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INCORPORATING SCENTS INTO VIRTUAL EXPERIENCES

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ABSTRACT

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The present aim was to investigate the effects of odor congruency and dynamism on recall of objects encountered in a virtual reality (VR). The effects on emotional responses were also investigated. First, participants (N=8) interacted in a maze-like VR environment with 12 virtual 3D objects. Eight of the objects had a scent, and half of the participants received objects where the scent was static, half objects where it was dynamic. In the dynamically scented objects the intensity of the odor changed according to the interaction so that the closer the virtual object was to the user the stronger was its odor. The congruency of objects and odors were also varied so that some objects had a semantically congruent odor and some had an incongruent odor. Following this the participants were to list as many encountered objects as they could. After this, the participants interacted again with the same stimuli and rated their experiences in terms of emotion related valence and arousal.

Results showed that odor congruency or dynamism did not have an effect on the amount of recalled objects. Odor dynamism did not affect valence ratings, but congruent objects were rated to be more pleasant than incongruent or odorless ones. Odor congruency or dynamism did not affect arousal ratings. As the number of participants was small, the experiment would need to be continued to find out if the nonsignificant trends of better recall of congruent and dynamic objects would become statistically significant.

Key words and terms: olfaction, virtual reality, olfactory display.

Contents

1. Introduction

Olfaction, or the ability to smell is one of our oldest senses and a crucial one in our everyday lives. Odors give us information about the edibility of food as well as if a situation is potentially dangerous. Olfaction also has direct routes to the areas of brain where emotional responses are processed, and experiences are encoded and processed further to long term memory. Therefore, odors can have intertwined effects on cognitive processes such as memory, emotions, learning and task performance.

Most of us know how smelling a specific odor, like freshly cut grass, can bring back pleasant memories from childhood. The connections have been shown in numerous studies as well. There is evidence that scented environments increase emotional responses, feelings of presence and memories of that environment, and scented objects tend to be remembered better and later recognized faster than unscented ones [Tortell et al. 2007, Krishna et al. 2010, Munya III et al. 2016]. Adding scents to objects tends to make them more distinctive from their environment, which means they will attract more attention and are more efficiently encoded to long term memory. Another hint of the strong connection between olfaction and memory is that weakened sense of smell is also an early sign of developing brain diseases that have negative effects on memory, like Alzheimer's disease [Jokelainen and Pulliainen 2004].

Because of the strong connections, the utilization of odors has raised interest in research in number of different areas. In the past couple of decades, especially the possibilities of incorporating odors into virtual reality (VR) has been researched much more. Virtual reality in its most basic form with only visuals and audio has already been effectively used in areas such as education, training, medical use, or simply for entertainment.

Designing VR to support multiple human senses or making it a multisensory experience by stimulating the five senses of vision, hearing, touch, smell, and taste, can have a number of positive effects on the feelings of presence and immersion inside a virtual environment (VE). There has been plenty of evidence for this, as increasing the number of sensory feedback channels in interaction seems to increase the sense of presence and therefore the amount and quality of emotions and memories of that experience in the VE [Dinh et al. 1999]. Humans perceive the real world with multiple senses, and if a virtual experience stimulates only some senses and completely ignores the rest, the experience will never feel as real as it could.

Adding odors to VR has been seen to have useful applications in creating odorous virtual environments for various areas such as entertainment, education, training or treatment of mental and physical health, as well as for research on the connections between multisensory processing, attention, memory, and emotions. Multisensory virtual reality can offer an easy to conduct, less time and money consuming option for these areas.

Odors can be delivered through olfactory displays, that carry scents to the user's nose. These displays can be used together with VR headsets. A range of different technical solutions have been tried to deliver the scents effectively.

Even though making VR a multisensory experience is facing increasing interest, the focus of research has for a long time mostly been on the dominant senses of vision and hearing, and sometimes touch, both inside and outside of virtual reality development. As virtual reality technology has been improving, the visuals and accompanying audio have become increasingly high quality and therefore immersive. But because incorporating odors has such clear additional benefits, and there are still some limitations and problems related to stimulating olfaction, it is worth trying to find out the best ways of adding odors to VR.

Main part of this thesis is in studying the effects of odors inside a virtual reality environment. Studying the subject will give important insights to help in the future research of incorporating odors into multisensory virtual reality experiences. Knowing what kind of scents are the most effective in which usage situation, what kind of qualities should the scents have, and in what way should they be delivered, will help to make odorous virtual experiences better.

In real life, the odor of an object will intensify when it is brought closer to the nose, but at the moment the same rule does not apply in virtual environments. Until now it has been suggested that especially congruent odors inside a virtual environment increase visual information recall at least in the short term. But how natural the scents should be in terms of intensity change when a scented object is moved closer and further from a person? The purpose of the experiment is to study whether changing the intensity of an odor in virtual reality has any effect on memory and emotions. The most important expected outcome will be the effects on visual information recall accuracy. The other expected outcome is the effects on emotion related valence and arousal ratings. A setup utilizing digitally controlled clean and scented air circulation, and a mask will be used to deliver the odors.

This thesis consists of seven chapters. First the theoretical background is discussed; chapter 2 will concentrate on multisensory virtual reality and olfactory displays, and chapter 3 on human olfaction. After that, the conducted experimental research will be discussed in chapters 4 and 5. Chapter 6 summarizes the thesis and discusses the future of odors in virtual experiences.

2. Scents in Virtual Reality

As human beings, we mostly perceive the world with multiple senses, often with all five of them. Take, for example, a forest scene. We can see the nature around us, we hear the birds singing, feel the shape of the ground below our feet, smell the flowers, and possibly taste the berries we find. The experience is a very holistic one, and we can most probably remember many details from the forest if we are later asked.

For many decades, we have been trying to recreate the wholeness of this sort of real experiences with technology. In the history of multisensory experiences, many technical difficulties have been faced, and especially the incorporation of scents into these experiences has been difficult. There have been problems in controlling the delivery of scents and matching them with visual stimuli, and the challenges persist. However, combining scents with virtual reality might be able to bring improvements to this area. In VR any type of object can be coupled with any type of odor, and together with accurate odor producing devices it creates endless possibilities for research and other domains. The interest towards coupling scents with VR has increased over the years, and the technologies have become increasingly efficient as well.

In this chapter the principles of virtual reality and the creation of multimodal presence within the virtual reality, especially by incorporating scents, are discussed. The underlying sensory integration processes are also reviewed, as well as the concept of olfactory displays. Finally, the role of olfaction in multisensory virtual reality is discussed regarding the possible applications the technology might bring.

2.1. Multisensory Virtual Reality

The concept of virtual reality is an old invention and some sort of devices have already existed for many decades. Many definitions and devices have been placed under the term, but in this thesis, VR can be described as a computer-generated, three-dimensional experience, that tries to simulate physical presence in the virtual environment by realistic sensory stimulation. Other close forms of VR are the augmented reality (AR) and mixed reality (MR), and all three of these can be placed under the umbrella term extended reality (XR).

The amount of virtual and real components in an experience can be described with the Reality-Virtuality Continuum, where the scale goes from real-world environments to completely virtual ones [Milgram and Kishino 1994]. VR is usually considered to be on the far right of the scale (see Figure 1).

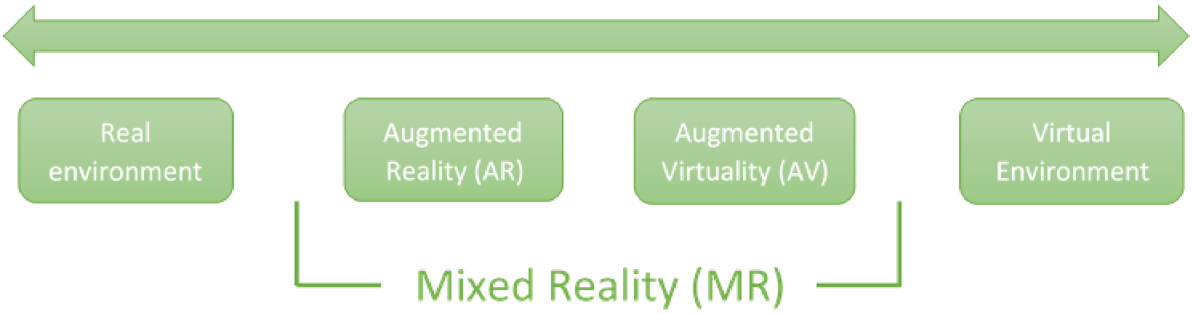

Figure 1. Reality-Virtuality Continuum. Adapted from paper by Milgram and Kishino [1994].

Even though VR devices have existed for decades, as has the consumer interest towards them, the technology really experienced a revolution in the 2010s. Before that, the devices existed mainly in research labs and as relatively simple consumer products. The reason for the late boom was in the many problems the technology had, such as a relatively high price tag, motion sickness symptoms caused by, for example, low frame rates, bulkiness of the headsets that caused discomfort in prolonged use, eye strain, and the risk of injury by moving around and tripping.

VR technology has seen fast development of more advanced and inexpensive devises over the years, and that is why VR has become increasingly known and widespread in both research use and in consumer markets. After 2010 the first Oculus Rift development kit became available and many others followed, such as the HTC Vive and the PlayStation VR. Today, the VR-industry is growing fast and new devices using state of the art technology allowing seamless virtual experiences are developed.

From the beginning, the goal of the development has been to make VR as immersive as possible, or in other words to induce a deeper sense of presence, by trying to stimulate real-time perception in a realistic way. For a virtual experience to be effective, a sense of presence is essential [Nichols et al. 2000]. When a person is fully immersed in a virtual world, the person is deeply engaged in the events happening in there and can ignore the real world outside. Many technological solutions have existed to create deeper immersion extending from rooms where each wall has images projected onto them (i.e. CAVE-systems), to headsets including head-mounted displays (HMD). Desktop-based solution with just a computer screen can also be counted as VR.

Virtual reality experiences can be described as multisensory experiences when considering the range of senses humans have and utilizing them as interaction modalities. If a virtual environment uses only some sensory feedback channels and completely ignores the rest, the experience might not feel as real as it potentially could. Therefore, in the quest of making VR a more realistic and immersive experience, the incorporation of multiple senses has raised interest.

The appeal towards multisensory experiences dates back to as far as the early 1900s, when there were multiple attempts in combining odors with cinema. Perfumes were, for example, sprayed from the ceilings to the theatre rooms. There was, however, problems with the uneven spreading and unwanted mixing of the scents. In 1960s Hans Laube created a system for scented films called the Smell-O-Vision. The system used 30 different scents that were released in accordance with the events of a specific film.

In the 1960s the first truly multisensory device was created by Morton Heilig. He invented the Sensorama, a device that was developed to stimulate several different senses. With the device the users could immerse themselves into a motorcycle ride through a city. The Sensorama included a stereoscopic screen showing the landscape, audio, fans creating the sensation of wind, odor diffusion to smell the city, and a tilting seat (see Figure 2).

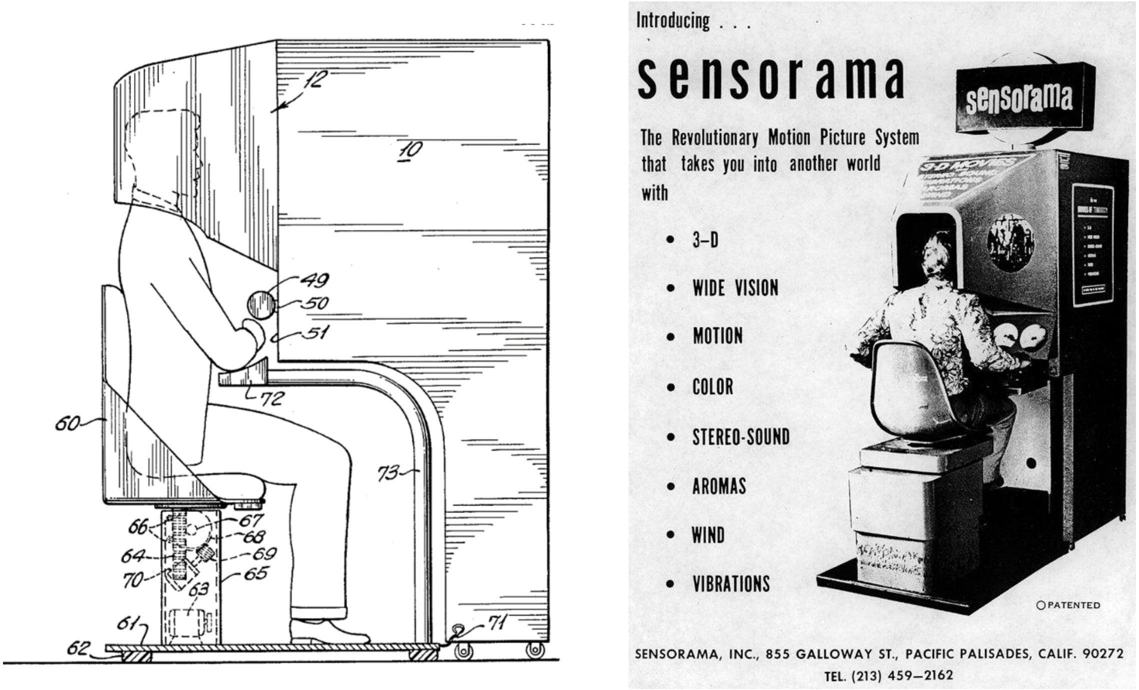

Figure 2. The Sensorama. Reproduced from Heilig [1962].

Both Heilig and Laube were very much ahead of their time, as multisensory VR has still not been comprehensively utilized, regardless of the technological advancements from their days. The focus of the research and development of VR, as well as more generally the whole field of human-technology interaction, has mostly been on the dominant senses of vision and hearing, and increasingly also touch. The quality of audio and video has constantly improved, and the sense of touch has also been successfully stimulated with devices such as vibrating controllers, haptic gloves, force feedback devices, wind machines, whole body suits, and omnidirectional treadmills.

The other senses of olfaction and gustation, on the other hand, have mostly remained untouched, partly also because of the technical difficulties of stimulating these senses.

It has been understood that increasing the graphics and audio quality only goes so far. After a certain threshold, adding more visual detail to VR does not seem to increase immersion nor memories of the experiences [Dinh et al. 1999]. This has been explained by the inherent inferiority of virtual experiences to real ones; adding more visual detail and quality does not change the fact that we can still see the difference between the real world and virtual reality. Compared to reality with all its high-quality visual cues, VR is still very graphically limited.

Utilizing also other sensory modalities, especially touch, olfaction and hearing, might increase immersion more effectively than increasing visual detail [Dinh et al. 1999]. Increasing the number of sensory feedback channels in interaction can help in shifting attention from the real world into the virtual one [Tortell et al. 2007]. When user's attention is fully focused on the virtual environment (VE), the user can have increased feelings of presence, as if the virtual experience was a real-world experience.

As the user is more immersed and perceiving the VE as a real environment, a number of positive effects on cognitive processes like emotions, memory, learning and task performance can emerge. Realistic-feeling experiences have the power to evoke higher emotional responses, and as the user of the VR is highly immersed and emotionally invested, both the amount and quality of memories of the virtual experience seem to increase [Tortell et al. 2007].

As explained in chapter 3, olfaction has significant advantages over the other senses, as the sense of smell is strongly connected to important brain areas processing memory, emotions and associative learning. As has been discussed, multisensory VR has been shown to have plenty of positive effects on cognitive processes. This applies particularly well to odors as part of multimodal interaction.

Odors in VR can be used as ambient ones or object-specific ones. So far, the findings in experiments made with both ambient and object-specific odors in VR follow the findings of traditional research of olfaction in that odors can trigger deeper emotional responses like pleasantness and arousal [Bensafi et al. 2002, Spence et al. 2017, Salminen et al. 2018], improve engagement and attract attention to the VE [Tortell et al. 2007], as well as increase the sense of presence [Tortell et al. 2007, Munya III et al. 2016, Dinh et al. 1999, Baus and Bouchard 2017]. Olfactory cues can also significantly improve memory for the contents of VE [Rantala et al. 2019, Tortell et al. 2007, Dinh et al. 1999]. Other general effects of odors could have the potential to emerge in VR interaction as well, like improved learning and task performance. The fact that presenting certain odors can affect the evaluation of, for example, visual stimuli, should be investigated in VR as well [Li et al. 2007].

Creating an even more effective version of multisensory reality by including odors in the interaction has the capability to be revolutionary in the human-technology interaction area. Odor stimulation could find a place in VR if the challenges are resolved and applications for scents are discovered. Scents as a natural part of VR is still in the future, but with extensive research the usage and the approval could be found.

2.2. Odors as Part of Multimodal Perception

In order to understand the underlying processes behind the increased immersion in multisensory experiences versus unisensory ones, we first need to understand how human perception and attention work. When we know how each of the senses interact with the others inside the brain, we will know how to utilize multiple sensory modalities the most effective way. We will also know how scents would work the best as part of the experience.

Multimodal or multisensory perception is the way by which the human nervous system and brain gathers information from different senses and combines them into a coherent perception of the world. The brain combines the information in a way that different sensory stimulations are merged into a single perception if they are congruent enough with each other. Any given sensory stimulus can have attributes of location, duration and intensity. Therefore, when integrating different sensory inputs, the brain needs to know where the stimulus is coming from, how long it lasts, is it constant or changing, and how strong it is. The closer the inputs are spatially, temporally and semantically, the more likely they are integrated into a single perception.

Our previous experiences and knowledge of the world influence perception to create semantic congruence and help either integrate or segregate stimuli. If there is an object, for example, an apple, we expect a certain type of smell based on our previous experiences with apples. If, however, we see the apple but smell banana instead of an apple, our brain segregates the incongruent visual and olfactory stimuli and concludes the smell of banana is coming from somewhere else.

The different sensory modalities can also interact with each other and affect the functioning of the others, as the resources for attention are always somewhat shared between the senses [Lavie 2005]. What would be the best combination of different sensory stimuli in that case?

On one hand, humans are a very visually dominant species. The ventriloquism effect is a well-known phenomenon where sound tends to be mistakenly localized to visual stimuli that the person is concentrated on. The same sort of visual-dominance phenomenon exists between vision and other sensory modalities as well, such as when adding color to a food or drink can affect its perceived taste and smell [Morrot et al. 2001].

On the other hand, when perceiving the world, the most useful modality usually changes according to the situation and the attributes we are interested in an observed object. When it is about three-dimensional qualities and location, vision is the best tool, and when it is the chemical properties, smell is the most accurate one. The weakness or uncertainty of a given sensory stimulus can also affect the likelihood of resorting to other senses than the dominating vision. In case of weak visual stimuli, even olfaction can dominate over visual information [Kuang and Zhang 2014].

As the importance of one sense in the whole blend of multisensory perception depends on the context, even a weak signal might be enough under certain conditions to induce a certain effect. Combined with visual stimuli, other, complementary sensory stimuli can be very subtle and still be effective. This is especially good news for the development of effective multisensory VR, as even a small amount of information delivered in a virtual environment might be adequate to evoke a certain perception. Research is needed for finding out, for example, how little of certain odorant is needed to make effective odorous VR experiences. What might also become important is that stimuli should not be made to compete for attention, but to make each of them work in synergy, similar to real life, in order to preserve performance [Gallace et al. 2011].

Our perception is based on electric signals travelling from our sensing organs to the brain through neural pathways, and we should take this into consideration when developing multisensory VR. It has been suggested that VR should not be based so much on how similar the content in VR and real world are, but instead on how to make the content of VR to induce neural activation, similar with real world content [Gallace et al. 2011]. Here neuropsychology will be of great help in understanding how the brain actually processes sensory stimuli, and in the case of odorous VR we can benefit from knowing what kind of amygdala and hippocampus activation certain odors elicit.

2.3. Olfactory Displays

Bringing scents to be a part of multisensory VR requires specific type of olfactory technology. Traditionally the word display has had the meaning of a visual display, but the word olfactory display (OD) has been used to describe the counterpart specialized in stimulating olfaction instead of vision. The basic idea behind an olfactory display is the processing and producing of a scent, either authentic or synthetic, and delivering it to the user’s nose for them to be able to smell it. The quality, concentration, duration, timing, and other variables can be modified with specialized hardware and software. Olfactory displays have been used in many different settings, by themselves and coupled with, for example, VR devices. The combining of ODs with VR headsets is a relatively new area of technology.

The technology in olfactory displays can be divided into producing the odors and delivering them to the nose. Many types of systems exist, for delivering only one scent or multiple ones, and producing them specifically for one object or creating an ambient odor. There are many different solutions but most of the current olfactory displays are made for specific research purposes, and they are not very versatile in terms of scalability, and they are also often quite expensive. It is difficult to deliver a variety of scents accurately in different intensities, and in a compact form.

After the first devices made for multisensory experiences described in chapter 2.1 such as the Sensorama, many attempts to make commercial olfactory devices have been made. Those attempts have so far been very simple, without truly being able to accurately control the produced odors or synthesize more than a handful of scents. Most of the past attempts to commercialize a sent device have failed, like the iSmell by DigiScents (https://web.archive.org/web/20070115214649/http://www.pcworld.com/article/id,13263-page,1/article.html) that failed mostly because there were no markets for scent producing devices of that type. There are a few devices that are currently in the market like the smartphone-controlled scent diffuser Scentee (https://scentee-machina.com/), and the Olorama (https://www.olorama.com/) that is meant for diffusing odorants into the air when watching, for example, films or advertisement. Many of these types of devices are simple fan-based systems placed on a table with just a handful of scents.

The few ODs that are meant to be coupled with VR headsets also do not have any scientific evidence to prove their effectiveness in enhancing user experience. Two examples of the most recent commercial devices that are meant to be used with existing VR headsets are the FeelReal (https://feelreal.com/) and the VAQSO (https://vaqso.com/). FeelReal can hold nine aroma capsules that can be changed according to the wanted experience. They claim that their device can be used to enhance games, movies, aromatherapy, and meditation. VAQSO is similar, but it can contain five scent cartridges that can be selected from 15 available scents. The problem is again that the solutions are not very versatile and there is no scientific evidence to back up their claimed effectiveness. The odors are also not dynamic, as in real life they would be.

Next, the different methods for producing and delivering scents with olfactory displays are reviewed.

2.3.1. Producing Scents

Natural odors are very complex in their chemical structures, and the number of volatile organic compounds (VOCs) in each odor makes it difficult to reproduce them accurately. Every odor is different in their chemical compositions and how they behave in each setting. Odor mixtures are especially difficult, as there are no basic odors that can be mixed like in colors there are the basic colors that produce all the other colors.

Most of the olfactory displays developed have used synthetic odors to mimic authentic odors by selecting just a few of the components present in natural smells [Thomas-Danguin et al. 2014]. The first step in producing synthetic scents is the selection of those odor components. It seems that synthetic odors can be just as efficient as authentic odors and perceived as natural if the right key odor components from the complex natural scents are picked. Some synthetic odors might, however, be perceived as less natural than others, if they are associated with some other synthetically scented products.

It can be difficult to predict how a certain odorant will be perceived based only on its chemical structure, but there has been an effort in modeling odor perception with machine learning algorithms. The model by Keller et al. [2017] can be used to predict the intensity and pleasantness of an odor, as well as semantic descriptions of "garlic", "fish", "sweet", "fruit", "burnt", "spices", "flower", and "sour". These models could be used to enhance the user experience of odor producing devices.

As the human nose is equipped for sensing odors from the air, the second step in producing odorants is that they need to be vaporized as they are often in liquid form. In their review of olfactory displays, Yanagida [2012] explains four different vaporization methods: natural vaporization, vaporization by air flow, vaporization by heating and vaporization by atomization.

The first one, natural vaporization, works without any mechanical interference, such as heating or airflows. It has relatively low controllability, and the delivery can be slow. Sensorama was one of the first systems using this method by using jars containing odorants that were opened to release a scent. The second one, vaporization by air flow, speeds up the natural vaporization. This can be done either by saturating the air with odorant vaporized from the surface of the liquid, directing air directly into the liquid and forming bubbles that release scented air, or by channeling air through a solid material like gel or porous material. The third method is heating, which has been traditionally used, for example, in incense burning. The fourth method is atomization, where small drops of the odorant form a mist that can spread in the air. This can be achieved with sprayers, diffusers, ultrasonic waves, or an ink-jet printer.

In multi-odor systems there also needs to be a mechanism to easily change the odor or blend multiple odors together. Smells can be difficult to change as fast and accurately as images and sounds. For example, mass flow controllers or solenoid valves have been used for this, as they can be used to digitally control the airflows. The techniques of vaporizing, blending, and switching of odors should be selected based on the type of application. For a good user experience the timing of odor switching should be made as accurate as possible.

2.3.2. Delivering Scents

There are multiple different delivery methods explored in research, and the most appropriate method seems to depend on the type of application, how many people the scent needs to be delivered to, and whether there is additional technology like a VR headset involved.

In the review by Yanagida [2012], six scent delivery methods are presented: natural diffusion, airflows, vortex rings, directing the scents through tubes from a device that is placed either off-body or on-body, and devices placed near the nose. The methods are illustrated in Figure 3.

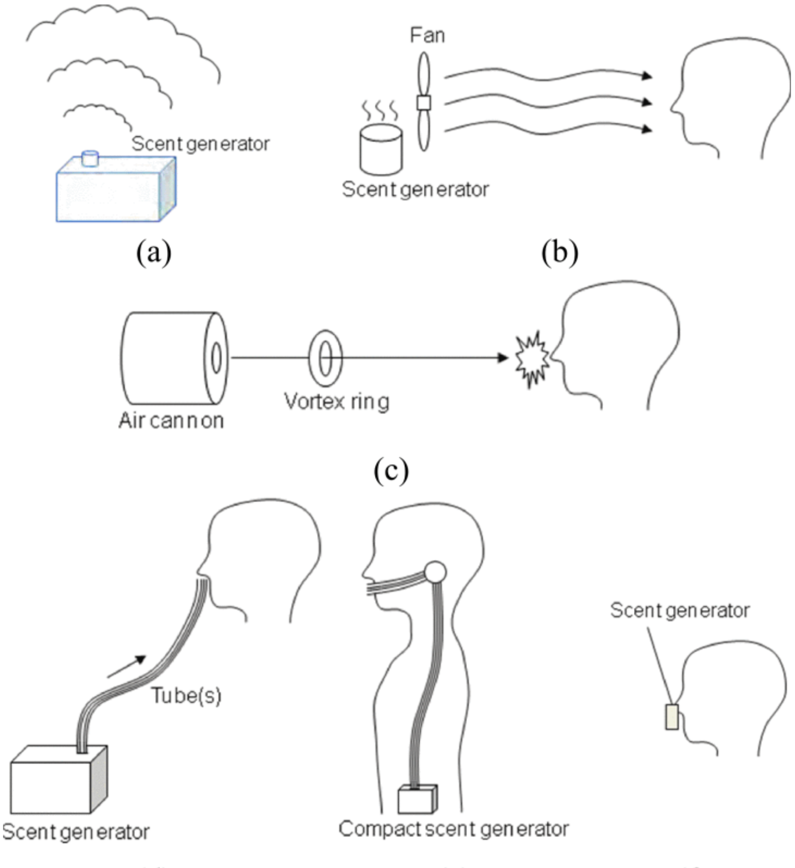

Figure 3. Scent delivery methods illustrated by Yanagida [2012]. © [2012] IEEE

The first delivery method, natural diffusion, is the traditional method used, for example, in household scent diffusers. These are usually placed on a table. This method is suitable for ambient odor release as a whole room can be scented with it.

In the second method the scented air can be directly routed to the direction of a user with airflow. Fans and pumps placed anywhere in a room are often used to achieve this. A cooking game by Nakamoto et al. [2008] used fans to direct food scents to the user and Matsukura et al. [2013] used four fans to combine air flows in the air and direct them accurately to the user's nose. Hasegawa et al. [2018] developed a device that delivered scents with ultrasound-driven airflows. The airflow could be accurately controlled electronically.

In the third method a vortex ring of scented air can be shot with an "air cannon" directly to the user's nose, more accurately than with airflow. It can be done with fans or pumps placed near the user. Yanagida et al. [2004] used head-tracking to detect the position of the user's nose, and then shot a scented vortex ring from an air cannon towards the nose.

The natural diffusion, airflow, and air-cannon devices can all be placed in the environment and hence are not too noticeable or intrusive. On the other hand, it can take time for the scent to reach the user, and the scent might be left completely unnoticed if it does not reach the user. The cleaning of the air of the old scent is also more difficult with these sorts of devices, and there has not been a proper functioning solution for this yet. Tsaramirsis et al. [2020] tried fixing the odor persistence by releasing the scents according to a smart algorithm and sucking the scented air back, but the problem of aromas mixing with each other accidentally still persisted.

The fourth method is the usage of tubes to carry scented air from a scent generator that is located on, for example, a desk. Salminen et al. [2018] used an olfactory display placed on a table, that carried scented air through tubes to a mask worn on face together with a VR headset.

The fifth method is an on-body device that can be either carried or is attached to the user. The scents can be transferred through tubes that go directly from, for example, clothes or a backpack to the nose, or alternatively releasing scents to the air from, for example, a collar or necklace. A helmet or another type of head-mounted device can also be used. Yamada et al. [2006] developed a miniaturized airflow-based olfactory display worn outdoors in a backpack that changed the odor intensity levels according to the distance from a virtual odor source. Dobbelstein et al. [2017] created a necklace odor diffuser that was used to amplify phone notifications. Amores and Maes [2017] also created a necklace type device that was used to affect the mood and cognitive performance of a user.

The sixth method is a scent generator that is directly placed near the nose and might even inject the odorants directly to the nose. Wang et al. [2020] demonstrated the usage of lightweight on-face olfactory interfaces by building four different versions of a display. They all resembled jewelry placed on face or were attached to eyeglasses. The results showed, however, that on-face devices might be less comfortable and less socially accepted than off-face devices like necklaces, and the perception of the scents does not change between off-face and on-face devices. The scents were not perceived by outsiders but were perceived by the user in both cases.

The fifth and sixth methods can be considered as wearable devices. The user experience can be improved when using wearable devices as the concentration, temporal accuracy, and disruptions from the natural air movements can be better controlled because of the reduced distance from the device to the nose. Wearables can, however, be intrusive, cumbersome, and noticeable by others. They can also only be used for one person at a time. Murray et al. [2016] suggests that displays worn on body like a collar or displays attached to clothes, could have more potential than those near the nose, because of the intrusiveness issue.

All these six methods have their drawbacks, and each of them might work in different usage cases. What has become a desirable objective especially in scent displays combined with VR devices, are the wearable, compact scent generators that contain all the necessary technology in a miniaturized form either near the nose or carried on body. These sorts of lightweight displays could be attached to VR headsets.

In recent years the incorporation of scents into VR has sparked many research attempts. An example of an OD used together with VR devices is the study of Tortell et al. [2007]. They used a collar that released scents from cartridges towards the nose while the user was playing a VR game. The scents and their strength and duration could be changed.

Hashimoto and Nakamoto [2016] also developed a miniaturized olfactory display that could be used together with a VR headset. The aim was to minimize the distance between the display and nose as this has been thought to be effective in reducing odorants to spread, as well as in reducing the quantity of odor components needed. Wearable olfactory display was thought to be best suited form for their technology.

Narumi et al. [2011] made an air-pump type OD for augmented biscuit eating. The users ate a real unflavored biscuit while wearing a VR headset that showed a virtual biscuit. The OD released different scents and together with the visuals made the users think the biscuit was flavored.

When designing an odorous VR experience to make either the objects or surroundings of a VE smell certain way, it is important to deliver olfactory stimuli according to the user's movements and actions within the environment, both spatially and temporally. There is one part that is still missing from the ODs for VR; dynamic change of odor intensity. It might make the interaction with virtual objects feel more natural if the odor became stronger the closer the source is to the nose.

There are several issues to pay attention to when designing odor delivery mechanisms regarding odor perception in humans. One issue is preventing adaption in a longer use. Kadowaki et al. [2007] developed an ink-jet ejection device to deliver odorants in small bursts according to breathing patterns of a user. The reduced amount of odorant in the air resulted in reduced adaptation.

Another issue is the spreading and persistence of a scent in the air. For a temporally accurate experience, odors should be removed from the air efficiently, and this has been a problem especially in the airflow and diffusion type of displays.

The environmental smells need to be controlled as well. If they are not controlled, they could change the user's perception of the situation in VR, if there is an odor that is completely unfitting in the situation [Spence et al. 2017].

Olfactory displays are also said to be quite passive, requiring only inhalation. In response to that Niedenthal et al. [2019] developed a handheld olfactory display that was used together with a VR headset. The authors claimed that the benefit of a handheld device is its naturalness in grasping and moving an object and then sniffing it. The smells are automatically attributed to the grasped objects, and they have a natural intensity control and ventilation through the hand movement. Of course, this type of device cannot be used for ambient scents or for scents that should be coming further from the VE.

2.4. Applications of Scented Virtual Reality

As there are clear benefits in integrating multiple senses, and especially odors, into VR, the utilization in different areas of technology and research has raised interest and multiple possible applications for multisensory and odorous environments have been suggested. The progress has, however, been slow and there has been little luck in commercialization attempts, especially when it comes to adding odors into the equation.

The number of VR applications that could potentially benefit from including olfactory stimuli, however, is vast as the VR experiences can induce deeper sense of presence, and as a consequence produce similar physical reactions and emotions as the experiences in the real world [Lombard and Ditton 1997].

The example domains explained in this chapter that could benefit from scented VR include entertainment, education, training, health, and research. Murray et al. [2016] and Spence et al. [2017] have also made reviews of the different applications. As the field is constantly growing and better technological solutions are invented, more application areas can emerge.

The first domain in which scents have been seen to add value, is the entertainment business. Scented cinema and VR experiences were the first ones to see development, in the form of, for example, the Sensorama and Smell-O-Vision. In the recent decades, more research has been done on the scented film and gaming experiences. For example, Nakamoto and Yoshikawa [2006] presented scents together with a film and showed that they could control the level of attention people paid to certain scenes in the film. Later, they also created a more interactive experience, a cooking game, where manipulating the ingredients, like meat, onion and curry, in the game resulted in odors of the same ingredients to be released [Nakamoto et al. 2008].

Other possible areas in entertainment are the cultural experiences of museums, theatres, and tourism. Adding scents to multisensory VR could make games, films, and other cultural experiences more realistic and engaging, and more development is likely to be seen in this domain in the near future.

The second domain is education. VR in general has the advantage of having easy to control environments as well as being cost-effective and safe. It also has characteristics that support learning such as being immersive, interactive, and making complex and abstract concepts visualized in an understandable way. Medical and military training as well as driving and flying simulators have already used VR successfully.

It has been suggested that including multiple sensory modalities in education can improve learning, as that is the way we have evolved to learn in natural settings as well, and there have already been promising results from the research in this area [see reviews of Murray et al. 2016, Shams and Seitz 2008]. As olfactory stimuli can make the user immersed, concentrated, and emotionally invested, the experience can facilitate learning and performance. The learning process can all in all be much more engaging than a traditional one. Odors have the ability to improve memory and recall of experienced events as well, so the learning experience in general as well as more details could be better remembered.

Having a controlled, versatile and affordable multisensory environment is a useful and promising solution in many areas of medicine and general wellbeing. As mental disorders and phobias have become increasingly common, an alternative to the traditional exposure therapy in the treatment of phobias and PTSD has been found from the safe and effective virtual reality exposure therapy (VRET). In exposure therapy the patient is exposed to the source of fear response in a controlled way, or alternatively imagining a traumatic experience. For example, in spider phobia the patient is first exposed to pictures of spiders and then eventually real ones. Slowly the fear response is conditioned to disappear completely.

For VRET to be effective, the virtual environment needs to be realistic and cause the same kind of physiological reactions as a real environment would and be able to be generalized to real situations [Krijn et al. 2004]. As odors have the potential to increase the physical and emotional responses in encountered experiences, incorporating odors into VRET could be extremely beneficial. Scents also have the ability to evoke otherwise hard to remember memories, which can help in the process of, for example, treating post-traumatic stress disorder caused by traumatic events.

Odorous VR can be used in other forms of rehabilitation as well, in both physical and mental health problems. Beneficial effects of odor-evoked memories on psychological and physiological health and wellbeing have been widely recorded. Positive autobiographical memories can reduce stress, negative emotions, and cravings as well as strengthen self-esteem, connection to one's past and social connectedness [Herz 2016]. Smell of lavender or orange can also be used for relaxing in uncomfortable medical operations or to relief stress in general.

People with sensory disabilities, such as deafblind people, might benefit from certain sensory replacement in VR as well. Replacing visual and auditory stimuli with haptic, olfactory and gustatory stimuli allows more people to enjoy VR experiences.

The incorporation of olfactory stimuli into VR offers interesting opportunities also for research and product design. In behavioral and cognitive sciences, the ecological validity in research is essential. Sometimes the real world is not an option to study certain complex phenomena, such as emotions, so they would often need a more realistic and controlled setting for the experiments in the laboratory. Multisensory VR has the power to offer all these. All variables of a virtual environment can be controlled, and multiple senses can be stimulated, which gives researchers a tool that effectively and realistically simulates real world settings in a desired way to gain reliable empirical data.

The interplay of odors, emotions, attention and memory is challenging to investigate, but with VR it can be made easier. There are still many open questions about human olfaction, and these could be addressed with the help of odor enhanced VR.

3. The Sense of Smell

Olfaction or the sense of smell is one of our oldest senses in terms of evolution, allowing us to sense important chemical signals from the environment. In everyday life, olfaction is an essential sense for identifying edible food, detecting dangers like the smell of smoke, finding potential mates, and identifying family members. Often olfaction works together with vision to add a necessary layer of chemosensory perception.

Odors do affect us in many ways, changing our subconscious behavior and thought processes, changing our mood and increasing wellbeing. Odors have also been said to be essential in remembering previous life experiences.

Olfaction is one of the least studied senses as it has for long been considered a lesser sense than, for example, vision and hearing, and because there has not been accurate technology for both stimulating olfaction and testing the functioning of olfaction [Hummel et al. 2016].

This chapter discusses the general view on human olfaction. In chapter 3.1 the focus is on the special characteristics of the sense of smell, in 3.2 in the perception of different odors, in 3.3 in the different positive effects of odors, and in 3.4 in the reasons behind olfactory dysfunction.

The principles of odor memory regarding the neuroscience behind its connections to emotions, and the special phenomena of odor-evoked memories and memory enhancing effect of odors are discussed in chapter 3.5.

3.1. Characteristics of the Sense of Smell

The sense of smell is part of the chemosensory system of human perception. Together with the sense of taste or gustation it forms a sophisticated system for sensing chemicals that enter our bodies through the mouth and nose, and determining whether they are safe to consume or possibly dangerous. The functions of olfaction can be divided into ingestion (e.g. recognizing food, appetite control), detecting environmental hazards (microbial and non-microbial threats), and social communication (e.g. detection of potential mates, emotional contagion of fear and safety) [Stevenson 2009].

The role of olfaction is to sense airborne VOC that are in gas phase or dissolved in microscopic drops of water in the air while inhaling. The inhaled chemicals travel to the nasal cavity where they attach to some of the 6-30 million olfactory sensory neurons found in the olfactory epithelium. Each of the neurons is sensitive to multiple different molecules that can attach to its receptor, and each molecule can attach to multiple different receptors. That is why we can differentiate as many as 1 trillion olfactory stimuli [Bushdid et al. 2014]. A certain odor will yield a perception only if at least one of the detection, recognition, or differential thresholds are met.

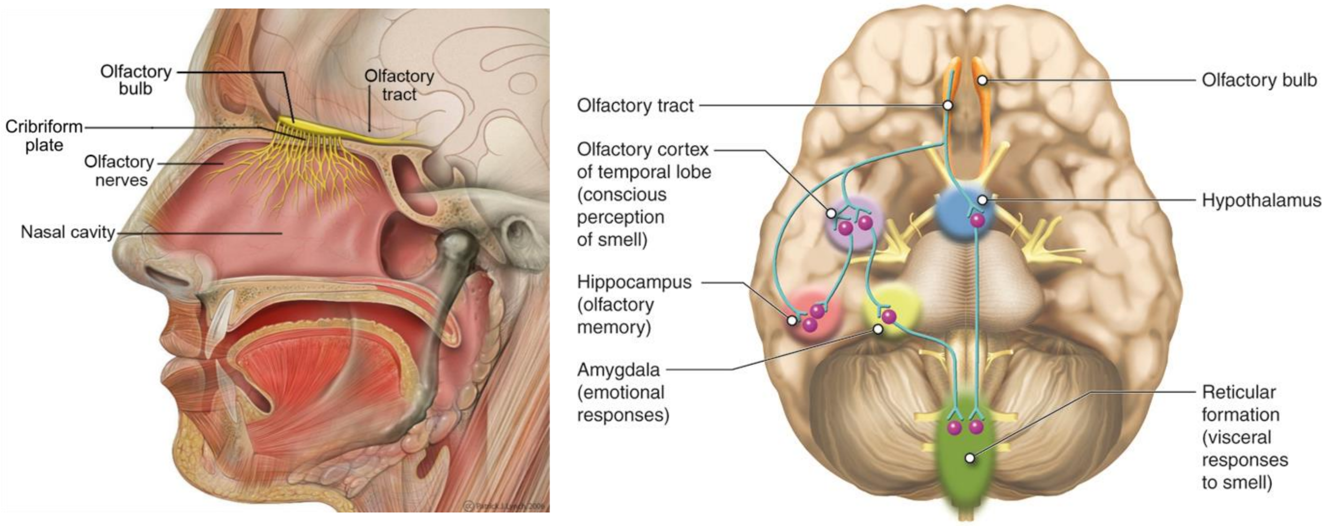

Figure 4. On the left olfactory nerve by Peter J. Lynch, and on the right the connections between the olfactory tract and central nervous system by Cenveo. Both images used under the CC BY 4.0: *https://creativecommons.org/licenses/by/4.0/*

From the neurons in the epithelium electrical signals about the chemical structures of the molecules are routed to the olfactory bulb that is responsible for sending the information forward to the primary (e.g. piriform cortex, amygdala) and secondary olfactory cortex. These areas are important for the processing of emotions, memory, and associative learning.

The olfactory tract is special also in that it is the only sensory tract that goes directly to these areas without passing through the thalamus [Sabri et al. 2005]. The special connections in the olfactory tract and the early intervening of the limbic system in odor processing form the basis for the strong associations between odors, memory and emotions that is discussed in more detail later in this chapter.

The olfactory cortex has several subareas that are suggested to be involved in different functions in olfactory perception and encoding. The different areas of the olfactory tract are responsible for the detection, discrimination, recognition and identification (knowing the name) of odors, as well as for determining their intensity and pleasantness [Savic 2005, Royet 2001]. Almost all types of olfactory stimuli activate the piriform cortex and the amygdala in the olfactory cortex [Savic 2005]. Other brain areas are activated simultaneously as well, for example, when needing to know if a certain odor comes from consumable food, the visual cortex activates [Royet 2001].

3.2. Perception of Odors

Most natural scents are compounds of many, even hundreds, of VOCs, but only a few of those are usually recognized by humans. For example, a strawberry contains over 360 VOCs. Because we cannot differentiate all the chemical compounds in an odorant, scents have been usually classified by the most distinct components to categories such as earthy, flowery, and fruity. Many different classifications have been used. Scents can also be divided into groups based on perceptions of scent qualities like pleasantness, intensity and familiarity.

Despite of having a relatively small area for the functions of olfaction in the nose and brain, humans have a good sense of smell. Although the intensity discrimination needs as much as 20% increase to be detectable compared to the 2% brightness increase required in vision [Rouby et al. 2002], the discrimination of different smells is far better than the discrimination of other sensory stimuli, with the ability to differentiate more than 1 trillion olfactory stimuli [Bushdid et al. 2014], and even on very low concentrations. The reason for detection, discrimination and recognition of odors being better than intensity estimation or identification is that those may have been more important for survival [Cain 1979].

How an odor is perceived depends on multiple factors, not only on the chemical composition of the odor or its intensity [Thomas-Danguin et al. 2014], but also on biological and emotional factors.

Thomas-Danguin et al. [2014] suggested a model about in which odor concentration affects perception of intensity, chemical structure affects perception of quality, and odor quality (mainly molecular structure) as well as cognitive factors affect perception of pleasantness. This is the case with simple odorants, but the effects of odor mixtures are not as well defined. More research is needed in determining if the same factors apply for complex mixtures.

Biologically, on average women do better in odor recognition than men, but the abilities of processing odors vary from person to person. There is much more variability in olfactory sensing than in other senses, because olfaction is not inter-subjective, that is, humans do not perceive smells the same way because there are not many shared inborn reactions in odor perception. [Rouby et al. 2002]

Firstly, everyone has a unique olfactory receptor set, so some people are more sensitive to certain odors than others [Keller et al. 2007]. Secondly, we learn to associate odors to certain meanings and emotions through our life experiences [Robin et al. 1999]. Familiarity and the ability to name the odor affects how well it is detected and recognized [Rabin and Cain 1984], as well as if the smelled odor fits the expectations of the associations formed in the brain between the odor and a visual object [Degel and Köster 1999].

People grown in the same culture might have some shared odor preferences due to the shared cultural experiences, but the only inborn reactions are the reactions to smells of dead bodies and decayed things like rotten foods [Rouby et al. 2002]. The smells of environmental hazards related to microbial threats tend to evoke the feeling of disgust and smells related to nonmicrobial threats the feeling of fear as well [Stevenson 2010].

It has been claimed that pleasant and unpleasant odors are processed differently in the brain. Similar to other negative sensory stimuli, malodors also induce stronger and quicker responses in physiological and psychological processes, such as autonomous nervous system activity, emotions and social responses [Delplanque 2008]. It has likely been relevant for survival to spot malodors efficiently from the environment. It has also been noticed that a stronger odor is perceived more easily as being unpleasant than a weaker one [Hertz 2016].

Olfaction differs from the other senses in another interesting way. Most people have difficulties imagining odors the way visuals or audio are imagined [Tempere et al. 2014]. So, imagining a certain odor might only activate the name of the odor, the memories and emotions associated with it, and whether it is a pleasant or an unpleasant smell.

Another difficulty in olfaction is that it is very hard to describe and discuss olfactory perceptions, as there are not many words in languages to describe odors, and they do not form a continuum like, for example, colors do. Most of the time odors are discussed regarding their origin, that is, coffee smells like coffee, and the ability to use any other type of descriptions requires training. The link between language and olfactory stimuli seems to be much weaker than in other senses.

Olfaction is also quite closely interconnected to gustation, and the retronasal route of smelling is the basis of flavor perception. It is said that as much as 75-95% of what we taste, actually comes from olfaction through the retronasal route. The tongue is only responsible for the basic tastes of sweet, salty, sour, bitter and umami. Adding aromas that are thought to be sweet, such as caramel, to food can change the perception of how sweet that food actually is [Piqueras-Fiszman and Spence 2016].

Olfactory stimuli can also be sensed unconsciously. Olfaction is different from vision which we use to search for information from our surroundings actively. We usually do not pay much attention to odors around us or are not aware of them at all [Rouby et al. 2002], and in certain situations, we might not realize that we are using all of our senses, as the attention is automatically focused on the dominating senses of vision and hearing.

Unconsciously smelled odors can, however, influence our behavior, mood, performance and social perception, even more than when we are aware of them [Li et al. 2007, Degel and Köster 1999, Rouby et al. 2002].

This was demonstrated in an experiment by Li et al. [2007], where participants received pleasant, neutral and unpleasant odorants and rated images of faces by their likeability. Only odorants that were below the detection threshold affected the likeability of the faces shown. The same applies to scents we have detected but have after a while been adapted to. Many of the non-detected odors are also encoded to the implicit odor memory that was discussed in chapter 2.2.

Olfaction has a strong tendency to adaptation and habituation as well. Adaptation is the loss of sensitivity because of reduced neural response that can happen after a stimulus is perceived for a long period of time, and habituation is the decreased attention or responsiveness if a stimulus is monotonous. Adaptation can raise the detection threshold of odors, decrease the intensity rating, and increase reaction time [Stuck et al. 2014].

Stuck et al. [2014] demonstrated how the concentration of an odorant affects in how long it will take to adapt to it completely, with higher concentration resulting in slower adaptation. Similarly, longer recovery time resulted in more reduced adaptation. The times were the same regardless of the odorant. Adaptation has also been suggested to be dependent on the importance of the odor [Kobayashi et al. 2008]. If an odor is critical for survival, like the sudden smell of gas, adaption takes longer to happen.

When considering applications that utilize odors, it is important to prevent unwanted adaptation happening. It is also essential in olfactory testing to know how quickly desensitization happens and how long it takes to recover from it.

3.3. Odors Influence Behavior

In addition to emotions and memory, odors can affect task performance, relaxation and behavior. The influences of odors can be used advantageously in many situations.

The enhancing power of odors on alertness and exercise or work performance has been demonstrated in multiple studies. Lavender has been shown to improve concentration and task performance, while jasmine has induced no effect [Degel and Köster 1999, Sakamoto et al. 2005]. Barker et al. [2003] demonstrated how the smell of peppermint improved typing speed and accuracy, and alphabetization. They suggested the effect to be due to odors enhancing attention and focusing.

A specific odorant may also induce relaxation and positive mood but only if the odorant is associated to relaxation, it is liked, and it is known to be what it is [Herz 2016]. For example, an ambient smell of orange in dental office was shown to correlate with higher relaxation [Lehrner et al. 2000]. Robin et al. [1999] demonstrated how an ambient smell in a dental office can amplify negative emotions caused by previous visits at the office, due to the same smell being unconsciously associated to the possibly painful treatment experience on the previous time. In a study by Morrison et al. [2011], music and a vanilla aroma had significant effect on consumer behavior in a store. The customers felt more pleasant and therefore spend more time and money in the store.

3.4. Olfactory Dysfunction

Olfactory dysfunction can be a mild condition with a reduced capability to smell or a more severe total loss of smell, anosmia, that can significantly affect the quality of life. A loss of sense of smell can cause different levels of anxiety and depression, as the enjoyment of eating food can be lost, and there might be fear of accidentally eating rotten food or smelling bad [Hummel et al. 2016]. The dysfunction can be in any of the subparts of olfaction from detection and intensity discrimination to recognition and identification.

The ability to smell can commonly be reduced for a short time due to infections, allergies and for a longer time due to smoking and simply normal aging as the receptor cells in the epithelium do not regenerate as fast anymore [Hummel et al. 2016]. Dysfunctional sense of smell can also be an indicator of much more severe illnesses, and even a predictor of a heightened risk of dying within five years [Pinto et al. 2014]. Olfactory dysfunction can be a sign of, for example, brain tumors, brain injury, schizophrenia, and depression.

Weakened sense of smell has also been shown to indicate a developing neurological disorder such as Alzheimer's disease and Parkinson's disease, the changes in sense of smell being one of the early symptoms even before any other symptoms can be detected. The changes in olfaction are due to the areas of the limbic system responsible for detecting and recognizing odors being damaged by the diseases. [Jokelainen and Pulliainen 2004]

3.4.1. Testing of Olfactory Dysfunction

As the level of olfactory functionality can be a clear indicator of several diseases, some curable if noticed early on, testing of olfaction is a crucial part of successful diagnostics.

Research in the field of olfactory dysfunction and its testing needs more work, as it has been shown that self-rating is not reliable enough. The tests should be controllable, easy to conduct and include at least two of the odor threshold, identification and discrimination subtests in order to form a comprehensive understanding of the functionality of the sense of smell. [Hummel et al. 2016]

There are many currently available tests that are used widely. For example, the University of Pennsylvania smell identification test (UPSIT) is used in several countries and concentrates on odor identification [Doty et al. 1984]. It consists of a paper with 40 microencapsulated odorants. “Sniffin’ Sticks” is another test developed by Hummel et al. [1997] and includes threshold, identification, and discrimination tests. It consists of pen-shaped containers with common odors. In a review by Hummel et al. [2016] the most popular olfactory tests are summarized.

There is, however, a need for more accurate and quicker tests, that can possibly be done by the patient themselves, and in here the technological advancements in odor production and delivery can become of great help. Tests producing accurate olfactory stimuli are not useful only in olfactory testing for diagnostics but can also be used in general studies of human olfaction.

3.5. Odor Memory

Odor memory seems to be very different from other types of memory in that it is very resistant to decay, it can bring back emotional memories (either autobiographical or associative) and it might play a part in improvement of recall accuracy of visual and verbal stimuli. Odor memory can be divided into processes of recognition, identification, imagining and autobiographical or associative odor-evoked memories.

Memory for other modalities works in a way that the more frequently you are exposed to a certain stimulus, the stronger the neural links for the memory of that stimulus become. Olfactory memory seems to work differently, and there seems to be different cognitive processes for short-term and long-term odor memory [Danthiir et al. 2001]. In odor memory studies it has been demonstrated that people forget odors more likely than words in a short timeframe, but the few odors that are remembered seem to be especially resistant to decay over time, and will stay in memory for maybe the rest of people’s lives compared to words that are lost eventually [Rouby et al. 2002].

The brain structures for odor memory seem to be separate from the parts for odor discrimination as well, because, for example, in Korsakoff’s syndrome patients have decreased odor discrimination ability but intact odor memory [Mair et al. 1980].

3.5.1. The Neuropsychology Behind Odor Memory

Amygdala is located in the anterior temporal lobe below the primary olfactory cortex and its main functions are the processing of emotions, especially fear and anger. Together with hippocampus, a part of the brain responsible for gathering sensory information and sending it to the cerebral cortex for long-term memory, amygdala is responsible for emotional learning.

Emotional experiences can be explained by dimensions of arousal and valence. The amygdala has been shown to accordingly process a combination of the level of arousal and valence that a stimulus evokes in order to form a more complex and comprehensive understanding of the emotional value of the stimulus [Winston et al. 2005]. The autonomic nervous system activity has been shown to respond to odors with these dimensions as well, as self-reported pleasantness of an odor correlates with heart rate and self-rated arousal correlates with changes in level of skin conductance [Bensafi et al. 2002].

Amygdala, hippocampus and the olfactory tract all have widespread connections between each other, and these connections and pathways seem to be essential in the creation of olfactory memories. These memories have a special task in adding emotional value and meaning to objects, that we have visually detected from our surroundings.

Smell of food can be perceived as more rewarding and pleasant when hungry, because of the learned associations between food odor and the rewarding act of eating in the amygdala and hippocampus [Rouby et al. 2002]. Life experiences shape the way we respond to certain olfactory cues. The valence of our emotional response to an odor depends on whether we have encountered the odor in a positive or negative state the first time. We unconsciously link encountered odors to the emotions experienced during smelling and save that memory to the implicit odor memory. When we smell that odor again, the associated memory is automatically evoked.

This kind of associative learning has been essential for survival, as adding emotional meaning to odors, such as the smell of a predator or food, can help in future encounters with these odors. It has been important to learn to recognize various scents originating from edible food. [Buchanan et al. 2003]

The intensity changes of emotionally salient odors are also more important to survival than emotionally meaningless ones. That is why it has been shown in brain imaging studies as well, that when an odor is emotionally neutral, increased intensity does not increase amygdala activity, but when an odor is either pleasant or unpleasant, intensity increase results in accentuated amygdala activity [Winston et al. 2005].

Hippocampus is an essential part in olfactory memory as well. Hippocampus in humans has special role in episodic and autobiographical memory [Burgess et al. 2002]. It functions in the formation of memories about personal experiences and especially in the context of spatial understanding enabling navigation in an environment where the experiences took place. Hippocampus organizes the recalling of episodic memories, and both hippocampus and parahippocampus organize the encoding of new ones. The fact that odor memories are for the large part episodic, as odor recognition and odor evoked memories are, might be explained with the close connection between the olfactory tract and the hippocampus.

3.5.2. Odor Memories Can Be Explicit or Implicit

Odor memory, as any other type of memory, can be divided into explicit and implicit memory. Explicit memory or declarative memory contains all the knowledge one is consciously aware of, such as factual information about the world, and episodic memories of experienced life events. Implicit memory or non-declarative memory contains all the knowledge that one is not consciously aware of, such as skills of being able to drive a car or being afraid of certain things.

Odor recognition and identification are part of the explicit memory, as explicitly remembered odors are remembered consciously. Odor recognition can be connected to the episodic memory, and identification to semantic memory. Odors can be explicitly memorized by naming them consciously, and it seems to improve the memorizing of odors in odor memory tests [Cain 1979]. Odor-evoked memories are part of the implicit odor memory, and they can affect behavior and mood and bring back memories without even consciously remembering to ever have smelled a certain smell.

In odor identification tasks, humans have been shown to be relatively bad at identifying odors by their name, and only remember when and where we have smelled a certain odor [Cain 1979]. However, when we take into consideration that odor identification seems to form a continuum, from pleasantness and familiarity to general classification ("flowery"), to knowledge about the source of the odor (that flower I saw), to a specific name (“rose”), we can conclude that knowing a specific name for an odor might not be as important for survival, than being able to connect an odor to a broader category, or to be able to associate knowledge about events and an odor [Schab 1991].

An indication of the unconscious implicit processes of odor perception was found in a study by Degel and Köster [1999]. Participants visited rooms all with a certain odor in the air. Later they were exposed to the same odors and asked to recall the name of a certain odor, as well as where and when they had encountered that odor last time. The memory of the odor was shown to be implicit because they did not remember smelling it in the rooms, but still connected the odor to the room they had visited before.

Interestingly this phenomenon occurred only for those participants who did not have a proper name for the odor. The explanation might be that perhaps the name of an odor in explicit verbal memory prevents getting information from implicit odor memory, or no new episodic memories can be built on top of already known odor name. Semantic memory may inhibit this in some way. It has been found in other studies as well, that explicit knowledge about an odor can interfere with the implicit memory of it [Rouby et al. 2002]. Knowing an odor name seems to have a positive effect only on odor recognition.

3.5.3. Odors Evoke Emotional Memories

Some people say that the most powerful characteristic of the odor memory is the so-called "Proustian memory". It is the phenomenon of smelling a certain scent and rapidly recalling a strong memory from the past. These sort of odor-evoked, emotional autobiographical memories are one indication that the part of the brain responsible for processing odors is located in the limbic system; an area responsible for processing emotions [Herz 1997]. Many studies show that the memories evoked by olfactory stimuli are more emotional than, for example, memories evoked by visual or verbal stimuli [Herz 1996] and they seem to be especially resistant to decay over time. Odor evoked memories are said to be especially resistant to retroactive interference as well. In other words, usually the first association to an odor will stay unchanged, even if the odor is encountered in the future and associated to different objects [Yeshurun et al. 2009].

Odor-evoked memories usually come from the first decade of life [Chu and Downes 2000], and in addition to being more emotional and positive, are generally more vivid, and rarer than memories evoked by other sensory stimuli or verbal description [Herz 1996]. They have been demonstrated to be quite important for emotional wellbeing in a number of studies as they allow deeper engagement in nostalgic recollection through more vivid mental images of the place and time the memories had been encoded in [see Herz 2016, for a review].

Some of the recorded effects of positive autobiographical memories evoked in therapeutic context can be reduction in stress and negative emotions, heightening of the self-esteem, and stronger feelings of connection to the patient's past and loved ones. On the other end, it is noticed in anosmia (the loss of sense of smell), that the patient faces decreased emotional wellbeing when the connection to their life events is lost. [Herz 2016]

Odor evoked memories can, on the other hand, also be highly negative and disturbing. For example, patients with post-traumatic stress disorder (PTSD) can recollect traumatic events from war triggered by the smell of smoke [Herz 2016], and memories evoked by trigeminally stimulating odors may be clearer but also more unpleasant [Czerniawska et al. 2013]. Robin et al. [1999] demonstrated that the smell in a dental office can later induce fear responses in autonomic nervous system activity if there have been negative experiences at the dentist in the past.

3.5.4. Odors Enhance Recall

Odors are powerful in how they can influence the human cognitive processes. It has been shown in numerous studies that presenting a specific, distinctive odor simultaneously with another stimulus such as images or words, and being later asked to recall information about the other stimulus, the information is both recalled and recognized better than when there were no odors present [Krishna et al. 2010, Herz 1997, Lwin et al. 2010]. The effect stays even when other possible variables like arousal, mood, environment, and time are excluded, and the effect can last from minutes to weeks [Krishna et al. 2010]. Rantala et al. [2019] demonstrated the effect to be especially strong for semantically congruent object-odor pairs, as in a free recall task congruent objects were remembered with 83% accuracy compared to the incongruent that were remembered with 63% accuracy.

Research has been done on both ambient odors, and on object-specific odors, and it seems that odors combined with single objects are remembered better [Krishna et al. 2010]. Ambient scents can enhance memory for a group of objects.

There are several different explanations for the memory enhancing effect of especially congruent odors. Most promising ones being the effects being caused by increased attention towards the odorous object either due to its distinctiveness because of the odor, emotional reactions, or object-odor congruency when the smell of an apple will automatically guide attention towards a visual apple object. The effects of dual coding have also been suggested to be one of the reasons.

Odors can function as cues for information retrieval, and it has been shown that the more contextually distinctive an odor is, the more effective it can be in said task [Herz 1997]. This is called the distinctiveness hypothesis. How distinctive from its surroundings the scent makes the object is how efficient the scent is when it comes to remembering object related information [Schmidt 1991]. Distinctive objects might be better in attracting attention and therefore enhance their memorability because more encoding resources are used. Distinctiveness hypothesis can be divided into primary distinctiveness; something is different from its surroundings and secondary distinctiveness; something is unexpected in the context.

If a stimulus evokes greater emotional responses like arousal, it can contribute to enhanced attention as well. Odors are known to evoke deeper emotional responses than other sensory modalities, what might also explain the memory improvement.

If an odor is present during both the time of encoding and retrieval, it might enhance memory for words even more than being just present during encoding. Both Herz [1997] and Schab [1990] have demonstrated this in word list memorization experiments. In other words, odors can function as powerful retrieval cues for words. On the other hand, when it comes to remembering, for example, objects, the same scent that is presented during encoding, might be even distracting if smelled during retrieval, as Tortell et al. [2007] showed in their experiment on memory of a virtual environment. It seems that the different memory processes for verbal and visual stimuli might affect to the necessity of retrieval cues.

The dual coding theory [Paivio 2007] proposes that events and objects encountered are better remembered if more than one sense processes information about the event. It has mostly been studied in respect to combining visual and textual information, but in the few studies concerning combination of olfactory and textual information, memory improvement is even greater, and lasts for longer [Lwin et al. 2010]. In these textual information recall tests, odors can improve memory on their own but in addition facilitate, for example, visual information's ability to improve memory for the textual information [Lwin et al. 2010]. When an event is being encoded into long term memory, scented objects' information is encoded better than unscented one's, and the associations to the scent about the object are stored in long-term memory.

The theory suggests that pictures or odors enhance verbal information recall because of the separate cognitive processing of different sensory stimuli. At the time of retrieval, the processes of the different systems are combined, and the combination can speed up and improve the information retrieval process. Compared to trying to remember only verbal information, odor information is stored and processed separately which reduces cognitive overload. That is, too much verbal information can result in reduced memorization ability [Cuevas and Dawson 2018].

Having at least two sensory stimuli memory traces of an object might also help in creating a more whole and concrete mental image of the object and that way make it easier to retrieve the information from memory and this way enhance recall [Paivio 2007]. When asked to recall objects, there is a whole "image" to be seen in memory about the object in question.

Even though there has been plenty of research on the connection between memory and odors, most of that is concentrated on ambient odors and autobiographical memories. Less is known and more research is needed about the effects of object specific odors on, for example, recall accuracy of those objects.

In the study by Rantala et al. [2019] the differences in recall and emotional reactions between synthetic and real scents, interaction type and odor congruency in VR were investigated. Attaching semantically congruent odors to specific objects was shown to have a positive effect on short term recall of visual information. They also found that congruent objects were rated as more pleasant and less arousing than incongruent ones.

The present aim was to continue and extend the study by Rantala et al. [2019]. More specifically the study was extended by adding an impression of dynamism of odors while interacting with VR objects so that the closer the nose the stronger the scent of the object.

An experiment was conducted, where participants moved and interacted in a virtual reality environment, with several scented and unscented objects placed inside. Some of those objects had an odor that changed in its intensity level in accordance with the interaction, and some objects had an odor that did not change. In addition, some of the objects had the odor matching the visual appearance and some did not. Immediately after the interaction the participants were to do a free recall task of the objects encountered. Finally, they were to rate how pleasant and arousing interacting with each object felt.

4. Methods

The research plan was evaluated and approved by the ethical committee of humanities of Tampere.

4.1. Participants

In total eight participants were recruited (6 females). The ages ranged from 22 to 59 with mean age of 31. The requirements were that the participants had to be over 18 and they should not have any illnesses affecting the sense of smell, or any allergies or asthma related to odors. The participants were all right-handed and one was a smoker.

4.2. Equipment

A simple olfactory display was developed for the experiment. The basic idea was to transfer clean air from a compressor, through bottles containing odorants, to the participant's nose. In total, there were six bottles. Three of the bottles contained lemon, each having a different amount of odorant. The same set up was for vanilla. By opening the valves to different concentration bottles an illusion of a dynamic change in odor intensity could be created.

The participants wore a CPAP-mask (Intersurgical EcoLite™ Adult, Intersurgical Ltd., UK) to receive the odorous air directly to their nose. This also prevented the odors from spreading to the room and mixing during the experiment.

The odor production functioned as follows. First an air compressor produced air that went to a cylinder containing silica gel for drying the air, and then to a cylinder containing activated carbon for purifying the air. Pressure regulator then set the air pressure to 1 bar and directed the air to eight valves. The valves controlled how much air was going through them into six flasks containing odorants either for lemon or vanilla. The evaporated odorous components inside the flask were then pushed to a tube that was connected to a mask that was worn together with the VR headset.

When a participant was interacting with a scented object the PC that was running the VR environment sent commands to the valves through an Arduino Uno to either open or close the airflow.

As seen in Figure 5, the valves A, B, and C controlled the airflow to the flasks 1, 2, and 3 that contained lemon peel. The valves D, E, and F controlled the airflow to the flasks 4, 5, and 6 that contained vanilla extract. The valves G and H controlled the clean air flow directly to the mask. The valves made an audible clicking sound, which is why there had to be two valves for clean air flow. That way the amount of clicking for both odorous and odorless objects was the same.

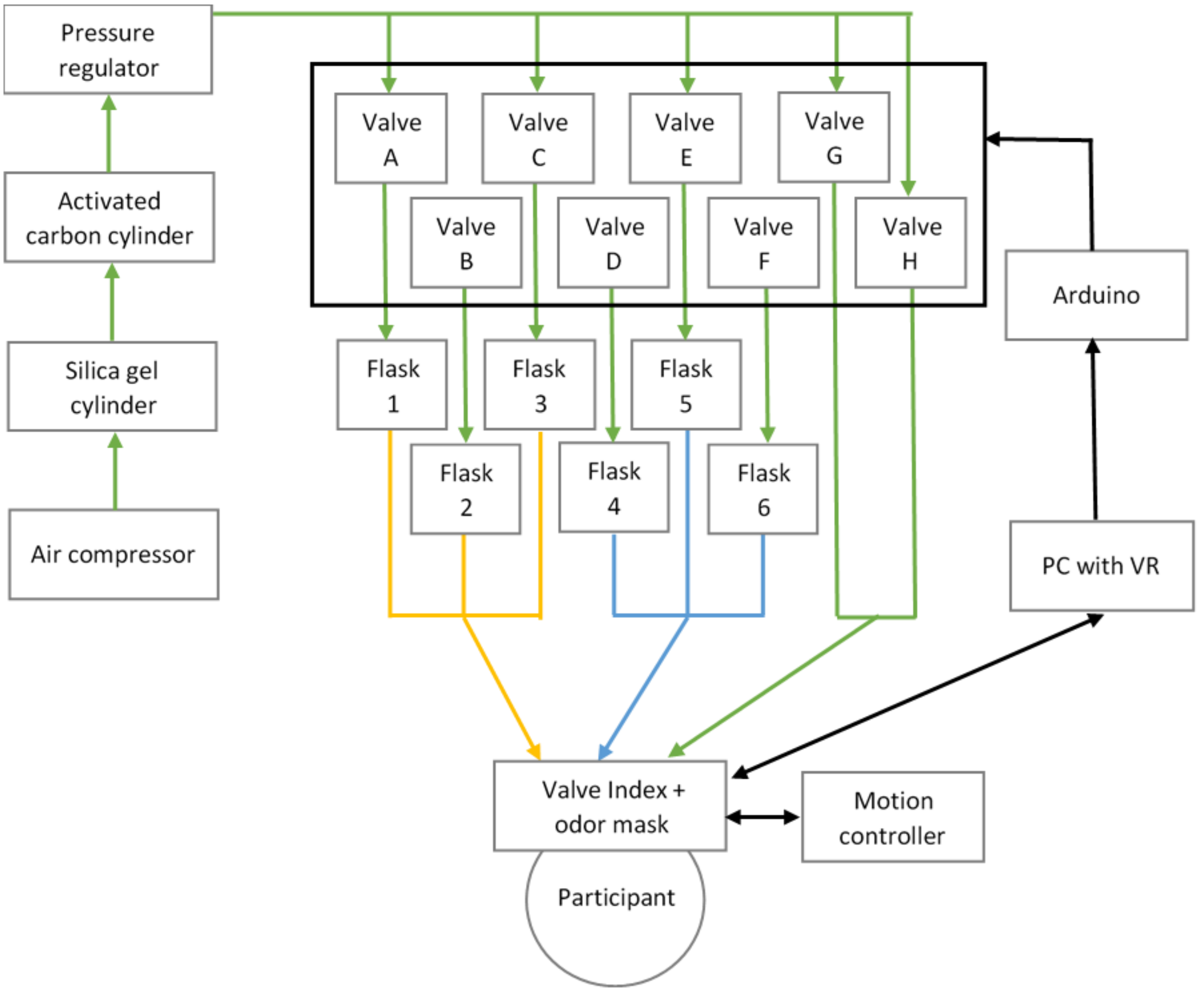

Figure 5. The flowchart of the equipment. Green arrows represent clean air, blue arrows vanilla scent air, yellow arrows lemon scent air, and black arrows data.

4.3. Objects

In total, 12 objects were selected for the study. The objects needed to be a size that could be picked up with one hand in real life, and they had to be easily distinguishable and identifiable. In addition, the scented objects needed to have a scent that could be easily used in the scent system. Selected objects were lemon, lemon tree, ice cream, cake, apple, grass, banana, mushroom, rose, milk, jasmine vase, and a teacup (see Figure 6). For each of them a corresponding 3D model was selected. The 3D models had to be high quality and could not contain text.

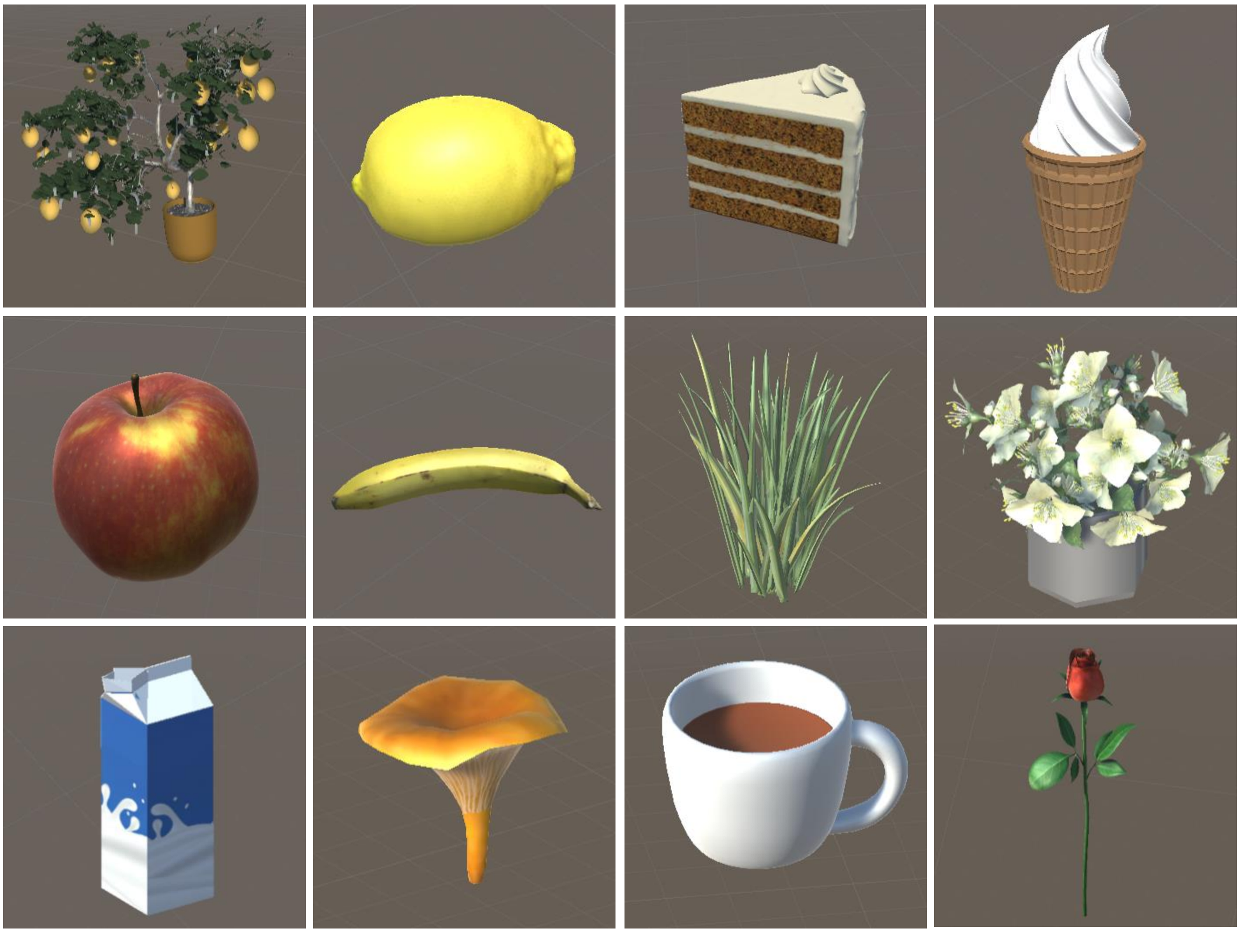

Figure 6. Selected 12 objects. The top row objects always had a congruent odor attached. Others were randomly assigned either incongruent odor or no odor.

4.4. Virtual Environment

The virtual environment where the objects were placed was made with Unity version 2019.2.10f1. The virtual reality system used was Valve Index. The interaction happened with a headset and a controller.

The environment consisted of a corridor with walls and 12 closed boxes with the selected objects inside. Before the actual test phase there was a practice phase to get familiar with the VR-system. The participant could move from one box to another by teleportation. The participants were instructed to open the boxes by touching them with their virtual hand. Once the box was open, the object inside was to be picked up and moved in the air for a closer examination. The object was then placed back inside the box and the box was closed by touching it with the virtual hand again (see Figure 7).

The placement of the objects was randomized so that the objects were in different order for each participant to reduce any bias.

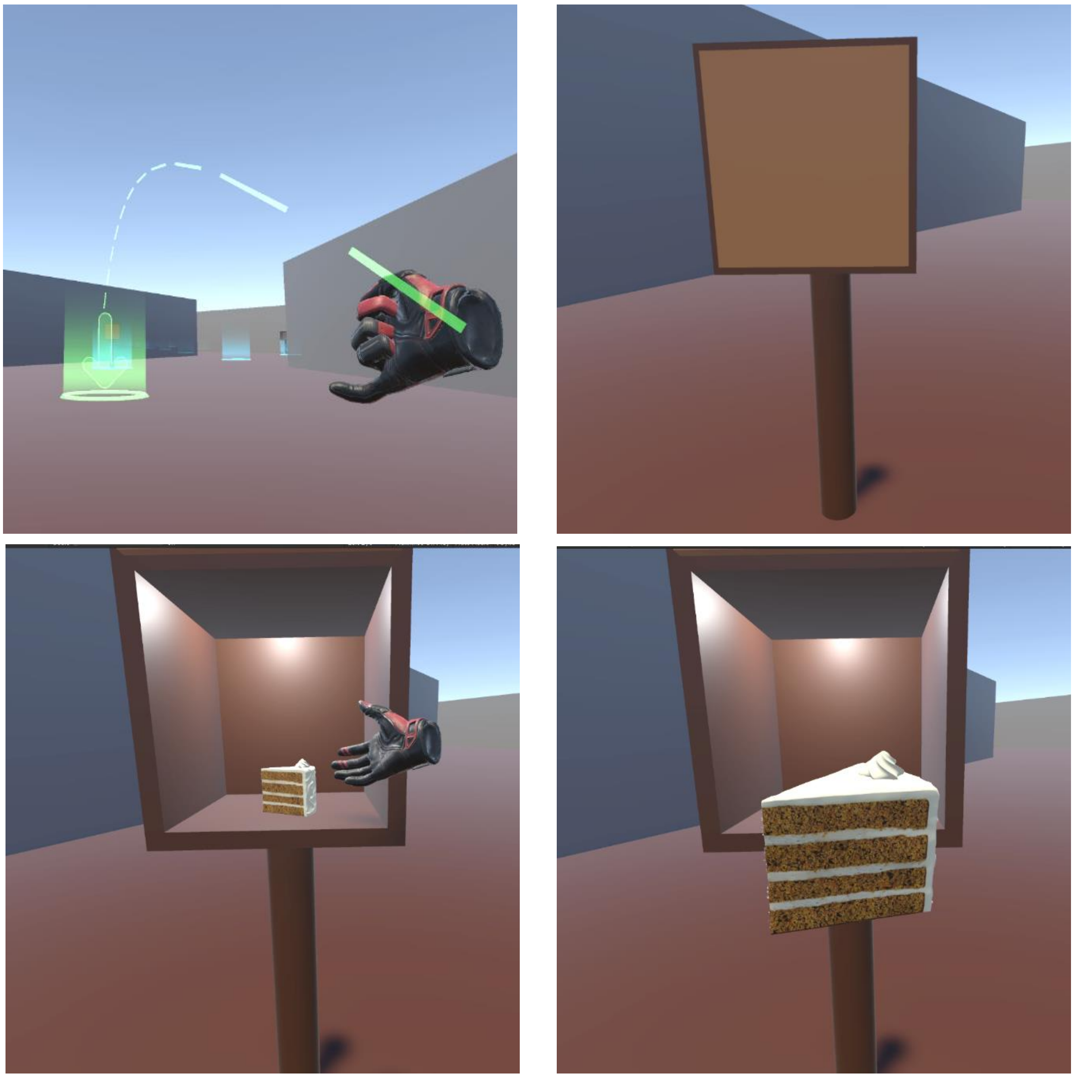

Figure 7. Moving inside the VE (top left), closed box (top right), opened box (bottom left), and object in hand (bottom right).

4.5. Odors

In the experiment two odors were used: lemon and vanilla, both authentic. The lemon scent was from lemon peel, and the vanilla scent from vanilla aroma extract used in cooking. Lemon and vanilla were thought to be simple and easily recognized, and the associations between the odor of a lemon and the images of a lemon and a lemon tree, as well as between the odor of vanilla and the images of a slice of cake and an ice cream were thought to be clear.

From the 12 objects, 8 had an odor and 4 were odorless. Half of the participants received only dynamically scented objects and half statically scented ones. Half of the image-scent pairs were congruent and half incongruent. The odor was randomized to be either incongruent or absent for the apple, banana, grass, mushroom, rose, jasmine vase, teacup and milk objects (see Table 1).

Object	Odor	Stability between participants	Congruency
Lemon	Lemon	Static / Dynamic	Congruent
Lemon tree	Lemon	Static / Dynamic	Congruent
Ice cream	Vanilla	Static / Dynamic	Congruent
Cake	Vanilla	Static / Dynamic	Congruent
Apple	Lemon	Static / Dynamic	Incongruent
Banana	Lemon	Static / Dynamic	Incongruent
Grass	Vanilla	Static / Dynamic	Incongruent
Mushroom	Vanilla	Static / Dynamic	Incongruent
Rose	No odor		
Jasmine vase	No odor		
Teacup	No odor		
Milk	No odor		

Table 1. The table of the stimulus arrangement.

In order to achieve an impression of dynamic odor intensity change in the dynamic condition, three different concentrations were used for each odor. For the scent of lemon 1 ml, 3 ml, and 5 ml of lemon peel were used for the distances of far, middle and close while holding an object and moving the controller respectively. For the scent of vanilla, 2.5 ml of vanilla extract mixed with 7.5 ml of propylene glycol (PG), 5 ml of vanilla mixed with 5 ml of PG, and 7.5 ml of vanilla mixed with 2.5 ml of PG were used for the same distances.

In the static condition the middle concentrations of 3ml of lemon peel for lemon, and 5ml vanilla extract mixed with 5ml PG for vanilla were used.

4.6. Experimental Procedure

An experiment with a mixed model design was conducted, where participants were instructed to move and interact inside a virtual reality environment. Inside the environment, there were several scented and unscented objects placed inside boxes. Some of those objects had an odor that changed in its intensity level in accordance with the interaction, and some objects had an odor that did not change. In addition, some of the objects had the odor matching the visual appearance and some did not.

The participants were asked to do a free recall task of the objects encountered, as well to evaluate how pleasant and arousing interacting with each object felt. The effects of odor stability and congruency on object recall accuracy and emotional ratings were analyzed.

The experiment consisted of three phases and lasted for about 45 minutes. First the participant was explained the procedure and given a consent form to sign. Following this they were given the olfactory functioning test from Kenzen Oy, similar to the Pennsylvania University UPSIT-test [Doty et al. 1984]. The participants scratched a notebook with scented pages and tried to recognize them correctly. It gave a quick assessment of the person's odor discrimination abilities. After that, the participant was instructed to sit in a chair and both the VR headset and mask were put on them. The motion controller was given to their dominant hand.

A practice area was presented to them inside the virtual environment where the participant could practice moving around, opening a box and picking up an unscented object (grey sphere). Once the participant had had enough practice, the next phase was presented to them.

In the second phase the participant was placed in a corridor with 12 boxes inside it. The participant was instructed to go through the corridor at their own pace and open all the boxes on the way. They were told to open the boxes, pick up the object inside at least once and examine it. In four of the objects, when the participant brought the object closer to themselves, the intensity of the odor increased in three levels, and in four objects the intensity stayed the same. The rest had no scent.

After the participant had gone through all the boxes, the headset was taken off and a free recall task was given to them. The participant was given a paper and a pen and told to write down as many objects as they could remember from the corridor.

In the third and final phase the participant was again put on the headset, the mask and the controller and the same corridor was presented to them. Now their task was to evaluate how pleasant and arousing interacting with each object felt. The participant answered verbally, and the experimenter wrote down the answers. The scales used were both 9-point bipolar emotional scales varying from -4 to +4. The valence varied from "unpleasant" to "pleasant" and the arousal from "relaxed" to "aroused". The center of the both scales represented a neutral point, that is, for example, neither unpleasant nor pleasant.

4.7. Measurements and Goals for Data Analysis

There were two main measurements for the experiment: recall accuracy and emotional ratings.

A free recall task was given to measure the unaided recall of the objects encountered to see if the received scents had any improvements on short term memory. Because the memorizing of the objects through incidental learning was tested, the participants were not told that there would be a recall task included in the experiment.

As the dimensional theory of emotions is considered an effective measurement when trying to understand affective experiences in humans, ratings of valence and arousal were asked from the participants to determine the subjective quality of interaction with the objects in the VE [Bradley and Lang 1994].

The goals for this research were to find out how semantic congruency in object-odor pairs and changes in odor intensity levels affect recall. The mediating effect of emotions is also taken into consideration.

The effects of the odors on valence and arousal because of changing intensity might be stronger than in the previous research, where the emotional ratings were neutral.

5. Results

The results of the experiment are divided into three sections: recall accuracy, valence ratings, and arousal ratings. The effects of congruency on recall, valence, and arousal were analyzed with separate one-way repeated measures analysis of variance (ANOVAs). The effects of odor stability on recall, valence, and arousal were analyzed with separate independent samples t tests.

5.1 Recall accuracy

First, the effect of odor congruency on the number of recalled objects was analyzed. In Figure 8 congruent objects seem to be better recalled than incongruent or odorless ones, but one-way ANOVA showed no statistically significant effect of odor congruency on recall of objects *F*(2, 14) = 0.358, *p* = 0.706.

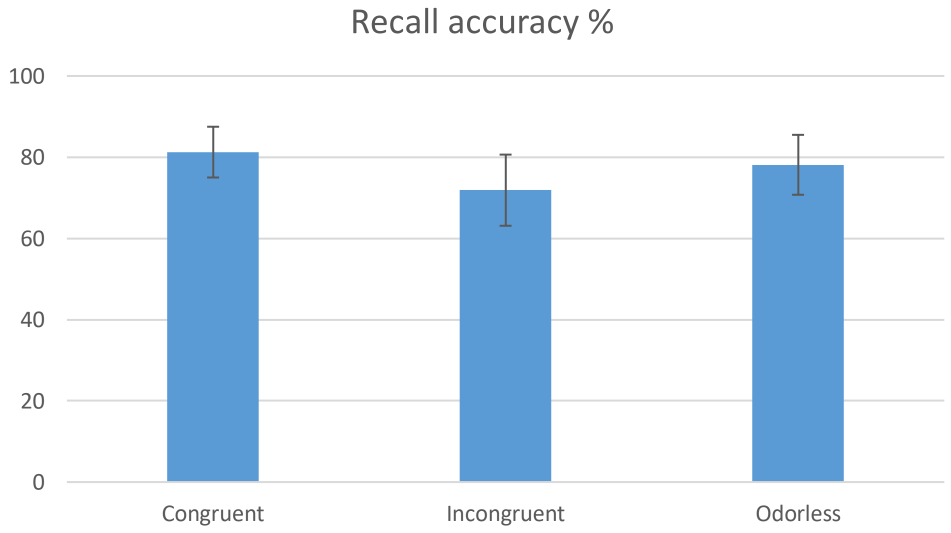

Figure 8. Mean recall accuracies by odor congruency.

To analyze the effects of odor stability on the number of recalled objects an independent samples t-test was conducted. As seen in Figure 9, recall accuracy between objects of static or dynamic odor varied just slightly. There was no statistically significant difference in the number of recalled objects between static and dynamic objects, *t*(6) = -0.499, *p* = 0.635.

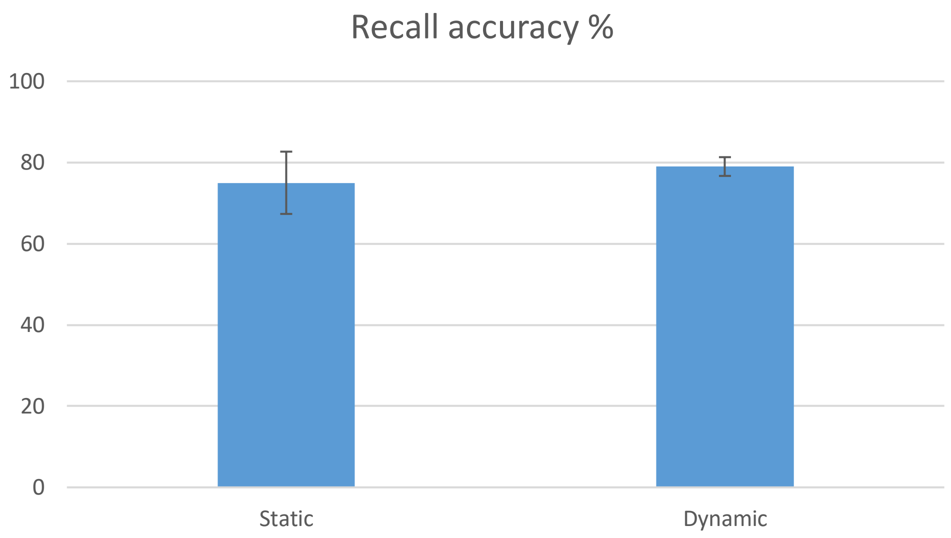

Figure 9. Mean recall accuracies by odor stability.

5.2 Valence Ratings

As seen in Figure 10, objects with congruent odors seem to be rated as more pleasant than incongruent and odorless ones. One-way ANOVA showed a significant effect of odor congruency on the ratings of valence, *F*(2, 14) = 5.743, *p* = 0.015. Post hoc pairwise comparisons showed that congruent objects were rated significantly more pleasant than incongruent *MD* = 1.3, *p* = 0.03, or odorless, *MD* = 1.1, *p* = 0.03 ones. The difference of ratings between incongruent and odorless objects was not significant *MD* = 0.95, *p* = 0.595.

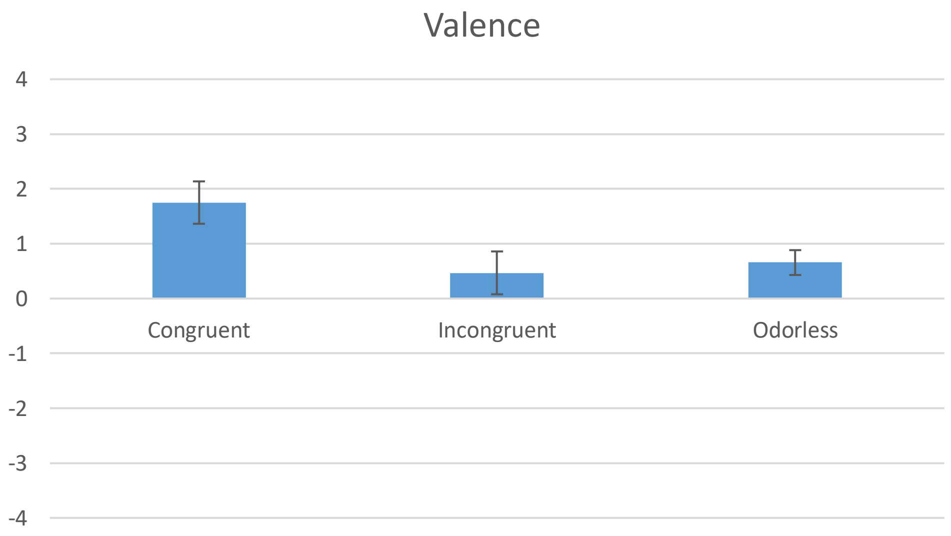

Figure 10. Mean valence ratings by odor congruency.

To find out the effects of odor stability on valence, an independent samples t-test was conducted (see Figure 11). There was no statistically significant difference in the ratings of valence between static and dynamic objects, $t(6) = -0.079$, $p = 0.940$.

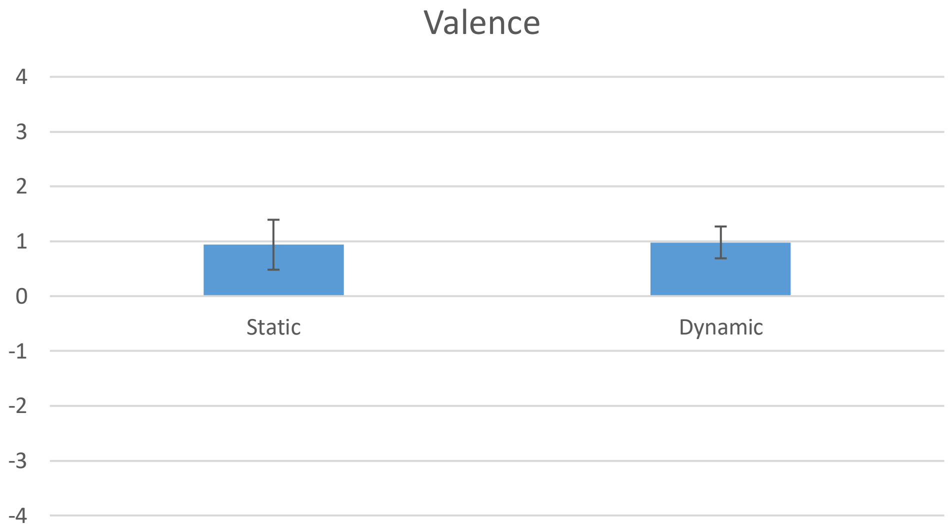

Figure 11. Mean valence ratings by odor stability.

5.3 Arousal Ratings

As seen in Figure 12, objects with incongruent odors were rated slightly more arousing than congruent and odorless objects and the odorless slightly more relaxing than congruent and incongruent objects. One way ANOVA, however, showed no statistically significant effect of odor congruency on the ratings of arousal $F(2, 14) = 1.425$, $p = 0.273$.

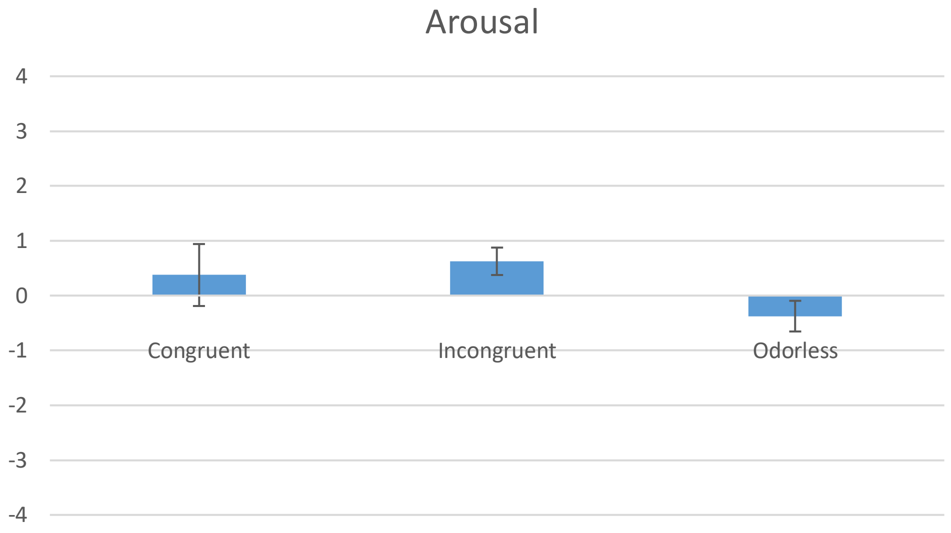

Figure 12. Mean arousal ratings by odor congruency

Dynamically scented objects were rated as slightly more arousing than the other objects (see Figure 13). Independent samples t-test showed no statistically significant difference in the ratings of arousal between static and dynamic objects, *t*(6) = -1.197, *p* = 0.277.

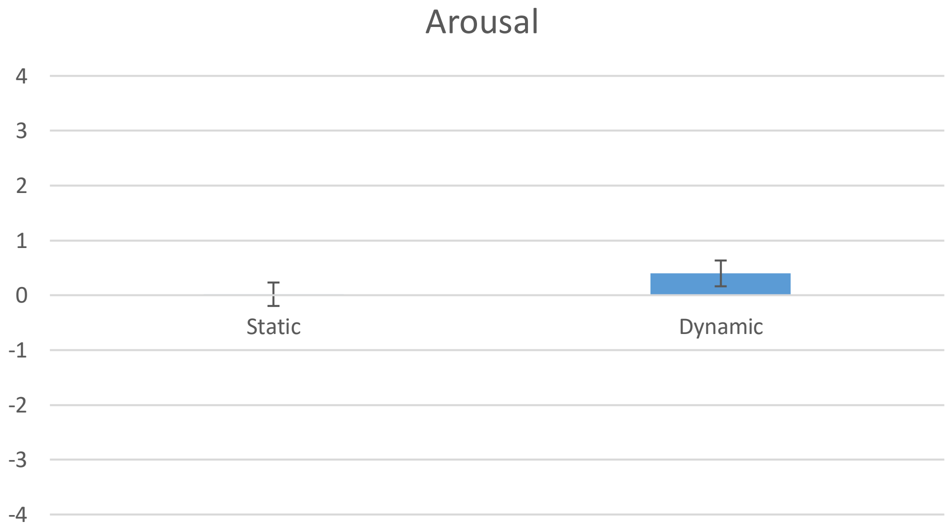

Figure 13. Mean arousal ratings by odor stability.

5.4 Discussion

The present results showed that there were no statistically significant effects of scent dynamics or scent congruence on the number of recalled objects immediately after the interaction with the experimental maze. There was, however, a nonsignificant trend towards better recall of congruent objects, which would be in line with previous studies [Rantala et al. 2019]. Odor stability also did not have other than a nonsignificant trend towards better recall of dynamic objects.

These trends would indicate that the object-odors pairs that have the most natural quality combinations, or in other words, objects that have matching, dynamic odors, would be recalled the best.

Highly arousing stimuli are shown to be remembered more accurately in free recall tasks [Bradley et al. 1992]. However, in the current study incongruent objects trended towards evoking the highest arousal ratings but were not recalled better than congruent or odorless ones. On the other hand, dynamic objects trended towards evoking higher arousal ratings than static ones and were recalled better. This difference might indicate that better recall of congruent and dynamic objects versus incongruent and static is not mediated by arousal.

Congruency and changing odor intensity might guide attention towards the objects more than incongruency and static odor intensity, and with that increases also the number of recalled objects. Congruency also helps with the dual coding of the encountered information by making an intact image of the object in memory which might also help with recall [Paivio 2007].

Main finding of the experiment was that congruent objects were rated as more pleasant (1.75) than incongruent (0.47), or odorless ones (0.66). This is in line with previous research [Rantala et al. 2019]. This finding also supports the research by Flavián et al. [2021] in that congruent scents increase affective reactions in VR experiences more than incongruent or odorless scents. Odor stability on the other hand did not have any effect on valence.

The object-odor pairs that were congruent might be more pleasant than incongruent pairs because participants smelled what they expected to smell. When seeing a lemon object, a lemon-like odor is expected. The object-odor pairs that were incongruent, were surprising and did not fit any mental models, and might have therefore been considered unpleasant. For example, mushroom was expected to smell mushroom-like, but instead it smelled like lemon. Odorless objects were probably considered more neutral than odorous ones, and therefore evoked only mildly pleasant emotions.

There were statistically nonsignificant trends towards incongruent objects causing higher ratings of arousal than congruent or odorless ones. Odorless ones were rated as slightly relaxing. Also, dynamic objects trended towards higher arousal than static ones.

This would support previous studies in that adding odors to objects makes them more arousing [Bensafi et al. 2002], and especially incongruent ones induce the highest arousal ratings [Rantala et al. 2019]. The surprising element of unmatching visual and olfactory cues might lead to greater arousal. When it comes to dynamic odors, the increased arousal might be due to two things. First, as the highest intensity level was only present in the dynamic condition, the stronger odor intensity in itself might have affected arousal. Second, adding dynamic intensity change increases the amount of information to be processed when interacting with an odorous object, which in turn might increase arousal.

The average arousal and valence ratings were quite neutral, ranging from -1 to 1, except the valence of congruent objects. The olfactory stimulus was probably not strong enough to cause any stronger emotional reactions.

The experiment had some limitations. First, the number of participants was low. The planned number of participants (30) was not achieved due to the COVID-19 situation, as many possible participants might have been too scared to come to the experiment. The nonsignificant trends might have turned significant with the planned number of participants, and it would be beneficial to continue the experiment to see if this would be true and to find out if there indeed are any effects of odor intensity change on recall accuracy.

Second, there was no objective measurement of the intensity change, the three levels were only tested on human nose. Therefore, there may have been slight differences between participants due to, for example, unwanted evaporation of odorants. Using only three levels is also not an adequate replication of real-world odor intensity changes, as real objects emit odors at a relatively constant pace and when the object is brought closer to the nose, the intensity increases smoothly without jumping from one level to the next.

The current experiment can pave way for future research on odorous virtual environments. Especially the intensity change of odors would need closer examination. Questions remain such as how important changing intensity is for successful virtual experiences in the first place, in other words, does it increase affective reactions and memories in a VR setting. And if it does, how accurately and similar to real life it should be done.

6. Conclusions

In this thesis the incorporation of scents into multisensory VR experiences has been discussed. Multisensory VR creates a multitude of opportunities for areas such as entertainment, research, and education. Odors have the ability to enhance these experiences even more, as they can affect human perception, cognitive abilities, and memory in many ways, as well as enhance the sense of presence in virtual environments.

Even though improvement has happened, odors are still not used widely in any digital applications. There are psychological, physiological and technical challenges specific to olfactory stimulation, such as how odors can be captured, produced, and delivered digitally in the most effective way. Human perception of odors is limited in many ways, and this creates certain restrictions on the design and development of odor delivery in VR. In the process of developing these systems, human perception, physiological limitations, and attentional capacities, as well as the reactions to these scent systems need to be studied well.

Many olfactory displays have been developed to deliver scents to users. As the development continues, more compact, versatile, and affordable solutions are hoped to be seen in the markets. Displays that can deliver any scent made from just few odor components, and devices that can be easily attached to VR headsets, have the ability to revolutionize multisensory VR.

In the future odors could also be captured from real environments and reproduced either in real time or later in a VE. This technology can be used in the creation of odorous virtual environments, where real locations are modeled and the scents from the real word counterparts are brought into the virtual environment.

In everyday life we tend to focus our attention to the dominating visual and auditory signals from our environment and ignore the scents, at least consciously. Because we do not notice the effects of olfactory stimulation on us that easily, we might mistakenly attribute positive emotions evoked by scents in a multisensory experience to the visual or auditory signals. This brings difficulties for the acceptance of olfactory technology. Olfactory information is not always perceived as bringing extra value, so the benefits should be researched and clearly stated.

An experiment to assess the effects of odor congruency and intensity change on recall accuracy, pleasantness and arousal of virtual objects was conducted. The results showed that congruent object-odor pairs were rated more pleasant than incongruent ones or objects with no odor. Other results, however, showed no statistical significance.

The high amount of nonsignificant results might be at least partly due to the low number of participants. The experiment should be continued with more participants to find out if odor intensity change in any way affects recall accuracy or emotional reactions. The non-significant trends of the current study would, however, be in accordance with previous knowledge about olfactory stimulation. In other words, odors could have a justifiable place in future digital applications, as they can affect the digital experiences in many positive ways.

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