	0.014	0.043
High.P.Low.C.Weak High.P.Low.C.Incongruent	-0.875	0.316	-2.767	0.006	0.017
High.P.Low.C.Strong High.P.Low.C.Incongruent	-0.100	0.316	-0.316	0.752	1.000

Trained	
High: α-Pinene Low: Citral	
N	10
Chi-Square	2.000
Asymp. Sig.	0.368

Untrained	
High: α-Pinene Low: Citral	
N	10
Chi-Square	8.769
Asymp. Sig.	0.012

Pairwise Comparisons (Sample 1 - Sample 2)	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adjusted Sig.**
High.P.Low.C.Weak High.P.Low.C.Strong	1.050	0.447	2.348	0.019	0.057
High.P.Low.C.Weak High.P.Low.C.Incongruent	-1.200	0.447	-2.683	0.007	0.022
High.P.Low.C.Strong High.P.Low.C.Incongruent	-0.150	0.447	-0.335	0.737	1.000

Table 7.10: These tables show the results from performing a Friedman's Two-Way Analysis of Variance by Ranks. The higher table shows an overall statistically significant difference, while the lower shows the break down of pairwise comparisons (only if a statistical significant difference is found). Where no statistical differences were found, no pairwise breakdowns are shown. I refers to IsoAmyl Acetate, P refers to α-Pinene, and C refers to Citral. Significance values have been adjusted by the Bonferroni correction for multiple tests (significance level p $<$0.05). The Null hypothesis assumes the distribution of the strong, weak, and incongruent data are the same.

Blank 1 Overall	
N	20
Chi-Square	1.680
Asymp. Sig.	0.641

Blank 1 Trained	
N	10
Chi-Square	5.160
Asymp. Sig.	0.160

Blank 1 Untrained	
N	10
Chi-Square	1.080
Asymp. Sig.	0.782

Blank 2 Overall	
N	20
Chi-Square	2.820
Asymp. Sig.	0.420

Blank 2 Trained	
N	10
Chi-Square	3.000
Asymp. Sig.	0.392

Blank 2 Untrained	
N	10
Chi-Square	1.320
Asymp. Sig.	0.724

Table 7.11: These table shows the results from performing a 'Related Samples Friedmans's Two-Way Analysis of Variance' on the data from the two blank trials. (significance level p $<$0.05).The Null hypothesis assumes the distribution of the four ranking datasets are the same.

7.3.4 Blanks

Blank trial results were processed using a Related-Samples Friedman's Two-Way Analysis of Variance by Ranks. This test was chosen since the data was rank based and thus ordinal, the sample population was random (in the context of this experiment), and the responses were essentially 4 different sets of results from the same group. For these trials, there was no correct answer and participants were essentially guessing, whether they were aware of this or not. The values for scoring each rank were taken as is i.e. "1" = 1, "2" = 2, "3" = 3, "4" = 4, and were processed as so.

Table 7.11 shows the results of these tests for the blank conditions conditions.

7.4 Discussion

This experiment aimed to investigate the possibility of olfactory attention masking effects in the context of a two smell environment, to see whether one odour would show a selection preference across a sample population when presented at the same time and at the same perceptual intensity as another. With this in mind, a series of statistical analyses were performed on results obtained from performing the method outlined above.

As shown above, all results were processed using appropriate statistical tests to check for statistically significant differences (p $<$0.05) between groups of data for the same set of participants. For each condition, three sets of results corresponding to the participant groups are shown: the Overall group (N=20), the trained group i.e. the participant group used in Chapter 6 (n_t=10), and the untrained group i.e. new randomly selected participants (n_u=10).

Table 7.6 shows the result of Wilcoxon Rank Sum Tests across the three single ”low” odour conditions on the three groups. In all three groups a statistical significant difference between congruent and incongruent rankings can be seen, which shows evidence that participants were able to distinguish the between when an odour was present (N_p=0.000, $n_{t\,p}$=0.005, $n_{u\,p}$=0.005). Additionally, in each of the three groups, all responses show a positive rank (denoted by a ”b”) which would indicate that participants were able to correctly determine the correct odour. In such a case, the incongruent scoring would be higher than the congruent, as correct ranks assigned by the participant would have a lower value, and this is shown in these results.

Table 7.7 shows the result of Wilcoxon Rank Sum Tests across the three single ”high” odour conditions on the three groups. These results are largely similar to the single odour ”low” conditions which gives evidence that participants were able to distinguish odours from no odours (N_p=0.000, $n_{t\,p}$=0.036, $n_{u\,p}$=0.006). In this condition, overall three out of the twenty had difficulty correctly identifying the correct odours (based on the ranks they assigned).

Table 7.8 shows the result of Wilcoxon Rank Sum Tests across the three dual ”low” odour conditions on the three groups. These results shows that the majority of overall participants were able to distinguish the two odours being presented as evidenced by the p values for each of the conditions with the exception of the trained Citral.α-Pinene and untrained IsoAmyl Acetate.α-Pinene groups (Low Citral.α-Pinene N_p=0.006, $n_{t\,p}$=0.107, $n_{u\,p}$=0.020; Low IsoAmyl Acetate.α-Pinene: N_p=0.020, $n_{t\,p}$=0.038, $n_{u\,p}$=0.206; Low IsoAmyl Acetate.Citral N_p=0.003, $n_{t\,p}$=0.016, $n_{u\,p}$=0.086). In all three groups, the same relationship is seen where certain pairs of odours are more readily identified as shown by the positive ranks (denoted by a ”b”) across groups and pairs though not as well as under single odour conditions. The positive ranks show that lower value scores were assigned to the correct odours since the incongruent scores would then have higher scores i.e. (1+2=3) congruent ¡ (3+4=7) incongruent. When ranked on successfully identified pairs Citral.α-Pinene scores lowest and IsoAmyl Acetate.Citral scores highest which would indicate α-Pinene is less distinguishable compared to the other odours under ”low” concentration conditions and thus be the least olfactorily salient of the three odours.

Table 7.9 shows the result of Wilcoxon Rank Sum Tests across the three dual ”low” odour conditions on the three groups. Similar to the ”Low” conditions, the same general trend is seen again showing the majority of participants being able to distinguish the two odours being presented as evidenced by the p values and ”positive ranks” in the analyses, for each of the conditions with the exception of the trained Citral.α-Pinene, IsoAmyl Acetate.α-Pinene, and IsoAmyl Acetate.Citral groups (High Citral.α-Pinene N_p=0.010, $n_{t\,p}$=0.301, $n_{u\,p}$=0.008; Low IsoAmyl Acetate.α-Pinene: N_p=0.002, $n_{t\,p}$=0.119, $n_{u\,p}$=0.006; Low IsoAmyl Acetate.Citral N_p=0.005, $n_{t\,p}$=0.033, $n_{u\,p}$=0.066). Again this points the least olfactorily salient of the three

odours being α-Pinene.

Table 7.10 shows the result of Friedmans's Two-Way Analysis of Variance across the six "High-Low" conditions on the three groups. While the data shows participants can distinguish in certain cases between specific sets of conditions, it is clear that there are fractured relationships within specific trials which can be most likely be attributed to a lack of data and thus a small population size. Statistical differences can be seen for individual pairings across the this set of results though more data would be needed to make a comprehensive conclusion. As a result it becomes difficult to discern whether specific odour shows a selection preference by participants. Table 7.12 shows a summary of individual pairwise comparisons where statistical significances were found:

Grouping	**High Condition**	**Low Condition**	**Pairwise Comparison**	**Sig.**
Overall	IsoAmyl Acetate	α-Pinene	Strong-Weak	0.002
Overall	Citral	IsoAmyl Acetate	Strong-Incongruent	0.002
Overall	IsoAmyl Acetate	Citral	Weak-Incongruent	0.004
Overall	Citral	α-Pinene	Strong-Incongruent	0.001
Overall	α-Pinene	Citral	Weak-Incongruent	0.017
Trained	IsoAmyl Acetate	α-Pinene	Strong-Weak	0.030
Trained	IsoAmyl Acetate	Citral	Weak-Incongruent	0.016
Trained	Citral	α-Pinene	Strong-Incongruent	0.005
Untrained	Citral	IsoAmyl Acetate	Strong-Incongruent	0.008
Untrained	Citral	α-Pinene	Strong-Incongruent	0.042
Untrained	α-Pinene	Citral	Weak-Incongruent	0.022

Table 7.12: Summary of the individual pairwise comparisons where statistical significances were found in the High-Low conditions (significance level $p < 0.05$).

Overall the data shows that Citral is readily distinguishable when paired with α-Pinene to the point where α-Pinene will be ignored, even in the case where a higher perceptual intensity of is presented with a low intensity Citral. Citral is also readily distinguishable when presented with IsoAmyl Acetate whether at a low or high intensity condition. This provides some evidence that there is an attention masking effect present and that Citral is overall the most olfactorily salient odour of the three.

Table 7.11 shows the result of Friedmans's Two-Way Analysis of Variance across the two blank trials. No statistical significance is found for either of the blank conditions which is to be expected since no odour was presented, so all answers would be a guess. The lack of a significance also suggests there is no inherent bias in the experimental design to sway participants towards certain ranking answers.

Overall there weren't any large differences between data on the trained and untrained groups, which was hypothesised. However, the analyses now reflect this and show there doesn't appear to be any inherent bias between the group used in Chapter 6 and the additional participants recruited for this study.

In summary, from these results, there is evidence to suggest that Citral is the most olfactorily salient odour of the three compounds and α-Pinene is the least olfactorily salient. This is shown by the higher proportion of correct odour distinction when citrate is present in dual odour mixtures either at similar or non-similar perceptual intensities. The presence of these saliency effects, in which participants were more inclined to pick certain odours, gives credence to the possibility of olfactory attention masking effects.

(Most Salient Odour) **Citral** >**IsoAmyl Acetate** >α**-Pinene** (Least Salient Odour) (7.1)

The preliminary findings from this experiment lays out a groundwork for further studies to investigate olfactory masking phenomena. In this small study, the evidence shows that it could be possible to forgo the use of α-Pinene or IsoAmyl Acetate when using it in the same virtual environment scenario as Citral. However to build a more comprehensive view of olfactory attention masking, additional research would need to be conducted with additional odours and with much larger population sizes.

7.5 Summary

This chapter outlined a procedure for attempting to discern whether olfactory attention masking phenomena existed in the context of a two smell environment, to see whether one odour would show a selection preference across a sample population when presented at the same time. Statistical differences could be seen for all single conditions and dual equal intensity conditions which showed participants were readily able to distinguish single odours and the majority were able to correctly distinguish odours at the same perceptual intensity. Citral stood out as being the most salient in terms of showing statistical differences against α-Pinene and IsoAmyl Acetate, even in trials where it was presented as the lower intensity.

Chapter 8

Conclusion

This chapter summarises this thesis' research and novel contributions to knowledge, providing the final conclusions that are drawn from the collective work, outlines limitations and states potential future work that can be carried out to compliment and continue this research.

8.1 Olfaction For Virtual Environments

The contents of this thesis aimed to address the problems of olfactory presentation for use in the context of virtual environments, which had been identified after carrying out an extensive literature review into the field. The core content focused around the delivery aspect of this presentation, having identified the need for calibrated olfactory stimuli. As discussed, in greater detail earlier in this thesis, the large majority of research using olfactory stimuli in virtual environments, is not calibrated such that it can be said with certainty what is actually being presented to participants during studies. There is also a general failure to state the conditions under which the stimuli was presented that is relevant to olfactory phenomena. The majority of researchers in literature do not outline the odour concentrations used or any of the atmospheric conditions present at the time of during their experiments or even address whether they took these factors into account. This makes it near impossible to repeat their work. This inherently makes it difficult to verify conclusions, should any studies be replicated. Other researchers can attempt to infer details from literature but this can lead to other problems like gross oversimplification of conditions, or focus on the wrong part, or ignoring the need to take any conditions into account. These conditions could be crucial for arriving at a particular conclusion.

In attempt to rectify these issues, this thesis provides a detailed approach for producing accurate and precise olfactory stimuli via the design of a calibrated olfactory display or 'olfactometer'. Chapter 5 outlines 2 procedures which, when completed for a given odour or volatile

compound, is able to provide accurate, precise, and consistent (repeatable) outputs.

While the olfactometer addressed the need for accuracy and repeatability on a physical level, a framework was outlined to address the need for accuracy and repeatability on a perceptual level. Many factors affect peoples' smelling ability so presenting a fixed concentration of odour may not necessarily have the same affect on different people. The framework provides a way of calibrating odour thresholds to a perceptual level for humans to smell regardless of their smelling ability.

As a way of showcasing the ability to produce both accurate, precise, and consistent olfactory stimuli presentation along with the ability to produce perceptually equivalent olfactory smell thresholds, a study was proposed to examine the potential existence of a olfactory attention masking phenomena in humans.

8.1.1 Calibrated Olfactory Delivery

Chapter 5 outlined a novel attempt at odour delivery by detailing a design of an olfactory display which is capable of consistently delivering sub-ppm concentrations of volatile odours, as well as incorporating the inclusion of individual properties of VOCs to improve concentration accuracy, namely vapour pressure in given conditions. The olfactometer was based on a sealed airflow design so used a simple 'volume of air in, volume of odour out' design, by which the air throughput was limited by a computer controlled gate and a pressured air supply at 202 kPa (2x typical atmospheric pressure). The olfactometer had a simple design but most importantly satisfied three main criteria which made it ideal for use in research within virtual environments:

- High Accuracy: The reproduction of real world equivalent olfactory stimuli, specifically in the context of concentration matching to ppm level.
- High precision: The repeatability of outputting said stimuli, such that the desired output is consistently and equally accurate across presentations.
- Low Cost: Having a low cost device, means it can be easily deployed for other research and a greater adoption means more researchers can benefit from the high accuracy and precision in their experimental studies.

The device had one main requirement to work correctly and produce the same accurate repeatable outputs. The volume of air above a given volatile compound (liquid or solid) needed to be fully saturated with the compounds gaseous counterpart. In any given sealed system, a natural equilibrium forms between the compound in its different phase states. This equilibrium and thus the concentration of gaseous compound is dependent on the atmospheric conditions, the

Table 8.1: Table showing the recovery rates of each of the three odour compounds, used throughout this thesis, under the specific atmospheric conditions: temperature 293K, atmospheric pressure 101kPa, and humidity +50%.

Compound	Perceived Smell	Headpsace Recovery Rate cm.s^{-1} (3 s.f.)
IsoAmyl Acetate	Banana	0.00794
α-Pinene	Pine	0.00575
Citral	Lemon	0.000552

most important being the temperature and pressure in the system. Under a set of given conditions, a steady state will be established between both sides such that the rate of vapourisation will reach the rate of condensation. It was for this reason, the experimental conditions used in this thesis remain consistent across all the work: temperature 293K, atmospheric pressure 101kPa, and humidity +50%. While the humidity does not value is not important in the context of this specific equilibrium, it is important for when the odour is outputted to any users. This means when gaseous odour is outputted, the remaining volume in the sealed vessel becomes diluted and the equilibrium needs time to re-establish the steady state to undo the dilution.

As a result to get consistent odorous stimuli, in terms of concentration, the time taken to recover this steady state must be known. Naturally this time will be proportional to the amount of odour removed from the headspace. Bearing this in mind, an analysis on the recovery rate at which a volatile odour is replenished from its liquid form was done, on three target odorous molecules: IsoAmyl Acetate, *alpha*-Pinene, and Citral. These odours were selected for both their chemical and physical properties, but also had characteristic smells which were familiar and easily identifiable which made them useful for use in human participant studies. Through the use of infra-red spectroscopic methods, recovery rates were determined for each of the compounds and are summarised in table 8.1. The recovery rate is proportional to the volume of headspace available in the sealed vessel (cm^3), the surface area interface from which the compound can vaporise (cm^2) and the time taken for the recovery to complete as shown by the infra-red spectra of the timed measurement (t). When dividing the volume by the time surface area and time, a final unit, cm.s^{-1}, is given. Naturally this can be converted to other units as necessary.

Following this validation of odour headspace, a calibration of the olfactometer output was conducted. Since the output was directly proportional to the input, a simple measurement of the real output, in ppm, could be used correlated to the input conditions. A photoionisation detector (PID) sensor was chosen for this measurement due to it robustness, and while they are available commercially in standalone handheld units, a separate sensor array was built using

Compound	Linear Fit of Calibration	R^2
IsoAmyl Acetate	y = 1.499x	0.9621
α-Pinene	y = 3.5166x	0.8771
Citral	y = 0.2382x	0.9849

Table 8.2: Summary of linear graph fits to the various outputs for each of the odours. The y-axis refers to concentration in ppm and the x-axis refers to the volume of throughput used in a given presentation in ml or cm^3.

a microcomputer with multiple PIDs. This gave flexibility in its use but also allowed for the measuring of any volatile compound, odorous or not, by following the procedure outlined. After measuring the output at different flow rates, by varying the percentage opening on the gate and time of the burst, a calibration chart was obtained for each of the three odours. Table 8.2 shows the summary of linear graph fits to the various outputs for each of the odours. The y-axis refers to concentration in ppm and the x-axis refers to the volume of throughput used in a given presentation in ml or cm^3. Again, a linear fit is used because the two axis a directly proportional due to the sealed 'volume of air in, volume of odour out' design. The graphs also have a strong fit as demonstrated by the R^2 being close to one (perfect fit).

By creating a calibrated olfactometer odours can be presented at appropriate concentration ranges equivalent to real world conditions. This design also aimed to standardise smell presentation by focussing on the properties of molecules and using that data in a calibration process to obtain repeatable results. The proposed framework provided can be used with any other VOCs via the use of readily available data lookup tables (for specific chemical/physical property values at given conditions). In the case where certain values might not exist, these can be simply obtained experimentally. While the olfactometer is calibrated by the sensor array, these are two different tools each with novel design elements and uses. Additionally both the olfactometer and sensor array devices have the flexibility of adding, in theory, unlimited numbers of additional smell channels or sensor cells, respectively. By providing odours at the accurate, and precise real world equivalent concentrations, researchers can attempt to create environments with the knowledge that they are providing reliable smell experiences which offer the highest fidelity but in such a way that environments designed will be repeatable. The benefits of this olfactometer design also extends outside the domain of virtual environments and as such can be used in other scenarios where calibrated olfactory stimuli are required.

8.1.2 Human Olfactory Perception Calibration

The work in chapter 6 attempted to address the need for a generalisable approach to creating odour thresholds for presentation of olfactory stimuli. It outlined a procedure for a perceptual calibration of three odours (IsoAmyl Acetate, α-Pinene and Citral) for humans and the calculation of generalisable odour thresholds. These thresholds provided a concentration of a given odour, where it could be said with relative certainty, not only that a given population would be able to perceive it, but specifically at the same perceptual intensity i.e. a high intensity smell for one person will be perceived as a high intensity smell for someone else.

These makes them extremely useful for carrying out olfactory research, especially for virtual environments, since it simplifies the process of recreating olfactory conditions whilst giving an assurance that participants will be able to experience similar conditions, and in general makes this area of research more accessible for researchers. There is also the possibility to calculate JND_{nC} values for different smells and link them across odours so that equivalent intensities can be matched accordingly, which again can be very useful for multi-odour studies. The procedure can be used to create new thresholds for other odours, Assuming the same conditions could be met, the procedure could be used to calibrate for any other smell.

JND_n	JND_1			JND_2		
Odour	IsoAmyl Acetate	α-Pinene	Citral	IsoAmyl Acetate	α-Pinene	Citral
JND_{nC} /ppm	1.8813	11.58	2.164	4.8603	24.48	2.9976

Table 8.3: Final calculated JND concentrations (JND_{nC} values), in ppm, for each of the JND plots. The α values describe the Δ value between the pedestal and the 75% point for JND_n. Thus for the final values of JND_{nC} for a given smell and step, the α value is added to the pedestal, where the pedestal is: 1ppm for JND_1, and JND_1 for JND_2.

There is one main requirement needed to produce other generalisable odour thresholds:

- Be able to produce an odour output at discrete concentrations with high accuracy and precision.

  For the work in this thesis, the three odours chosen had already been calibrated for with a novel olfactometer calibration under a specified set of conditions as discussed in chapter 5. Thus the thresholds determined in this chapter could be considered equivalent across odours for any JND_{nC} values above the 1ppm mark. Creating additional odour threshold levels i.e. JND_{nC} values for these same smells require the following conditions:

  - under a temperature of 293K
  - under an atmospheric pressure 101kPA
  - under a humidity of +50%

Chapter 6 outlined a procedure for a perceptual human calibration. This allowed for the calculation of just noticeable difference concentration thresholds which can be used as generic high and low concentration points for three difference odours, IsoAmyl Acetate (JND_1 0.8813ppm, JND_2 2.0453ppmppm), α-Pinene (JND_1 10.58ppm, JND_2 23.48ppm) and Citral (JND_1 1.164, JND_2 1.9976ppm). These determined stimuli levels can subsequently be utilised as generalisable points for further experimental use with participants when investigating both olfactory phenomena and relationships between olfactory and other sensual stimuli.

8.1.3 Olfactory Masking Investigation

Finally Chapter 7 investigated possible olfactory masking effects between the three calibrated odours in the context of a two smell environment, to see whether if one odour would show a selection preference across a sample population, when presented at the same time. Statistical differences could be seen for all single conditions and most dual ”equal perceptual intensity”

conditions, which showed participants were readily able to distinguish single odours and the majority were able to correctly distinguish odours at the same perceptual intensity. Some statistical differences could be discerned from the "High-Low" dual pairings but largely are lacking. This is ultimately a problem which stems from a lack of data which could be rectified in further studies with more participant data. Table 8.4 shows a all statistical significances found in this experiment.

Overall there weren't any significant differences between data on the trained and untrained groups, which was hypothesised. However, the analyses now reflect this and show there doesn't appear to be any inherent bias between the group used in Chapter 6 and the additional participants recruited for this study.

Across these results, Citral stood out as being the most salient in terms of showing statistical differences against α-Pinene and IsoAmyl Acetate, even in trials where it was presented as the lower intensity, whilst α-Pinene showed to be the least salient with the lowest level of distinction, both standalone and in dual conditions.

(Most Salient Odour) **Citral** $>$**IsoAmyl Acetate** $>\alpha$**-Pinene** (Least Salient Odour) (8.1)

Chapter 7 outlined the preliminary findings and laid out a framework for further studies to investigate olfactory masking phenomena. In this small study, the evidence shows that it may be possible to exclude the use of α-Pinene or IsoAmyl Acetate in the same virtual environment scenario as Citral, due to it's high relative saliency. However to build a more comprehensive view of olfactory attention masking, additional research would need to be conducted with additional odours and with much larger population sizes.

8.1.4 Beyond Research

While the frameworks, devices and experiments described in this thesis was geared towards olfactory research in virtual environments, these methods can applied to contexts outside this context. There are many commercial settings, as mentioned earlier, which require or would benefit greatly from both physically and perceptually calibrated olfactory stimuli. Examples could include virtual re-enactments or digital cultural heritage projects for accurate portrayals of past historic times and settings, education and training where professionals like fire fighters or doctors can recreate conditions to prepare them for real life events like a burning building or complex surgery, and multimedia entertainment consumption to add new levels of immersiveness to their experiences.

Condition	Group	Sig.
Low Single	Overall	0.000
Low Single	Trained	0.005
Low Single	Untrained	0.005
High Single	Overall	0.000
High Single	Trained	0.036
High Single	Untrained	0.006

Condition	Odour 1	Odour 2	Group	Sig.
Low Dual	Citral	α-Pinene	Overall	0.006
Low Dual	Citral	α-Pinene	Untrained	0.020
Low Dual	IsoAmyl Acetate	α-Pinene	Overall	0.020
Low Dual	IsoAmyl Acetate	α-Pinene	Trained	0.038
Low Dual	Citral	IsoAmyl Acetate	Overall	0.003
Low Dual	Citral	IsoAmyl Acetate	Trained	0.016
High Dual	Citral	α-Pinene	Overall	0.010
High Dual	Citral	α-Pinene	Untrained	0.008
High Dual	IsoAmyl Acetate	α-Pinene	Overall	0.002
High Dual	IsoAmyl Acetate	α-Pinene	Untrained	0.006
High Dual	Citral	IsoAmyl Acetate	Overall	0.005
High Dual	Citral	IsoAmyl Acetate	Trained	0.033

Grouping	High Condition	Low Condition	Pairwise Comparison	Sig.
Overall	IsoAmyl Acetate	α-Pinene	Strong-Weak	0.002
Overall	Citral	IsoAmyl Acetate	Strong-Incongruent	0.002
Overall	IsoAmyl Acetate	Citral	Weak-Incongruent	0.004
Overall	Citral	α-Pinene	Strong-Incongruent	0.001
Overall	α-Pinene	Citral	Weak-Incongruent	0.017
Trained	IsoAmyl Acetate	α-Pinene	Strong-Weak	0.030
Trained	IsoAmyl Acetate	Citral	Weak-Incongruent	0.016
Trained	Citral	α-Pinene	Strong-Incongruent	0.005
Untrained	Citral	IsoAmyl Acetate	Strong-Incongruent	0.008
Untrained	Citral	α-Pinene	Strong-Incongruent	0.042
Untrained	α-Pinene	Citral	Weak-Incongruent	0.022

Table 8.4: Summary of all statistically significant results across all trial data from the study

8.2 Contributions

This thesis set out to answer the following research question:

How can a generalisable approach for recreating real world olfactory conditions in virtual environments be created?

This main research question was optimised into the below question based on context from literature, since it was identified that some of the biggest challenges when using olfactory stimuli in virtual environments revolved around key aspects of the delivery of said stimuli:

- How can physical and perceptual olfactory accuracy be best approached?

The primary contributions of this thesis was providing two frameworks which each allow for the physical and perceptual calibration of olfactory stimuli, respectively. The physical accuracy is achieved through the design of an olfactometer calibrated by a novel gas sensor array. The perceptual accuracy is achieved through the outlining and implementation of a framework which allows for the calculation of perceptually generalisable olfactory concentration thresholds, where perceived odour intensity is equivalent across people and can be matched to be equivalent across individual odours.

Having created a framework for producing physical and perceptually accurate olfactory stimuli, the next logical step was to use tools created to answer a crucial question for olfaction in virtual environments:

- Can olfactory masking effects between multiple odour stimuli be quantified?

This question is important since it has the potential of reducing computational cost which has big ramifications for virtual environment generation. An example could be if a computational fluid dynamic simulation was required to show the movement of odours through an environment so that the correct concentration was delivered to the user from the olfactometer to match the simulated 'expected' concentration in the simulation. If it was found a particular odour overrides another in certain contexts, the savings in computation in not having to model two smells would be significant.

An attempt is made at answering this secondary question, however, while the experimental design is robust, the number of participants required to have a far more conclusive result need to be far higher to achieve statistical significance. There is evidence, however, to suggest the existence of a masking effect in which there is a preference of certain odours over others. This

could be potentially due to a olfactory saliency affect in which certain odours may be more salient than others, though more participant response data across more odours with varying smell characteristics would be needed to validate this.

The specific contributions of this thesis are outlined below:

- A novel design for olfactory display which is calibrated and provides high accuracy delivery of olfactory stimuli.
- A procedure so that any other odours can be calibrated to give the same level of accuracy and precision.
- A flexible design for a low cost gas sensor array capable of measuring volatile odours to sub-ppm level.
- A validation framework for calculating headspace recovery rates of volatile odorous compounds, which can be employed with any airflow based olfactometer to prove the accuracy of the output is repeatable.
- An outline for a framework which allows for the creation perceptually generalisable olfactory thresholds across odours, where perceived odour intensity is equivalent across people and can be matched to be equivalent across individual odours.
- An experimental procedure to quantify possible attention masking effects that may occur between odours in a multi-odour context, with evidence to suggest the existence of such an effect.

8.3 Limitations

There are some limitations in the work which is outlined in this thesis. While the greatest amount of effort was taken in trying to make the frameworks outlined as flexible as possible, there are still some issues which may not be applicable to all researchers or users, but are still nonetheless present. There is also some niche cases where certain problems void the calibrations without adapting the frameworks accordingly.

The ionisation sensitivity of the compounds are dependent on the energy emitted by the ultraviolet light lamp in the cell. This means if a particular compound is very thermodynamically stable, it becomes difficult to ionise and thus detect. However, this is unlikely to be a common problem since the majority of odorous compounds are organic (carbon based), and these types of molecules are readily ionisable.

The digital mass flow controller used in this olfactometer design and calibration was able to produce percentage outputs of 1L per minute. For this reason, in chapter 6, the starting pedestal value chosen for the study was 1ppm, since this was lowest possible reliable output for the three odours. It could be possible to use a mass flow controller with finer gate controls, however this requires increasingly expensive hardware for diminishing returns. It could yield smaller JND_{nC} values which could be useful where certain odours are perceived as too strong even at very low concentrations.

The current state of the device is not made for portability but could easily converted into a portable setup. All eletrical compounds could run off a battery but the main drawback of a portable system would be the need for a portable air supply i.e. a tank of air. This would make the device very heavy and bulky which can put strain on participants, though would open the door for more interactive and mobile virtual environments. Its current form factor is more suited to stationary or 'cave' type virtual environments. One potential solution would be to use a portable air compressor though this still doesn't alleviate the weight/space issue.

One thing that can't be be addressed without changing the atmospheric conditions of the environment, is that certain compounds are just very volatile or non-volatile at room temp (293k). In most cases, smells are volatile at the temperature, which is the reason we're able to smell them so readily. However, for niche scenarios, it becomes difficult to generate specific odours since they either vaporise and dissipate too quickly, or do not vaporise at all without being heated heavily. Heating any compounds breaks the inherent rules the calibration framework outline in chapter 5, so any odours used in this way will not be calibrated and thus not accurate, precise or repeatable.

With regards, to the human olfactory perception calibration outlined in chapter 6, the biggest limiting factor of this work is the sample size used. It's accuracy as a generalisable threshold across humans is dependent on a very high sample population of participants, since the more people there are, the more representative the resulting JND_{nC} values will be. It would be fair to say the population sizes for both experiments were relatively modest for both the studies in chapters 6 and 7, however, it should be stated that the work in the former is there to provide a framework for bigger studies and is more of a proof-of-concept. In the case of the later, had a large enough population size been used, possible correlations could be drawn between specific demographics and smelling ability which could be very useful information in other studies.

8.4 Future Work

A sensible piece of future work would be to increase the number of participants used in chapters 6 and 7 but specifically the latter. While some conclusions could be drawn from the results

of the olfactory masking investigation, the statistical power of the sample size is far too low. Ideally, a lot of participants would be added and the results recalculated to include the new participant responses. Again, the work in chapter 6 is mainly there to provide a framework JND_{nC} concentration values, but with more initial particpants for each JND_{nC}, the thresholds would move towards a more representative value, so that more people would be able to smell at the level. Essentially, the value would move towards a theoretical mean value for the bell curve of that given threshold level for that odour.

There are many dimensions to extend the work outlined in this thesis by both using the frameworks outlined but also iteratively improving on the frameworks themselves. Continuing on from the findings of this work, it would be sensible to test the saturation rates for more substances, with a wide variance of vapour pressures to verify the trend between vapour pressure and saturation rates shown in figure 5.8. This immediately grants more freedom in the substances that can be tested, so one can simply look up specific vapour pressures and find suitable compounds which match the value and other properties, to avoid doing a new calibration and use an existing one. In general it would be beneficial to the research community to calibrate more odours, so that they can be used to create increasingly richer virtual environments.

Whilst small variations in temperature and pressure are likely to not have a large affect on both calibration and saturation measurements, it would still be interesting to explore the extent of the temperature dependence as within a broader range, to examine and classify any relationships. This would also test the versatility for this framework with regard to temperature and pressure dependence. This could also extend the framework to allow for condition flexibility, for temperature, pressure and/or humidity, if appropriate trends were found and validated when testing for the odours dependence on them individually or compounded.

8.5 Final Remarks

As stated at the start of this thesis, olfaction within VR is still a niche field, though an important one. There are still many challenging obstacles to overcome before perceptual equivalent virtual environments become available. However, the work presented in this thesis was meant to provide a platform as a starting point, and while does not provide all possible support, will hopefully help others advance the field.

Appendix

Appendix A: Python code for capturing sensor readings

```
from ABE_ADCPi import ADCPi
from ABE_helpers import ABEHelpers

i2c_helper = ABEHelpers()
bus = i2c_helper.get_smbus()
adc = ADCPi(bus, 0x68, 0x69, 18)

import time
import datetime

starttime = datetime.datetime.now()
def writetofile(texttowrtite):
f = open('adclog.txt', 'a')
f.write(str(datetime.datetime.now()) + " " + texttowrtite)
f.closed

while (True):

writetofile("Channel 1: %02f\n" % adc.read_voltage(1))
writetofile("Channel 2: %02f\n" % adc.read_voltage(2))
writetofile("Channel 3: %02f\n" % adc.read_voltage(3))
writetofile("Channel 4: %02f\n" % adc.read_voltage(4))

print ("Channel 1: %02f" % adc.read_voltage(1))
print ("Channel 2: %02f" % adc.read_voltage(2))
```

```
print ("Channel 3: %02f" % adc.read_voltage(3))
print ("Channel 4: %02f" % adc.read_voltage(4))

time.sleep(0.5)
```

Appendix B: Participant sheet for perception calibration experiment

Participant ID:

Which has the stronger smell, 1 or 2?

☒ Mark the appropriate box

Trial	1	2
1	☐	☐
2	☐	☐
3	☐	☐
4	☐	☐
5	☐	☐
6	☐	☐
7	☐	☐
8	☐	☐
9	☐	☐
10	☐	☐
11	☐	☐
12	☐	☐
13	☐	☐
14	☐	☐
15	☐	☐
16	☐	☐
17	☐	☐
18	☐	☐
19	☐	☐
20	☐	☐

Appendix C: Participant sheet for olfactory masking experiment

Participant ID:

What do you smell?

Rank from 1 to 4 in the appropriate boxes
(with 1 = strongest smell, and 4 = weakest)
Mark any guesses with an *

Trial				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				

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