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Towards large scale smell display for enhancing immersion during walking in virtual environments

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in

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by

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to the Faculty of Informatics

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Vienna, August 15, 2025

Christoph Götz   Hannes Kaufmann

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Christoph Götz, BSc.

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Christoph Götz

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Kurzfassung

Die Einbindung olfaktorischer Reize in die virtuelle Realität (VR) entwickelt sich zunehmend zu einem vielversprechenden Forschungsfeld, das neue Möglichkeiten zur Steigerung der Immersion und des emotionalen Erlebens bietet. Bestehende Lösungen für olfaktorische Displays sind derzeit oft durch stationäre Duftquellen oder tragbare Geräte limitiert, die entweder die Bewegungsfreiheit der Nutzer:innen einschränken oder als störend empfunden werden. Diese Arbeit präsentiert einen neuartigen Ansatz für großflächige Geruchsinteraktionen in VR durch ein robotergestütztes, mobiles Duftsystem, das eine ortsbezogene Geruchsausgabe während natürlicher Gehbewegungen ermöglicht. Das System basiert auf einem mobilen Boston Dynamics Spot-Roboter in Kombination mit einem Olorama-Duftgenerator, navigiert autonom zu vordefinierten Duftzonen und synchronisiert die Geruchsemission mit der räumlichen Nähe der Nutzer:innen. Dadurch werden zeitlich und räumlich abgestimmte olfaktorische Reize ermöglicht, ohne dass zusätzliche Hardware getragen werden muss.

Das System wurde in einer Nutzerstudie in einem raumgroßen virtuellen Waldszenario mit drei verschiedenen Geruchserlebnissen evaluiert, dabei wurden die Erkennungszeit, die Erkennungsgenauigkeit, die wahrgenommene Intensität sowie der wahrgenommene Komfort während der Interaktionen erfasst. Die Ergebnisse zeigen, dass die meisten Düfte korrekt erkannt wurden, wobei die Reaktionszeiten durch Unterschiede in der Duftintensität beeinflusst wurden. Insgesamt belegen die Ergebnisse, dass eine großflächige, robotergestützte Geruchsausgabe sowohl technisch umsetzbar als auch wahrnehmungsmäßig effektiv und gut verträglich ist und von den Nutzer:innen gut toleriert wird.

Durch den Verzicht auf tragbare Komponenten, permanente Installationen oder raumspezifische Infrastruktur bietet das System eine skalierbare und flexible Lösung für immersive Geruchsanwendungen. Es unterstützt gehbasierte VR-Szenarien, ohne die Bewegungsfreiheit von Nutzer:innen einzuschränken, und ermöglicht eine natürlich wirkende, kontextbezogene Geruchsausgabe für vielfältige Anwendungsfelder wie Storytelling, Therapie oder Ausstellungen. Insgesamt unterstreicht diese Arbeit das Potenzial mobiler Duftsysteme als vielseitige und praktikable Erweiterung immersiver VR-Erlebnisse.

Abstract

Incorporating olfactory stimuli into Virtual Reality (VR) has become a growing area of interest, offering new ways to enhance immersion and emotional engagement. However, current olfactory display solutions are often constrained by stationary emitters or wearable devices, which either restrict user mobility or cause discomfort. This thesis presents a novel approach to large-scale smell interaction in VR through a robot-mounted olfactory display that enables encounter-based scent delivery during natural walking. Built on a mobile Boston Dynamics Spot robot and an Olorama scent generator, the system autonomously navigates to predefined smell zones and synchronizes scent emission with user proximity, allowing for timed and spatially aligned olfactory cues without requiring users to wear additional hardware.

The system was evaluated with a user study in a room-scale VR forest scenario with three distinct olfactory events, where the detection time, recognition accuracy, perceived intensity, and comfort of users during the interactions were assessed. Results show that users were generally able to detect and identify the smells correctly, with reaction times being influenced by differences in scent intensity. The results demonstrate that large-scale, robot-assisted scent delivery is not only technically feasible but also perceptually effective and well tolerated by users.

By avoiding wearable gear, permanent installations, or room-specific infrastructure, the system offers a scalable and portable alternative for immersive olfactory interaction. It supports walk-based scenarios without confining users to a small area, enabling natural, spatially grounded scent delivery in various applications, including storytelling, therapy, or exhibitions. Overall, this work highlights the potential of mobile scent systems as a flexible and practical modality for enhancing immersion in VR.

Contents

CHAPTER 1

Introduction

The sense of smell plays a fundamental role in how humans experience and navigate the world, as the ability to sense odors in the environment affects our daily decisions. Smell accompanies humans when deciding if a particular item of food is still edible; it is an indicator for environmental hazards, a smell can induce strong emotional feelings, alter behavior, and the way humans communicate with each other, depending on their smell, and is even able to act as a stimulus to enhance memory. The importance of smell in daily life is gaining recognition from various commercial sectors, such as food, cosmetics, and cleaning products. These industries work to create scents that effectively convey the qualities of their products. This effort clearly affects how consumers view their attractiveness and therefor make the products seemingly more desirable [ABE+22]. However, in the fields of Virtual Reality (VR), robotics, and human-computer interaction, olfaction remains one of the most underexplored sensory modalities, especially in comparison to using sounds or the visual sense. This is particularly true for large-scale VR environments, where delivering smell in sync with user actions remains a challenge. Reasons for this are that VR environments are often not designed realistically enough to be able to convey the realistic feeling of being able to smell in VR, that methodological limitations exist in study design or the development of smells, and that the mechanisms of delivering the odors to users in VR are too unsophisticated [ABE+22].

This thesis investigates how mobile robots can be used to create encounter-based, location-aware olfactory interactions in VR environments, focusing on the integration of the Boston Dynamics Spot robot with the Olorama scent generator. By combining spatial movement with controlled scent delivery, this work presents a proof-of-concept system that enables users to experience scents in immersive, multi-sensory ways. The following chapters outline the background, related work, system architecture, and practical evaluation of this approach.

1.1 Background and Motivation

Virtual Reality makes the simulation of real-life situations in a computer-generated environment possible. Through stimulation of different senses such as the sense of smell, by using vibrations, by increasing the sense of movement by blowing air into users faces, by adding touch or taste or auditive feedback, or even by using a bright light source to simulate the feeling of sun on the skin to stimulate touch, as well as by using many other possibilities that stimulate the different human senses, in combination with using VR technology, it is possible to immerse into a completely different scene [SBB16]. In general, Virtual Reality, Augmented Reality (AR), and Mixed Reality (MR) provide the means to evoke a sense of presence for users, where they can feel as if they are physically present in a virtual environment [Hol23].

While the sense of immersion is commonly achieved through adding 3D visuals, spatial audio, or haptic feedback, or in more rare cases by expanding the application with olfactory feedback, VR experiences have so far predominantly focused on stimulating the visual and auditory sense of users. In recent years, however, multiple studies have explored the effects of stimulating additional senses beyond sight and hearing to enhance the sense of presence in VR further. Their findings consistently demonstrate that the more senses are being engaged, the stronger the sense of presence users report [DWH+99].

For example, Hoffman et al. [HHSR98] investigated the role of tactile sensations and confirmed that adding haptic feedback improves the sense of presence in virtual environments. Similarly, other studies have proposed that olfactory stimuli in VR can not only strengthen the feeling of immersion but also evoke specific emotional responses, which directly influence user behavior. Tortell et al. [TLD+07] demonstrated that the inclusion of smell in a VR experience significantly enhanced the ability of participants to memorize visual items that are encountered during their journey through the virtual environment, compared to participants who experienced the same environment without any olfactory input [TLD+07].

Nevertheless, despite these promising findings, the implementation of olfactory feedback into large-scale VR environments remains challenging due to multiple fundamental hurdles that remain unsolved in current literature. One of the most significant problems is that stationary emitters are limited to a dispersion range of one to two meters, requiring near-nose placement of the sensors to maintain a detectable concentration of the smell. In addition to that, temporal precision issues manifest through a mixture of latency delays between the different components that are being used, resulting in a delay between scent activation and user perception, which proves to be a critical barrier to effective multi-sensory experience synchronization [IBM+14]. Moreover, controlling the timing and intensity of scent releases poses significant challenges, even more so when using them in multi-user scenarios with multiple smell releases, where cross-contamination between different scents can occur [SH21]. These constraints restrict the scalability of smell in larger VR environments, making it challenging to deliver olfactory stimuli effectively in scenarios where users are allowed to move around freely [SBB16].

The lack of scalable olfactory solutions for VR is particularly noteworthy, as no existing work has successfully addressed the challenge of delivering scent cues across physical spaces in a VR context. This limitation confines current olfactory VR solutions to being small-scale applications, despite their potential to transform into various fields, and prevents deployment in applications that require synchronized multi-user feedback or large-scale environmental priming, such as collaborative training simulations. Similarly, smell could be used for large-scale spaces, such as in museums, where immersive exhibit spaces could employ pre-delivered ambient odors to generate environmental smell contexts before visual scene transitions appear, making users more immersed in the exhibition.

However, recent advancements in robotic mobility platforms and programmable odor generators offer promising avenues for overcoming these challenges. Emerging research in multi-sensor robotic navigation demonstrates the feasibility of combining olfactory tracking with autonomous mobility for scent delivery. Studies, for example, already show that robots can localize odor sources with an accuracy of two meters, using bio-inspired algorithms [SLW11]. Although current implementations primarily focus on odor source localization rather than scent delivery, these systems lay the groundwork for navigation frameworks that adapt to their environments, serving as a solid foundation for further development. While quadrupedal robots, such as the Boston Dynamics Spot robot, have not yet been explicitly tested for scent delivery, their autonomous navigation capabilities, as demonstrated in the example for odor localization, suggest a viability for maintaining optimal emission distances when integrated with programmable generators such as the Olorama [LYZ+23].

Successful implementations of robotic mobility platforms, such as the Spot, in combination with programmable scent generators, such as the Olorama, could improve smell interaction in VR. By combining both technological aspects, it may be possible to achieve precise spatiotemporal control over scent deliveries, enabling applications that were previously unfeasible. Successful implementation could have far-reaching implications, from revolutionizing therapeutic VR through graded exposure environments for anxiety disorders to creating new paradigms in architectural design by enabling scent-augmented virtual walkthroughs of unbuilt spaces, pre-delivering smell in immersive museum exhibits, as well as creating more immersive training scenarios, which, for example, firefighters could use.

1.2 Problem Statement

The integration of olfactory stimuli in VR environments has gained attention for its potential to enhance immersion, emotional engagement, and realism.

However, most existing implementations rely on static scent emitters, such as, for example, the Olorama Smell generator, which is generally a static device, or wearable olfactory displays, such as the one that has been built throughout the study by Yamada et al. [YYT+06], which are typically cumbersome. Stationary systems are typically fixed to a single location and cannot adapt to a users movement. In contrast, wearable solutions, although mobile, often suffer from limited scent intensity, discomfort, and diffusion range, making them unsuitable for multi-user or large-scale environments. These limitations restrict the use of olfactory interaction in spatially dynamic VR scenarios that involve walking or physical navigation, since in such cases, scent delivery should ideally adapt in real time to a users position and their actions within the physical environment immediately. The lack of flexible, mobile, and scalable solutions for delivering smell in large VR spaces remains a significant challenge and presents a gap that this thesis aims to address.

Current research and applications often rely on fixed scent emitters positioned in the environment or integrated into head-mounted displays. While these solutions can provide localized olfactory feedback, they are often cumbersome for users, as they require wearing additional hardware or being tethered to a specific area. This makes them impractical for larger environments, multi-room setups, or experiences that involve free movement [LYZ+23]. Moreover, delivering scents at the correct time and place, in sync with a user's actions and the corresponding virtual stimuli, remains a significant technical challenge. Many existing systems struggle with precise timing, resulting in delayed or lingering odors from emitted smells that are still in the air and that do not align with visual or spatial cues. Such mismatches can break the immersion or lower the amount of immersion that users feel and reduce the effectiveness of the experience [PD20].

To address these challenges, this thesis is guided by two overarching research questions:

- **RQ1 (System Design):** How can a mobile robotic platform be designed to deliver olfactory stimuli dynamically in large-scale virtual environments?
- **RQ2 (System Evaluation):** How can the usability, effectiveness, and user experience of a mobile olfactory display system be systematically evaluated in VR?

1.3 Aim of the work

The goal of this thesis is to design, develop, and evaluate a mobile, location-based olfactory interaction system that combines the Boston Dynamics Spot robot with the Olorama scent generator in VR. The central idea is to use Spot as a dynamic carrier of scent, enabling real-time olfactory experiences that respond to user movement and interaction within a physical environment that is simultaneously experienced through a VR headset.

To achieve this, the system architecture integrates multiple technologies, including Unity for scene and interaction control, a Python backend to manage the communication between the VR application and the physical devices, especially the Spot robot and the Olorama scent generator, and VR hardware for spatial tracking as well as user immersion. The aim is not only to demonstrate the technical feasibility of such a setup but also to investigate its usability and flexibility for future use cases with a proof-of-concept application.

Through the implementation of a forest-based virtual scenario, the work further explores how different scents and scent delivery patterns influence the user experience, while also assessing the technical performance of the system. In particular, it is important to evaluate whether the Spot robot can deliver scents with sufficient precision and reliability. In addition, the study examines practical considerations that arise when deploying such a system repeatedly in real-world conditions.

1.4 Structure of the thesis

This thesis is divided into several chapters that collectively describe the background, design, implementation, and evaluation of the proposed system.

Chapter 2, Related Work, provides an overview of the scientific and technological foundations relevant to this thesis. It summarizes olfactory output technologies across wearable and room-based systems, and highlights current evaluation methods used in VR studies. The chapter discusses trade-offs in mobility, spatial accuracy, and timing. It concludes by identifying a research gap in mobile scent delivery and positions this work as a novel contribution addressing that gap.

In **Chapter 3**, System Design and Methodology, introduces the overall system setup and describes the hardware components, including the Boston Dynamics Spot robot, the Olorama scent generator, the HTC Vive setup, as well as the integration of all parts. Following, the software architecture is discussed in detail, combined with a breakdown of the scenario logic and interaction design. The chapter ends with a discussion of the key limitations of the current prototype setup.

Chapter 4, Evaluation and Results, is dedicated to the evaluation of the system. It begins by outlining the design and objectives of the user study, followed by the user study, which includes a description of the experimental procedure and the collected data. The analysis combines quantitative metrics with qualitative feedback to assess user experience, realism, and perceived immersion. Afterwards, results are presented along defined categories, reflecting the hypotheses and evaluation goals of the study. The chapter concludes with an integrated summary of outcomes based on statistical trends and the feedback of participants.

Chapter 5, Discussion, critically reflects on the findings and outcomes presented in the previous evaluation chapter. It contextualizes the results in relation to the initial research questions and existing literature, highlighting key insights and interpretations. Limitations of the system and study design are discussed, alongside suggestions for improvement. The chapter concludes by outlining implications for future research and potential applications of mobile olfactory VR.

Chapter 6, Conclusion and Future Work, summarizes the primary outcomes of the thesis and reflects on the research questions. It concludes with a critical reflection on the prototype and suggests potential avenues for future development, both in terms of technical enhancements and research directions.

CHAPTER 2

Related Work

The integration of olfactory stimuli into immersive systems is a growing research field at the intersection of Virtual Reality, robotics, and multi-sensory interaction. Although visual and auditory modalities are well-established in VR, the sense of smell remains underutilized despite its potential to deepen presence, evoke memory, and influence behavior [TLD+07]. This chapter reviews the existing literature and the technological foundations relevant to this work. It begins by outlining the fundamentals of olfactory perception and its role in human experience, followed by an overview of scent delivery technologies, including electronic noses and programmable diffusers. Subsequently, it discusses prior attempts to incorporate smell in VR and AR environments, as well as the challenges associated with spatially accurate and timely scent deployment. Finally, related approaches involving robotics and mobile scent systems are reviewed, highlighting the need for location-based, real-time olfactory interaction systems, which is precisely the gap this thesis aims to address.

2.1 Human Smell Sensory System

Senses can perceive information and allow humans to interact with the environment more intimately. By absorbing photons of light, the rods and cones in the human eyes are activated. The ears use compressions and rarefactions of sound waves to perceive and understand sound. At the same time, acidic is responsible for the taste and sense of smell in the tongue, probably making it the most intimate sense, turning odorant molecules into electrical messages that the brain interprets [Bro10].

The olfactory system is responsible for the sense of smell and is made up of several specialized structures and organs, visible in Figure 2.1. Odorant molecules enter the body through the nostrils and travel into the nasal cavity, where they encounter the olfactory epithelium, which is a specialized sheet of tissues located deep within the upper part of the nasal cavity. The olfactory epithelium contains three main types of cells, which are olfactory receptor neurons, which detect odorants, supporting cells, responsible for providing structural and metabolic support, and basal cells, needed to serve as stem cells to regenerate olfactory neurons. Olfactory receptor neurons are bipolar cells with cilia that extend into the mucus that covers the epithelium. These cilia contain olfactory receptors that bind to dissolved odor molecules in mucus, initiating the sensory transduction process [KGS+24][HKC+23]. The axons of the olfactory receptor neurons bundle together to form the olfactory nerve, which passes through to reach the olfactory bulb, a structure located at the base of the brain just above the nasal cavity. Within the olfactory bulb, the axons of receptor neurons converge in spherical structures and synapse with the primary projection neurons of the olfactory bulb. These projection neurons transmit processed olfactory information through the olfactory tract to various regions of the brain, including the olfactory cortex, amygdala, and other structures of the limbic system involved in perception, memory, and emotion of odors. This complex organization allows the olfactory system to rapidly detect, discriminate, and process a vast array of smell molecules [MSR06].

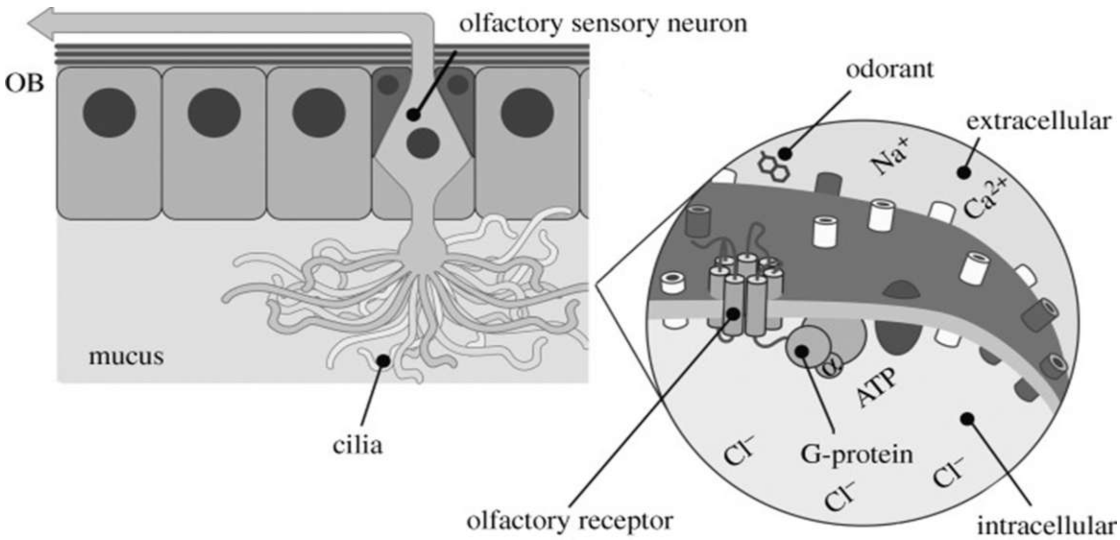

Figure 2.1: The human olfactory system. An olfactory cue enters the human smell system, travels through the nasal complex and the mucus to the cilia, where the olfactory receptors perceive the odor, start a chemical transformation, and turn the odor into an understandable signal for the human brain [Bro10].

When smell is derived from their unique chemical properties, the molecules travel through nasal passages at different speeds, leading to different interactions with the receptors within the nose of a human and can make the olfactory system perceive different olfactory signals [CF23]. The smell molecules are small enough to reach deep into the nasal cavity and diffuse through a 10 to 40 micrometer thick mucus layer and then interact with the different elements that the olfactory sensory neurons deploy [Bro10]. As can be seen in Figure 2.1, the mucus layer is secreted by acinar cells and acts as the final barrier to odorant access. Molecules must pass from the air to the mucus, diffuse through it, and then reach the receptor sites with the olfactory receptor neurons, which expel the necessary chemical elements to perceive the odor. The mucus circulation functions not just as a gatekeeper of molecules, but also has the important role of assisting in the removal of odorants from the receptor sheets after a transduction has occurred, so that new smells can be derived and do not overlap with smells which have already been perceived [Lin98]. There are approximately 347 related and various olfactory receptors which can react to odorants [Bro10]. Furthermore, there are around 1000 types of receptor cells, with which people can distinguish around 20,000 different smells, thus creating a ratio of smells to receptors of about 20:1 [PBH17]. Some of them are specifically set to perceive specific molecules. When receptors receive an odorant, they release a protein unit, initiating a chemical process that converts the olfactory sensory neurons message from an odorant molecule into an electric signal interpretable by the brain [Bro10].

In general, humans constantly encounter odors in daily life, often perceiving the quality of a smell without being able to identify its source specifically. Smells are a combination of molecules that vary in thousands of physicochemical dimensions, while odor concentrations in the everyday environment of humans can differ by ten thousand times due to distractions and external factors such as air quality, wind, or distance [Bro10]. Airflow rates and turbulence can also be affected by actions by the human being itself, such as by active sniffing, which boosts the air velocity and can therefore have a critical influence on how the receptors in the nose perceive a smell [Lin98].

2.2 Importance and Impact of Smell

The human sense of smell is important for vital functions such as warning and protection from environmental hazards, eating behavior, nutrition, and social communication. By using this sense, humans can extract nutritional information from olfactory food cues, which can trigger specific emotions, such as in this case, a particular appetite and direct food choices, while not directly impacting the actual eating behavior. Furthermore, smell can transfer and regulate emotional conditions, and therefore has a massive impact on social relationships [BP21].

2.2.1 Effects on Emotion

When people smell the fragrance of flowers or well-smelling food, they feel relaxed and happy, whereas they feel disgusted when they smell contaminated food. Therefore, exposure to odor affects the mood of people, and correspondingly, unique smells could potentially influence human behavior. Since brain structures such as the amygdala, hippocampus, orbitofrontal cortex, and insula are involved in olfactory processing while also being the primary structures for emotional processing, the connection between these characteristics becomes logical [LJW20].

Research has shown that odors that are liked or disliked have a congruent impact on the mood and cognition of people. Ambient odors can elicit mood effects on cognition and behavior in a simple manner, which could be used for daily life. The presence of a pleasant ambient odor has been found to help in solving creative problems in relation to an unpleasant odor condition. In contrast, the presence of a reeky odor reduces the likelihood that participants can make objective judgments. Furthermore, a foul-smelling odor lowers the tolerance for frustration, which also has an impact on the cognitive effort of a human being. Herz et al. [HSB04] argue that associative learning is responsible for such emotional responses since the different smells can act as cues to past emotional experiences and therefore exert the same type of cognitive and behavioral effects that the emotions would cause. Therefore, not only is the sense of smell closely linked to our emotional experiences, but odors, in addition to being pleasantly or unpleasantly smelling, can become linked to emotions in humans' memory [HSB04].

2.2.2 Effects on Learning and Memory

Improving learning abilities is an important aspect for every human being in nearly every situation.

Studies have found that presenting cues, such as odors or sounds, during both learning and sleep can significantly enhance memory performance. In the study by Smith et al. [SSdM92], participants learned a list of 24 words while being exposed to one of two odors, which were either jasmine incense or Lauren perfume. Subsequently, the subjects had to relearn the list with either the same or the alternative odor present. The results showed that superior memory was found when the same odor was used for the initial learning phase and the relearning session, demonstrating that the odor makes a difference when trying to remember something [SSdM92].

Smell can also be used for associative learning, which is the process where one item or event is linked to another through an experience. This art of learning is involved in human cognition and behavior, and is specifically interesting regarding how smell can change the setting of such learning experiences. If one were to smell the odor of a rose in an unpleasant setting, such as at a funeral, for the very first time, this smell would likely keep reminding the person about the funeral, even if the smell occurred at a different time and place in the future [HSB04].

2.3 Olfactory Technologies and Evaluation in VR

Historically, the foundations for immersive multi-sensory environments were laid by Morton Heilig, who in the 1950s built the first virtual environment, which provided users with a multi-sensory experience in the form of a simulated motorcycle ride through New York, combining 3D visuals, stereo sound, wind, vibrations, and even aroma cues [AAS20]. He later developed the Telesphere Mask, the first head-mounted device with 3D vision and stereo sound. Developments continued with Comeau and Bryan's "Headsight" in

1961, incorporating head-tracking and dual video screens. By 1966, Furness III introduced the first VR flight simulator, and internal motion sensors were added to HMDs by 1968. Over time, VR technology has expanded across various domains, from immersive gaming experiences to teaching new skills, to therapy, which assists in treating psychological disorders, and even allows terminally ill patients to embark on virtual journeys through the world [AAS20].

In past studies, it was already noted that surgical training simulations, which are one of the most advanced and important developing VR applications, feel incomplete without olfactory input. This has led to increasing research into scent delivery systems that can release odors in real-time, reproducibly, and in sync with events and user actions. Ideally, these systems must support multiple odorants, maintain spatial and temporal accuracy, avoid contamination across trials, and operate without tactile distractions [DWH+99].

In general, humans tend to underestimate the importance of smell as a source of information and an interaction tool with our environment. However, olfactory cues can evoke memories, convey meaning, such as by warning us of danger, and can promote instinctive behavior, such as keeping a distance from a bad-smelling object. These qualities make smell a powerful tool for designing spatial interactions, especially in VR, where scent can significantly enhance the sense of presence in multi-sensory experiences. While there is growing interest in integrating olfactory stimuli into VR to enrich user experience and in developing wearable scent interfaces, the exploration of smell in relation to its spatial characteristics and interaction logic remains limited [DMP+21].

2.3.1 Wearable Olfactory Systems

Wearable systems bring scent emitters close to the user's nose, often integrated into or mounted on HMDs. This configuration offers spatial precision and immediacy but often introduces design and comfort challenges.

Sezille et al. [SMB+13] and Nakamoto and Minh [NM07] developed early wearable olfactory displays capable of releasing 15 and 30 distinct smells, respectively. While those devices looked promising in terms of odor diversity, their systems relied on significant, heavy components, long tubes, and suffered from delivery noise, making them impractical for consumer VR.

To overcome these constraints, Yanagida et al. [YKN+04] introduced a novel system that used a kind of "air cannon" to project "clumps" of scented air into the area beneath the user's nose. Unlike tube-based emitters, this setup avoided direct contact or attachments on the face. The goal was to provide spatio-temporal control over olfactory cues, avoiding residual scent clouds in the surrounding environment.

On the downside, this system only worked with a very limited number of smells, as each new smell had to overlap with and overcome the previous one. This led to users not being able to recognize the low-concentrated smells. Systems that are not mounted are often placed at a distance from the user, which automatically produces latency in the system.

When the extraction of the smell happens, possible airflow fluctuations or positional changes of the user can make the smell less effective and probably even unconceivable, which makes it very complicated to adjust smells to the amount and intensity that an odor would require so that the recipient can recognize the smell accordingly [IBM+14].

Another study, by De Paiva Guimarães et al [DPGMD+22], presented a non-intrusive, mobile, and low-cost wearable olfactory display combined with a software service that enables developers to integrate olfactory stimuli into VR applications easily. The system uses Google Cardboard, a Raspberry Pi 3, and Unity as the game engine. A small olfactory device was mounted on the front of the Google Cardboard headset, as illustrated in Figure 2.2.

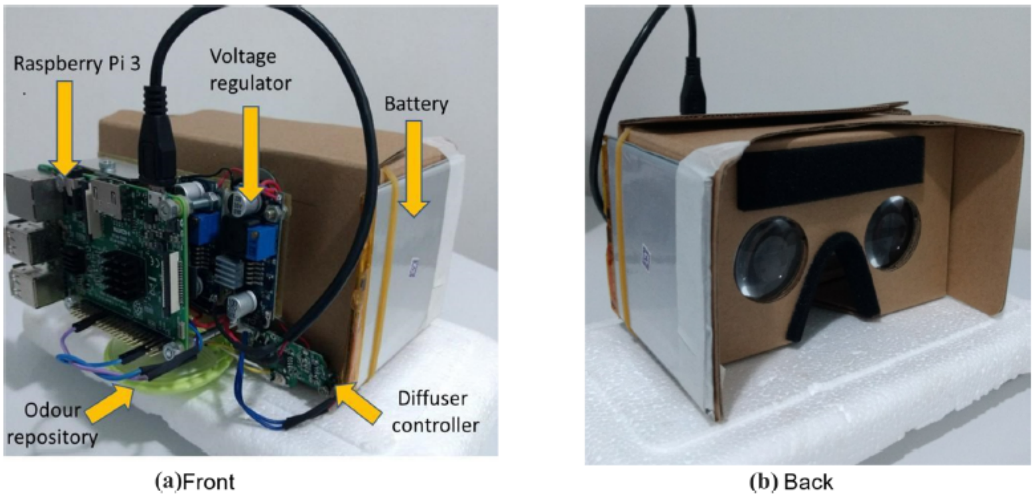

Figure 2.2: Google Cardboard VR headset equipped with a wearable olfactory display. The system integrates a Raspberry Pi, an odor repository, and a diffuser controller for scent delivery during VR interaction [DPGMD+22].

De Paiva Guimarães et al. [DPGMD+22] also conducted a user study to evaluate how comfortable and usable the wearable system was, and how users perceived the integration of scent into VR. In the virtual scene, as can be seen in Figure 2.3, users walked across a bridge toward a set of flowers. Upon reaching the flowers, a stream of vapor containing either lavender cologne or plain water was released. After the experiment, participants were then asked to complete a questionnaire. Results showed that 94 percent of users who experienced the lavender fragrance agreed or strongly agreed that the odor was pleasant, and 94 percent agreed that odors should be part of VR applications. In contrast, of the group that smelled the pure water odor, while 81 percent still agreed with the statement that odors should be part of VR applications, only 25 percent rated the smell as pleasant, further supporting the role of scent in enhancing VR experiences [DPGMD+22].

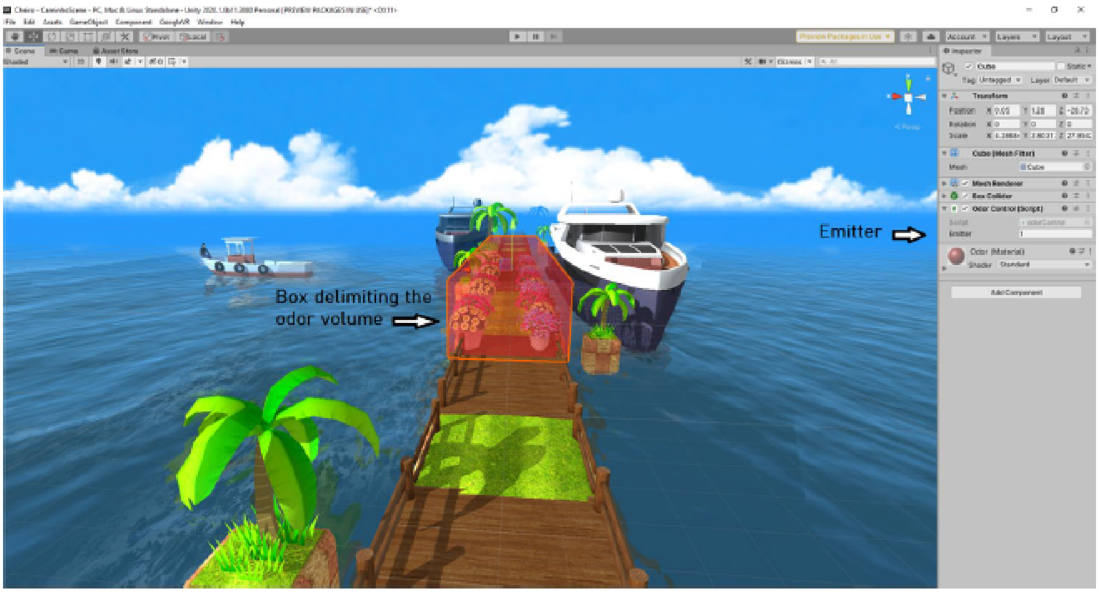

Figure 2.3: Virtual Reality scene used in the user study. Participants walked toward a flower field, where scented vapor, lavender or plain water, was emitted to evaluate the impact of olfactory cues in immersive environments [DPGMD+22].

In parallel to systems integrated into VR headsets, other wearable devices offer standalone solutions for context-aware scent delivery. In general, wearable olfactory systems are gaining interest, with numerous use-cases emerging beyond notification or integration into VR systems, including support for relaxation, well-being, and enhancement of physical activities. Dobbelstein et al. [DHR17], and Amores et al. [AHD+18], propose wearable olfactory devices that are not integrated with VR, but worn around the neck, and which both rely on the atomization of liquid phase odorants.

Amores et al. [AHD+18] present BioEssence, which is a wearable olfactory display that can be worn as a clip or as a necklace, visible in Figure 2.4. It can also easily be attached to various objects, including pockets, shirts, necklines, jewelry threads, and cords. The BioEssence device was developed in response to research showing that essential oils such as lavender, citrus, or vanilla can reduce anxiety, improve sleep, and alleviate pain and depression. BioEssence is a novel wearable olfactory display capable of releasing up to three different scents based on the users physiological state. For example, lavender scent is emitted when the heart rate exceeds 80 beats per minute. The device is lightweight, wireless, and designed to be worn daily, allowing for seamless, context-aware scent delivery throughout the day.

Figure 2.4: BioEssence: A wearable olfactory display that can be clipped onto clothing or worn as a necklace. The device delivers scents based on real-time physiological signals such as the heart rate of wearers [AHD+18].

In addition, Amores has published another paper with Maes [AM17] on the topic of how olfactory interfaces can, for users unconsciously, influence the mood and cognitive performance of wearers of the olfactory device. Amores and Maes presented Essence, which is an olfactory computational necklace, which can be seen in Figure 2.5, that can be remotely controlled through a smartphone. It was possible to change the intensity and the frequency of the released scent, based on biometric or contextual data. The paper discusses the role of smell in designing pervasive systems that affect the mood and cognitive performance while being asleep or awake, and a set of applications for the device is given and reviewed. Due to its lightweight and wireless design, the necklace can be worn throughout the day and night, making it suitable for various scenarios.

Amores and Maes identified their necklace as beneficial not only for sleep, memory, and learning, but also for improving cognitive performance and social interactions, particularly in immersive environments such as VR or MR. It is mentioned that in a physical social interaction, people are constantly using their sense of smell and unconsciously responding to the present odors [AM17].

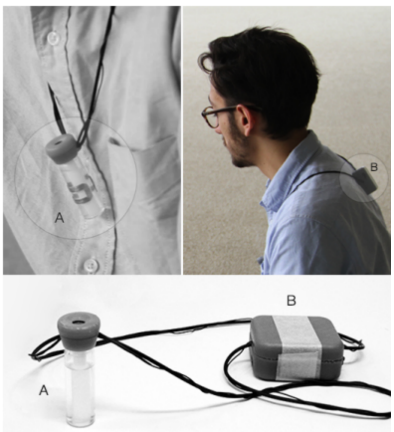

Figure 2.5: The Essence Necklace. A contains the fragrance, while B displays the device which manages the function [AM17].

Dobbelstein et al. [DHR17] on the other hand, built the inScent device, which can be worn on a necklace, that contains up to eight different smell cartridges. inScent also refers to the effect of smells being used to create or enhance experiences and is used to utilize artificially emitted scents to invoke emotions and experiences for users in everyday life situations. Primarily, the use case of the olfactory device in the Dobbelstein et al. study is to complement and amplify received mobile notifications by using scent as an additional emotional notification channel, which they call scentification. Messages that the life partner of the wearer sends can, for example, be emphasized by emitting a pleasant, related scent, such as flowers or the other person's perfume aroma, to reflect the emotional link to that person.

In Figure 2.6, a user can be seen wearing the inScent smell device on a necklace. When the user receives a message, an odor is deployed. In pleasant anticipation, the user then reaches for her phone to read the message.

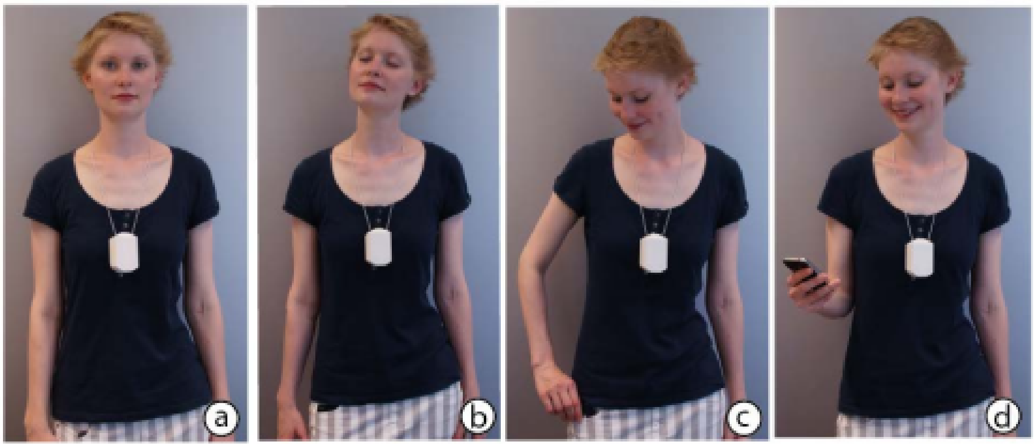

Figure 2.6: A user wearing the inScent wearable olfactory display. The sequence shows the process of receiving a message via scent (a–c), followed by reaching for the phone in pleasant anticipation (d) [DHR17].

The main contribution of the inScent device is that it is a novel, unobtrusive, wearable, and miniaturized olfactory display that allows a passive amplification of received notifications with scents, by using an open-source hardware and software framework that allows developers and researchers to add scents to their mobile applications and use cases. In addition, the study finished with a qualitative user study, investigating the perception of such scentifications of users in public [DHR17].

The use of scents can be applied in almost any context, as demonstrated by Zhou et al. [ZZAL25], whose system, the E-scent Coach, provides olfactory cues to assist users with breathing control during yoga exercises. While the correct breathing technique is essential for every sport, the coordination of yoga postures with deep and slow breathing is one of the core elements for practitioners. When a yoga posture expands the chest or the abdomen, such as when stretching, backwards bending, or when moving upward, it requires inhalation to enhance the effect of the pose, while compression of the same areas, such as when practitioners twist, bend forward, or move downwards, requires exhalation. Due to the poses being challenging, practitioners often become too focused and, as a result, neglect the rhythm of their breathing, which affects the effectiveness and increases the risk of exercise-related issues due to poor breathing technique.

Many studies have already tried resolving this issue by leveraging visual, auditory, and haptic feedback during yoga sessions. However, these methods require users to constantly focus on additional feedback, making it even more challenging for them to focus on everything at once. Due to olfaction being processed rapidly and unconsciously by the human brain, olfactory feedback for guiding breathing has a lower cognitive load for users, allowing them to focus better on their physical activity. Studies have shown that scents can indeed alter breathing patterns, as demonstrated by [VBMRS14]. Furthermore, scents are becoming increasingly embedded into applications to enhance multi-sensory experiences, such as through the use of tools from Aromatherapy [ZZAL25].

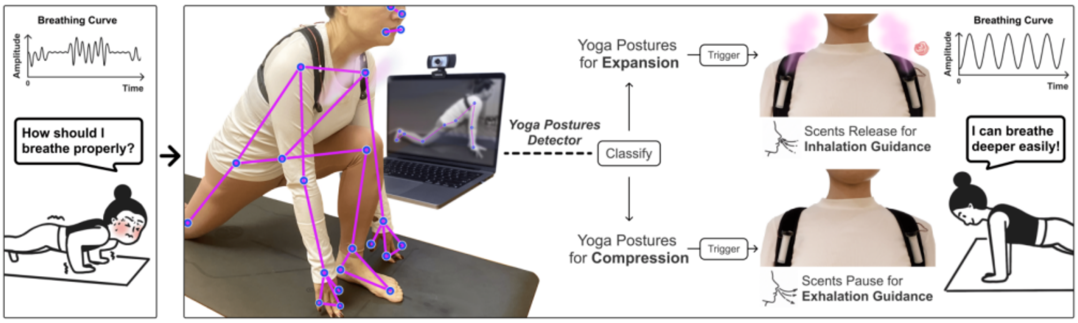

Figure 2.7: The E-scent Coach is a wearable olfactory device designed to support correct breathing during yoga sessions. Many practitioners struggle with proper breathing technique. Using a webcam to analyze the users posture in real-time, their pose is classified into either expansion or compression. Based on that, the wearable releases or pauses scents to guide inhalation and exhalation, promoting a stable and deep breathing rhythm [ZZAL25].

Zhou et al. [ZZAL25] followed up their research with a user evaluation with 16 participants. Participants practiced 12 different postures, each for a total of 5 minutes, in 5 different scent conditions. While one condition included having no additional smell present, the others were based on different smell families, which are listed in Figure 2.8.

Families	Definition	Representative Scents
Floral	Based on the smell of flowers in nature.	Rose, Lavender, Lilium
Fresh	Based on refreshing scents of fruits, plants, and ocean.	Lemon, Peppermint, Peach
Woody	Based on the smell of wood and forest in nature.	Pine Tree, Sandalwood, Sage
Amber	Based on exotic scents of oriental herbs and spices.	Cinnamon, Myrrh, Vanilla

Table 2: Emotional valence and arousal level rating scores of 12 scents.

	Emotional Valence Level		Arousal Level	
Representative Scents	Mean	SD	Mean	SD
Lemon	**4.15**	**0.88**	**3.90**	**0.64**
Rose	**4.11**	**0.45**	**2.45**	**0.69**
Lilium	**4.00**	**0.56**	2.60	0.82
Peach	**3.95**	**0.89**	3.55	0.60
Vanilla	**3.65**	**0.93**	3.45	1.15
Sandalwood	**3.35**	**0.75**	3.45	1.15
Peppermint	3.00	0.92	4.55	0.51
Lavender	2.80	0.62	3.65	1.04
Cinnamon	2.45	0.89	3.45	0.83
Pine Tree	2.05	0.89	4.05	0.83
Sage	1.90	0.91	3.95	1.00
Myrrh	1.60	0.68	3.80	1.15

Figure 2.8: Four Scent Families and their Representative Scents for the Experiment of Zhou et al. [ZZAL25]

The study by Zhou et al. [ZZAL25] finishes by discussing that participants found all scented conditions to be effective and usable, emphasizing the potential of scents to influence breathing patterns. The results showed that high-arousal scents can activate the olfactory system more effectively, including physiological changes in users and enhancing perceptual experiences. Furthermore, the results indicate that the inclusion of smell as a guiding tool has the advantage of being seemingly implicit and unconscious for users, which allows them to focus on their breathing and thereby enhance their immersion naturally.. It was verified that the use of scents in yoga can not only stabilize the emotion and enhance the concentration of practitioners, but also serve as a medium of information, resulting in enhanced respiratory responses [ZZAL25].

Wearable displays remain a key area of research, particularly when exploring mobile and embodied olfactory interactions, as proposed in the present work, due to their portability and potential for synchronized delivery in personal VR scenarios.

2.3.2 Room-Based and Static Emitters

Room-based or static olfactory systems involve devices placed at fixed positions in the environment. They are commonly used in labs or exhibitions and offer a non-intrusive alternative to wearables.

A prominent example is the oPhone DUO, see Figure 2.9, a table-top transmitter that could send digital scent messages over the internet. While innovative, it lacked integration with user position or timing, limiting its effectiveness in immersive environments [DVO16].

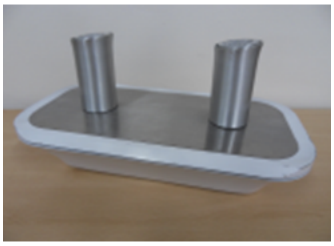

Figure 2.9: oPhone DUO [DVO16]

Another example is Scentee, visible in Figure 2.10, a scent-based add-on for iOS devices like the iPhone. It connects via the headphone jack and uses replaceable scent cartridges that are activated through an app. Users can control the duration and interval of scent releases, which are emitted as a misted cloud that requires proximity (around 10–15cm) to be detected. While Scentee allows user control, it supports only one scent at a time, limiting its expressiveness in immersive environments [DVO16].

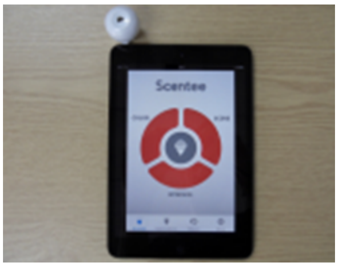

Figure 2.10: Scentee on an iPad [DVO16]

Lastly, also prominent, is the Aroma Shooter device by Aromajoin, which is shown in Figure 2.11. It connects via USB and includes six scent cartridges. These cartridges can be precisely activated with directional airflow, enabling controlled scent transmission up to 30cm after about 3seconds. The system requires the user to be accurately positioned, as even slight deviations may result in missed scent perception. Developers can adjust which scent is deployed, how intensely it is released, and the blower activation time. According to [DVO16], the Aroma Shooter achieves high distance and volume performance with a high-speed output.

To improve spatial targeting, Ischer et al. [IBM+14] proposed directional scent jets that project odors at the user, reducing dispersion time. However, even these setups suffer from air-based delivery delays, making it challenging to match scent release to precise virtual events. Additionally, when using multiple smells in such manner, smells start to overlap, where previously released odors still linger in the air, which poses a significant challenge in multi-smell sequences [LYZ+23]. These mismatches can break immersion or create confusion for users.

Figure 2.11: Aroma Shooter device by Aromajoin [DVO16]

Static emitters also struggle to support personalized or multi-user VR sessions and cannot follow users through space. This limits their use in large-scale, free-roaming experiences, where mobility is crucial.

An example of a projection-based setup is the Brain and Behavioral Laboratory – Immersive System (BBL-IS) introduced by Ischer et al. [IBM+14]. This system featured a fully interactive visualization environment designed to deliver complex scents at specific times and spatial locations without contaminating the broader environment. As illustrated in Figure 2.12, the setup included coated projection screens, a dedicated scenting chamber, and real-time stimulus synchronization. Such precise and isolated delivery was essential to avoid the blending or lingering of odor traces that can disrupt multi-scent sequences and degrade realism.

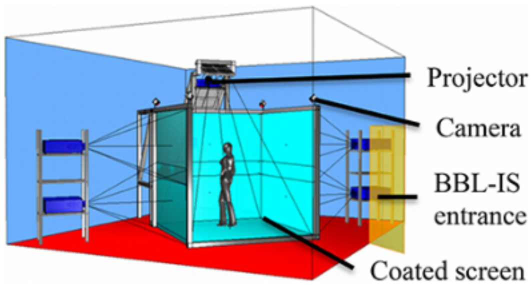

Figure 2.12: Schematic representation of the "BBL-IS"-system [IBM+14]

Although highly controlled, room-based emitters like the BBL-IS or oPhone DUO struggle to scale beyond isolated experimental setups. They often require careful positioning, limited mobility, and environmental constraints that reduce their applicability in dynamic, multi-user VR scenarios.

In addition to research prototypes, several commercial room-based olfactory systems exist today. For instance, the "Moodo Smart Diffuser"[1] offers a modular design with swappable

[1] https://moodo.co/

scent capsules and remote app control, allowing users to personalize ambient scent profiles. The "Aromajoin Aroma Shooter"[2], though often used in research, is also sold commercially and provides targeted scent delivery with fast-switching capabilities. Another example is "Scentys"[3], a French company offering programmable scent diffusion systems used in retail and event installations. These systems reflect growing commercial interest in olfactory display technologies, even though they are typically optimized for ambient use and lack the real-time tracking or interactive control required for VR immersion.

2.4 Summary

Olfaction remains an underutilized sensory channel in both robotics and VR, despite its well-established role in influencing human emotion, memory, and spatial perception. While technological advances have made it possible to integrate scent into immersive environments, most systems still face limitations in terms of personalization, spatial accuracy, and mobility.

This chapter reviewed a wide range of olfactory systems, categorized into wearable, room-based, and robot-mounted solutions. Each approach offers trade-offs in terms of timing, localization, and user freedom. Recent efforts have moved toward more dynamic setups that allow for controlled, contextual scent release in sync with virtual or physical events.

To our knowledge, no prior research has explored robot-mounted olfactory displays in immersive VR. This work introduces a novel approach to mobile scent delivery using a quadruped robot, enabling precise spatial alignment with users during locomotion.

The novelty of this thesis, therefore, lies in combining robotic mobility with olfactory output. By using the Boston Dynamics Spot robot as an active scent carrier, it becomes possible to deliver smells at specific locations and times, supporting user-dependent, real-time interactions. This approach moves beyond static or head-mounted solutions and opens up new application areas such as therapy, storytelling, and large-scale interactive installations.

[2] https://aromajoin.com/products/aroma-shooter
[3] https://www.scentys.com/en/

CHAPTER 3

System Design and Implementation

This chapter outlines the design and implementation of the mobile olfactory system developed for this thesis. It provides a comprehensive overview of the core components, both hardware and software, and describes how the Boston Dynamics Spot robot, the Olorama scent generator, and the Unity control system were integrated to enable large-scale smell interaction in VR. The chapter details how the system enables location-based scent delivery synchronized with user position, and lays the groundwork for the evaluation conducted later in the study.

3.1 System Overview

This thesis investigates how olfactory interaction can be effectively deployed in large-scale physical environments using a mobile, multi-sensory system that combines robotic mobility with olfactory output to create dynamic, location-based scent interactions in physical and virtual environments.

To explore this, a custom system was developed, which integrates the Boston Dynamics Spot robot and the Olorama scent generator through a unified control architecture implemented in Unity, serving as the central hub for coordinating mobility, interaction, and scent output.

By doing so, the exploration of different scents and intensities, which are controllable through Unity's interface by simply adjusting the timing, duration, and frequency of scent releases, becomes possible. The feature allows for future experimentation with different perceived scent strengths in a diversity of test settings and enables future studies on how users react to variations in olfactory outputs under different conditions.

Lastly, the system is designed to be modular, allowing for flexible scenario design and scalable experimentation in real-world conditions. The technical setup integrates multiple components, which are more detailed in section 3.2, such as a Windows 11 PC equipped with an Intel Core i9-9900K @3.6GHz and an NVIDIA RTX 2080Ti (W-PC), serving as the central control and computation unit. Other components include:

- The Boston Dynamics Spot robot acts as the mobile transportation tool for the scent generator as well as for the tracker. The robot can navigate a wide range of environments with precision and safety while carrying the tools, thereby enabling the delivery of scents to specific physical locations or users. The robot is controlled through TCP commands received from a Python-based server, enabling precise mobility within the environment.

- The Olorama Scent Generator, a compact electronic scent device capable of releasing multiple scents on command, is mounted on top of Spot. It receives trigger signals via Wi-Fi from a Unity application, which allows precise control of the type, timing, and duration of scent release.

- An HTC Vive Tracker, mounted on Spot for real-time position tracking of Spot Robot within a defined VR space, used to calculate the distance between the robot and the user's HMD in real time for proximity-based scent triggering.

- A VR Setup, including an HTC Vive Head-Mounted Display (HMD) and VR controllers, is used to place users within a multi-sensory, spatially coordinated environment. In addition, Vive Base Stations, which are mounted on the walls in the room where the user study takes place, are used to enable real-time tracking of both users and the robot in the physical space.

- The central control logic is implemented in the Unity Engine, which coordinates robot movement, scent deployment, and user interaction. Unity connects to both the Spot SDK and the Olorama device, serving as a tool for designing the environment and executing interaction scenarios in the application.

- A Python-based backend server acts as a communication bridge between Unity and Spot. It handles messaging, command forwarding, and timing coordination between these two components, ensuring low-latency and synchronized operation, acting as a middleware that translates the relative goal position into Spot's coordinate frame before sending the command. Olorama, on the other hand, is directly controlled from Unity via UDP, without any backend server.

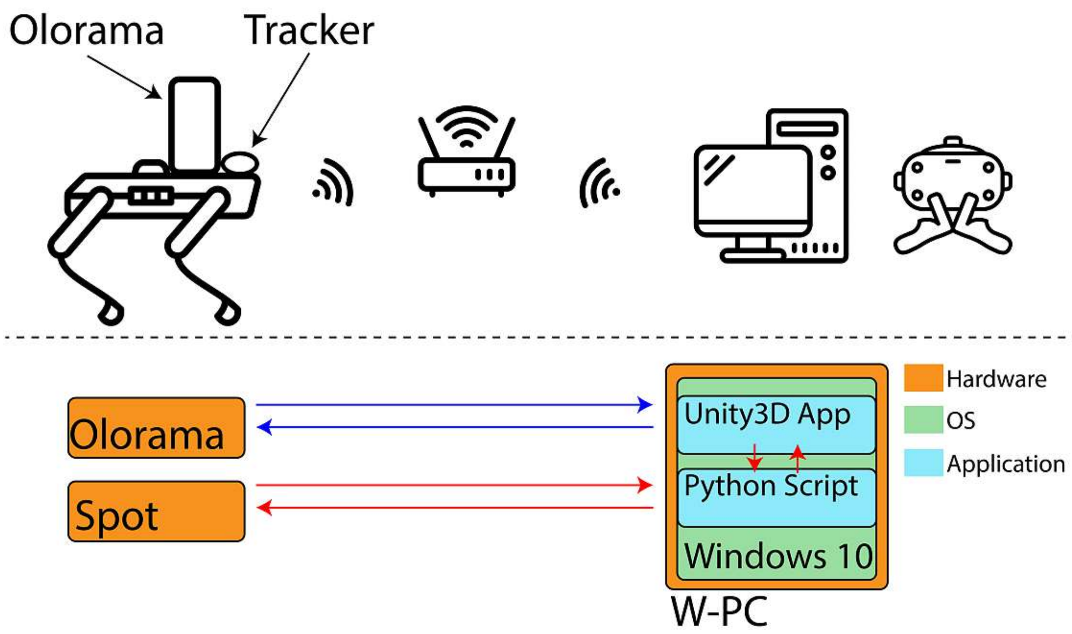

Figure 3.1: Overview of the hardware components (top) and software system (bottom). Red arrows indicate TCP-based communication (Unity to Spot via Python), while blue arrows represent direct UDP commands (Unity to Olorama).

Altogether, these components, as illustrated in Figure 3.1, form a modular and tightly integrated platform for exploring mobile, multi-sensory interaction through scent in real-world and virtual environments. The system coordinates multiple hardware and software components in real time, ensuring a synchronized experience across physical robot movement, olfactory output, and user interaction in VR.

A typical execution loop proceeds as follows:

1. Unity continuously monitors the user's position in the virtual environment and determines when the user approaches an interactive object or smell zone.

2. Upon reaching a predefined distance threshold, Unity sends a TCP message to a custom Python server, specifying the next target position for the robot.

3. The Python server, acting as a middleware layer, parses the command and uses the Spot SDK to control the Boston Dynamics Spot robot, instructing it to walk toward the designated position.

4. As Spot arrives near the goal, it readjusts its orientation to face the user, ensuring optimal delivery conditions for the upcoming scent emission.

5. Simultaneously, Unity transmits a UDP message directly to the Olorama scent generator, containing the spray parameters such as scent channel, duration, and intensity.

6. The Olorama device releases the scent into the environment. At the same time, Unity triggers a visual feedback system, spawning a subtle particle effect above the object, accompanied by a light glow and an auditory cue, to indicate its activation.

This process happens with near real-time responsiveness and requires precise coordination between spatial logic, network communication, physical hardware, and VR feedback. Section 3.2.3 provides a more detailed technical breakdown of the communication flow and implementation details.

3.2 Hardware and Software Setup

The following sections present the technical setup of the system in more detail, beginning with the robotic platform and continuing with the scent hardware and supporting software components.

3.2.1 Boston Dynamics Spot

General Description

Boston Dynamics is known for developing bioinspired robots with agility, stability, and complex motion capabilities that push the latest technology to new heights. One of these robots is the quadruped Boston Dynamics Spot Robot, which, in this thesis, serves as the central mobile platform in this project and is responsible for carrying the Olorama scent generator, which can be seen in Figure 3.2, thus enabling mobile scent deployment while simultaneously acting as as a moving tracked unit within a VR-aligned space, enabling dynamic and spatially accurate smell delivery.

Figure 3.2: The Boston Dynamics Spot robot equipped with the Olorama scent generator and the HTC Vive Tracker. The scent device is mounted on the rear plate for spatial alignment and synchronized scent emission based on the user's location.

Spot's hardware is almost entirely custom-designed and includes processing boards for more control as well as advanced onboard computation and perception systems. Sensors are mounted on the front, rear, and on the sides of the robot. Stereo cameras, wide-angle lenses, and structured light projectors are distributed across the whole body, enabling robust 3D sensing and autonomous operations. Spot is capable of forward and lateral walking, turning in place, and climbing, with a top speed of 1.6m/s. Its legged morphology allows navigation across uneven terrain, making it suitable for complex or unpredictable physical environments.

In the scope of this study, Spot was used to navigate between two spawned target objects and respond to proximity-based user interactions. Since users wore VR headsets and could not see the robot physically, the motion system had to be tightly coupled with virtual content. Spot was responsible not only for locomotion but also for stopping, rotating to face the user, and releasing scents at predefined spatial points. This setup created spatially contextual olfactory interactions that would not be possible with static scent emitters [Gui19].

Spot has a payload capacity of up to 14kg, and due to its precise trajectory execution ability and the possibility of mounting the Olorama onto the robot, the Boston Dynamics Spot was an ideal choice for this study. The mobile scent generator setup directly supported the thesis objective of investigating scalable and flexible smell delivery in VR environments. In addition, a Vive tracker was mounted to Spot's rear plate, enabling the robot's spatial tracking within the system. Unity used this tracker to localize Spot in real-time and trigger scent emissions based on the users location and the predefined procedure logic. Particular attention was given to the mounting configuration to ensure both visibility for the tracker and unrestricted motion for the robot, while keeping the robot, the tracker, and the scent generator safe.

Spot was then controlled indirectly from Unity using a custom Python server, which interpreted JSON messages over TCP and translated them into motion commands via the Boston Dynamics SDK. For more on the control pipeline and messaging architecture, see Section 3.2.3. The robot's movement execution is explained in more detail in the following subsection.

Motion Control and Spatial Alignment

To control Spots movements in a precise and spatially aligned way, all motion was defined using relative poses in something named "SE(2)". SE(2) is a combination of multiple notations and stands for the mathematical space of Special Euclidean transformations in 2D. In SE(2), "S" stands for "Special" and implies that the transformation preserves the original orientation of an object without any flipping. "E" is short for "Euclidean", which means that the distance is preserved, without any stretching applied. And lastly (2) correlates to working in the 2D space with an x-position, a y-position, and a heading. In other words, SE(2) combines all possible 2D movements that translate and rotate an object, but do not scale or skew it, and, in this study, therefore, is the math space for moving Spot around on a flat surface to move the robot forward, sideways, and to make it turn. In general, SE(2) is commonly used in robotics for mobile navigation. Each pose can be encoded into a 2D position (x,y) and a heading angle θ, compactly represented as a 3×3 matrix:

$$T = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & x \\ \sin(\theta) & \cos(\theta) & y \\ 0 & 0 & 1 \end{bmatrix}$$

This matrix-based representation allows combining transformations via simple multiplication. In this thesis, Spot's relative goal poses were computed in Unity and transformed into the robot's global coordinate system using:

$$T_{\text{goal}}^{\text{global}} = T_{\text{body}}^{\text{global}} \cdot T_{\text{goal}}^{\text{body}}$$

This composition demonstrates that the global position of a goal can be determined by taking the robots current global pose and applying a relative offset from its body frame. In essence, the goal's global position is determined by transforming its local offset via Spot's current world pose. The following SDK code was used to perform this transformation:

```
out_tform_body = get_se2_a_tform_b(transforms, frame_name, BODY_FRAME_NAME)

out_tform_goal = out_tform_body × body_tform_goal
```

In Unity, the relative position of a goal object was computed using matrix multiplication. Spot's tracked transform (via the Vive Tracker) and the goal object's transform were used to calculate their relative offset:

```
Matrix4x4 relativeMatrix = t1Matrix.inverse * t2Matrix;
Vector3 local_position = relativeMatrix.GetColumn(3);
```

However, since Unity and Spot use different coordinate conventions, a frame conversion was necessary. Unity uses a left-handed coordinate system (with +Z forward), while Spot uses a right-handed system (+X forward). The terms "left-handed" and "right-handed" refer to how the three axes (X, Y, Z) are oriented in a 3D space, and specifically how to determine the third axis depending on the first two. A practical example can be shown with everyone's own hands. When making an L-shape with the left, by pointing the index finger forward, which resembles the Z axis, and by pointing the thumb to the right, which stands for the X axis, the middle finger, the Y axis indicator, will point upward. On, literally, the other hand, when doing the same procedure, the middle finger, which again resembles the Y axis, will point downward. This is the indicator that the coordinate system is adjusted to "right-handed".

This transformation therefore affects how objects are rotated, how angles are measured, and also how coordinates are converted. By ignoring it, everything will move in the wrong direction or be mirrored falsely. Regarding this thesis, when Unity computes a position relative to Spot in VR, it does so in left-handed space, but Spot's SDK expects right-handed inputs. Consequently, the coordinate axes must be converted accordingly before sending the motion commands. That is precisely what the next few lines of code, which are essential, do.

```
jsonObject["x"] = -local_position.y; jsonObject["y"] = -local_position.x;
jsonObject["yaw"] = 360 - local_rotation.eulerAngles.z;
```

This flips and swaps the axes, so that Spot walks in the correct real-world direction. In addition, in the last line, another transformation was applied to match Unitys local offset to Spots format, which, in total, mathematically can be displayed by the following equation.

$$x_{\text{spot}} = -y_{\text{unity}}, \quad y_{\text{spot}} = -x_{\text{unity}}, \quad \theta_{\text{spot}} = 360^\circ - \theta_{\text{unity}}$$

Then, once the converted pose is calculated, it is sent to a custom Python server using TCP. The server then generates an SDK-compatible Spot movement command, with which the robot knows what to do next. Furthermore, to control Spot's walking speed, Unity included a speed parameter in the JSON message. This is translated into a velocity constraint within the Python server:

```
vel_limit = SE2VelocityLimit(max_vel=SE2Velocity(x=speed, y=speed),
angular=1.0)
```

Before scent emission, Spot was also instructed to rotate and face the user. This orientation was computed based on the relative angle between Spot's current pose and a designated Unity object, which in this case was the HMD that the users wore during the study experiment. A yaw-only command was issued to ensure that the scent generator pointed in the user's direction, increasing olfactory clarity. A yaw-only command tells Spot to turn around on its vertical axis, basically spinning the Spot. Spot was therefore instructed to only rotate in place and to change its facing direction, to point towards the user's position, but not to move forward or sideways, so that the Olorama scent generator is aimed directly at the user's location. This ensures that the smell is emitted towards the nose of the user, instead of into a random direction. This improves how clearly and quickly users can perceive the scent.

Spot's entire behavior is based on a self-written predefined Unity procedure, which controls the sequence of calibration, movement, rotation, and scent release. This structure ensured consistent interaction timing across participants and made the movement logic reproducible, with each part working independently yet synchronously.

3.2.2 Olorama Scent Generator

In this study, the Olorama scent generator was physically mounted on the Spot robot to turn it into a mobile scent-delivery unit. Instead of having a static smell device, fixed in just one spot, the idea was to make the olfactory output move through space, triggering scents dynamically and depending on the user's position in the virtual environment. This setup allows for more context-sensitive and spatially aligned smell experiences.

The Olorama system was selected due to its modularity, its wireless communication capabilities with different plugins and SDKs over Wi-Fi, as well as for its ease of integration with third-party software such as Unity. It is possible to release up to 10 different scents on command, making it a good match for this mobile VR scenario where multiple smells are deployed, without having to use extra cables or an onboard PC.

Communication with the Olorama is possible through direct UDP messages that are being sent from Unity. During this thesis, a custom UDP sender script was implemented in C#, which formats and transmits the control strings according to Olorama's command structure. Messages include the definition of the output channel, the intensity, spray time, fan duration, and a few other parameters. Unity sends this message over the local Wi-Fi network directly to the device's IP address. Unlike the robot, which is controlled via a separate Python server, Olorama does not require any backend, since it is controlled entirely from within Unity.

In the experiment, the scent trigger is tied to user proximity in the VR environment. When the user gets close, below a certain threshold distance, to a designated smell object, Unity sends the corresponding UDP message to release the scent in the real world. While the Olorama hardware does not allow direct control over intensity or fan speed, these effects can still be approximated by adjusting the timing and duration in the Unity Inspector.

The Olorama Scent generator was then mounted onto the Spot using 3M Dual Lock adhesive strips, which provided a non-invasive, vibration-resistant method of attachment that could be adjusted easily and did not require drilling. This ensured that the device remained stable during the robot's movement without obstructing the robot's sensors or its locomotion ability.

3.2.3 Software Architecture

The software architecture was designed to enable coordinated operation between multiple components: the mobile Spot robot, the Olorama scent generator, the virtual environment in the Unity game engine, and user interactions within the virtual world. Unity serves as the central orchestration layer, managing user tracking, triggering Spot's movement through a defined and automated procedure, handling the scent release logic based on user behavior, and providing both automatic and manual control options to monitor and adjust the application. All components are synchronized in real time via message-based communication protocols but remain largely independent from one another. For example, if a user does not approach an object linked to scent deployment, the scent generator will not release any odor.

To coordinate these interactions and ensure that all components are informed when a scent should be released, the system introduces the concept of "Smell Zones." Smell Zones are predefined positions in the virtual environment where the Spot robot must arrive in order to trigger a scent. These zones are placed in Unity's world space and are linked to specific virtual objects, such as small rocks used in the experimental scene, in this thesis. When a user approaches a smell zone, detected through the real-time tracking of their head-mounted display (HMD), and enters a defined distance threshold, the system initiates the next procedural step by sending the corresponding commands to Spot and Olorama.

Upon detecting such an event, Unity generates a structured JSON command that describes the desired action. This message is sent via TCP to a custom Python-based server running locally, which parses the command and translates it into instructions for the appropriate hardware. Commands related to Spot, such as movement, posture changes, or yaw rotation, are forwarded to the Boston Dynamics SDK and executed through its interface. In contrast, scent-related commands are sent as UDP messages directly to the Olorama device, containing the scent channel, spray duration, fan timing, and related parameters.

Rather than relying on Unity's classic trigger zones, which depend on collider-based physics events, the system uses a custom distance-based approach. This method computes the real-time proximity between the user and each Smell Zone without requiring any physical colliders or rigid bodies in the scene. It allows for precise and context-sensitive activation of both the scent release and Spot's orientation logic. Once the user enters the defined proximity range, a scent is emitted, and before each release, Spot consistently realigns its yaw to face the user, ensuring the scent is directed toward the users nose for maximum perceptibility. This orientation is calculated in Unity and sent as a dedicated rotation command to Spot via TCP.

To support the development and allow for detailed debugging and calibration, a manual control interface was implemented directly in Unity. This inspector-based interface enables researchers to send predefined Spot commands, override automatic behavior, or verify system functionality during testing. The User Interface includes numeric fields for defining Spot's walking speed and rotation angle, as well as interactive buttons for commonly used actions. Each button sends a structured TCP command to the Python server. The available commands are summarized in the following table, Table 3.1, and can also be seen in Figure 3.3:

Button	**Description**
Boot	Initializes and connects Spot to the SDK
Move	Sends a test movement command with a relative pose
Rotate	Rotates Spot based on a user-defined yaw value
Bend	Changes Spot's body posture (e.g., to a lowered stance)
Bend Reset	Resets Spot's posture to the default upright configuration
Stop	Interrupts the current Spot activity or walking routine

Table 3.1: Manual control functionalities available in Unity's Spot interface.

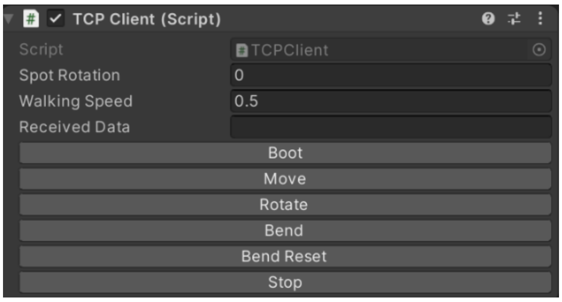

Figure 3.3: Inspector-based interface in Unity for manual Spot control.

While this manual interface greatly aided development and debugging, it also represents a key layer in the system architecture. During user studies, it served as a fallback mechanism in case of tracking failures or unexpected robot behavior. Most importantly, it ensured that every action Spot performed was intentional, either by being triggered by a well-defined automatic procedure or manually initiated by the experimenter. This hybrid design supports both flexibility and safety, which are essential for real-time, user-facing robotic systems.

3.3 Evaluation Task and Study Logic

The goal of the evaluation task was to assess the technical feasibility and timing accuracy of a mobile scent delivery system integrated into a spatial VR experience. To do so, a walking-based scenario was designed in which users moved through a small forest environment and encountered three olfactory interaction points. Each of these points was linked to a specific virtual rock and triggered the release of a scent when the user entered a proximity range during a predefined sequence. The idea for this project was to create a natural setting in which olfactory interactions would make intuitive sense and where scents like wood, wet ground, or freshly cut grass would feel immersive rather than artificial, such as in realistic scenarios. The system was designed to coordinate the robot's movement, orientation, and scent release based on the user's position and task progression.

The entire virtual forest environment was implemented in Unity and sized to fit within a 5×5 meter tracked space. As shown in Figure 3.4, users were surrounded by a square-shaped wall of trees, forming the boundaries of the forest scene, and small rocks, which represented the interactive smell goals that were positioned at the four edges of the virtual environment, were placed to define the olfactory targets. The Spot robot would move to the small rocks, the smell goals, in a predefined global sequence that stayed the same throughout all trials with all participants. One additional large rock in the center served as a visual obstacle and safety measure, ensuring that users moved around it instead of walking directly towards the robot. This central rock also acted as a starting position for the robot before the sequence began, due to users being told not to step straight into the rocks.

Figure 3.4: Top-down view of the virtual forest environment with predefined smell targets and boundary trees.

The experience begins with the user standing at the starting rock on the left side of the forest scene. No scent is released at this point. After the study examiner manually initiates the procedure, the Spot robot autonomously moves to the first scent location. Once the robot reaches its designated pose, a soft blue smoke particle effect appears above the first target rock to signal the active smell zone. A subtle glow effect is also used to guide the user's attention. The smoke never appears before Spot is in position, ensuring users do not approach the robot prematurely. In general, users are initially instructed to start walking only when a new smoke effect appears. During the procedure itself, after having done the first smelling, they can hear a subtle sound cue, which clarifies that a new smoke has spawned somewhere in the environment, which they have to find, which signals them that they can start moving again. As shown in Figure 3.5, this particle system rises gently and fades upward to provide a clear but unobtrusive signal. Together with the glow, it helps users visually locate the scent interaction point in the forest scene.

Figure 3.5: Subtle blue smoke with glow effect marks the active scent zone in the VR scene.

When the user walks towards the smoke and enters a defined distance threshold of 75 cm from the target object, the smoke effect disappears. At this moment, Spot aligns its body to face the user's head position, ensuring that the scent is sprayed directly toward the user. Users are instructed to remain stationary once the smoke disappears, both to avoid walking into Spot and to ensure consistent delivery conditions. However, when Spot is moving and the user is not, it moves around objects and the user, making this measure essential for both user safety and the robots safety.

Figure 3.6 depicts the synchronized real-world and virtual implementation of the scent emission mechanism. On the left, the Spot robot releases the scent upon proximity threshold detection; on the right, a corresponding visual particle effect is rendered in the virtual environment to indicate scent delivery.

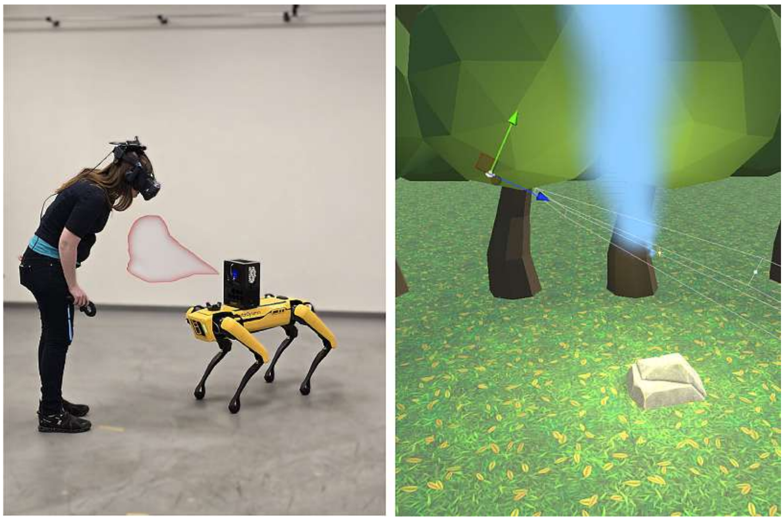

Figure 3.6: Visualization of synchronized real and virtual scent emission once the 75cm threshold is crossed.

Once the user detects the scent, they confirm the perception by pressing the button on the back of their VR controller. If no confirmation is received within 20 seconds, the system automatically continues to the next step. This setting can be seen in Figure 3.7. In such cases, an auditory cue is played to signal that the time has expired, and a new smell interaction is starting. The robot then moves to the following target location, and the particle glow system is reactivated at the new smell zone to guide the user. Users are told that they may resume walking once a new smoke zone appears.

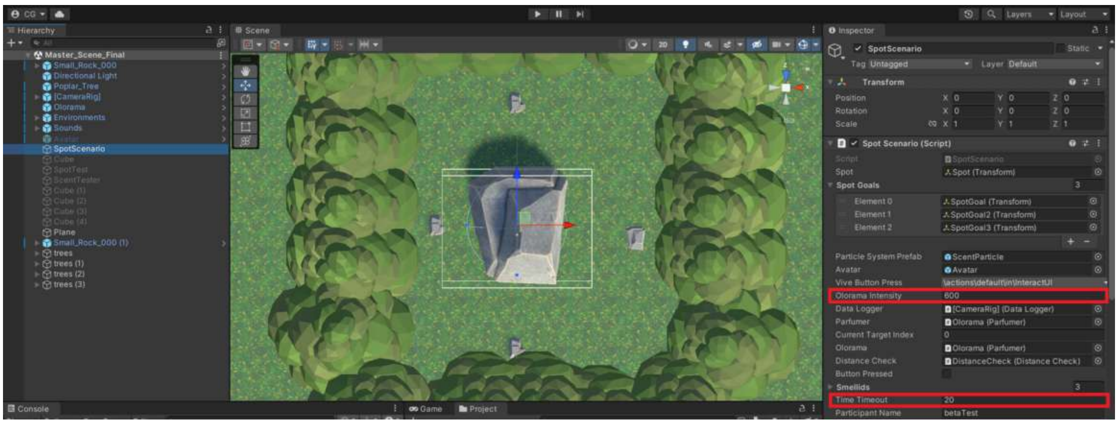

Figure 3.7: Inspector settings in Unity defining the smell intensity and timeout logic for the evaluation sequence.

This cycle is repeated for three olfactory interaction points, each associated with a different smell, which are "wet ground", "wood logs", and "roses". The objects are arranged to encourage a walking path from the left to the bottom, then to the top, and finally to the right. After the third interaction, and once the scent is confirmed or the timeout elapses, Spot performs a final behavior by stopping and sitting down. This indicates the end of the trial, and users can take off the HMD.

This entire sequence was repeated across all participants under identical conditions and serves as the foundation for the study design discussed in Chapter 4.

CHAPTER 4

Evaluation and Results

This chapter presents the evaluation and results of the Spot-based scent delivery system, focusing on its effectiveness and on how users perceive smell within a VR environment. The main objective of the evaluation was to investigate how different smells, with varying intensities and smell types, affect the perception of participants and overall experience in VR. Furthermore, the evaluation aimed to assess whether such a mobile scent system could be integrated into future studies, enabling it to be applied to more complex use cases and features. By considering various measurements, this chapter aims to inform about the usability and impact of future large-scale olfactory VR systems, laying the groundwork for potential improvements and broader deployment in similar applications.

4.1 Study Design and Hypotheses

The user study was designed as an initial evaluation of the Spot-based scent delivery system, aiming to investigate how different smell intensities and smell types influence the ability of participants to detect smells, as well as their overall experience. An additional goal was to assess the system's applicability for future studies involving more complex use cases, interactions, and scenarios.

Three naturalistic scents, already described in the section 3.3, were used to match the forest theme and provide sensory contrast. Additionally, three scent intensity levels (200, 400, and 600) were selected based on the Olorama specifications for low, medium, and high intensity, according to their user documentation. These values were chosen to explore how the strength of olfactory input may affect detection performance and perceived intensity throughout the whole thesis.

Deciding on the three different types of smells was a long process, ranging from choosing the right environment, such as in this case a forest, rather than, for example, a beach or a meadow full of flowers, to determining which forest elements should be displayed throughout the procedure. In early iterations, a wider range of smells was explored using both preset scent capsules from the Nature Pack, such as lavender, jasmine, wet ground, or rosemary, and a custom selection tailored to fit the designed environment, including scents such as forest, peppermint, lemon, or coconut. This flexibility in smell selection, provided by Olorama's modular cartridge system, allowed for thematic alignment and emotional tone adjustments based on insights from aromatherapy and multi-sensory experience design. The three specific smells, namely wet ground, wood logs, and roses, were chosen to represent a balanced and realistic range of forest-related olfactory impressions that differ clearly in character. Each scent reflects a distinct semantic category within the natural environment:

- Wet ground was chosen as a subtle, earthy base note often associated with freshness and outdoor nature.
- Wood logs represented a more neutral, dry, and woody tone, typical of forest surroundings.
- Roses added a floral and more intense contrast to the other two, providing a distinguishable scent with higher perceptual salience.

This selection ensured that the user experience remained thematically coherent with the forest scene, while also enabling the study to explore how smell intensity and character affect detectability and perception. The combination allowed for comparative analysis between a subtle (wet ground), medium (wood), and intense (rose) scent profile, helping to understand which types of natural smells are more effective or salient in mobile olfactory VR contexts.

In addition, it had to be tested which fan duration should be chosen as a constant, as well as which distance the Spot should maintain from users before emitting the smell to, on the one hand secure a safe environment, but on the other hand provide sufficient testing possibilities. In the end, the fan duration was set to a constant of 4 seconds, which was recommended as a value from the Olorama constructor for this study, and the 75 cm proved ideal.

A within-subjects experimental design was selected to ensure that each participant experienced a range of smell intensities and smell types, thereby reducing the impact of individual differences in olfactory sensitivity and VR familiarity.

To systematically vary the presentation of smell intensities and smell types, while avoiding overwhelming each participant with all possible combinations, a Latin Square counterbalancing design was implemented. In this approach, each participant was assigned one specific combination of each smell type with one smell intensity per block, ensuring that all smells and intensities were represented across all participants.

Each participant completed three experimental blocks, each block corresponding to one specific smell intensity (low, medium, high). During each block, participants experienced all three smell types, which were also all delivered at the same intensity. Since users went through the experiment three times, namely one block per intensity, they experienced each smell type at each intensity level across the whole session. This design ensured that all intensities were tested for each participant, not within a single block, but across the entire user test. The order of the smell intensities was counterbalanced, so that one participant might have received the smell intensities in the order of low, medium, high, while another participant might have experienced them in the order of medium, high, low. This approach allowed us to systematically investigate both the intensity and the smell type effects while minimizing bias due to the block intensity order.

The study was designed to test the following hypotheses:

- H1: Higher smell delivery intensities would result in faster detection times, due to the increased concentration of scent molecules.
- H2: Different smell types would result in varying detection times, reflecting on how easily specific scents can be recognized.
- H3: Higher smell intensities would lead to higher perceived smell strength ratings.
- H4: The addition of olfactory stimuli would not significantly increase VR sickness symptoms.

These hypotheses guided the analysis of both the objective detection times and the subjective ratings collected during the study. The aim was to systematically investigate how users interacted with the system and how different smell intensities and types shaped their overall experiences, ultimately providing valuable insights to guide the development of future olfactory VR systems.

4.2 Participants and Apparatus

A total of 14 participants (7 female, 7 male) participated in the study. The ages of the participants ranged from 21 years to 60 years (Mean M = 29.5, Standard Deviation SD = 4.15). The distribution was pretty even across ages, with no significant clustering in any particular range. None of the participants reported having olfactory disorders or any prior experience with olfactory display technologies, making their impressions throughout the study even more unbiased, genuine, and reflective of their first-time user experience. At the same time, participants had different levels of exposure and familiarity with VR. 5 of the 14 users were first-time VR users, 5 had tried VR at least once before, and 4 of them were regular VR users. All participants signed an informed consent form before participating in the study and were naïve to the purpose of the study. The study was carried out in a dedicated 5m×5m workspace where participants, equipped with an HTC Vive Pro HMD, could move freely. To enhance immersion and safety, the setup included a Vive Wireless Adapter, which eliminated the need for physical cables. This not only allowed users to explore the environment unimpeded but also prevented potential tripping hazards for both participants and the Spot robot. The battery for the Vive wireless adapter was stored in a small belt pocket or securely mounted on the user's clothing, as shown in Figure 4.1.

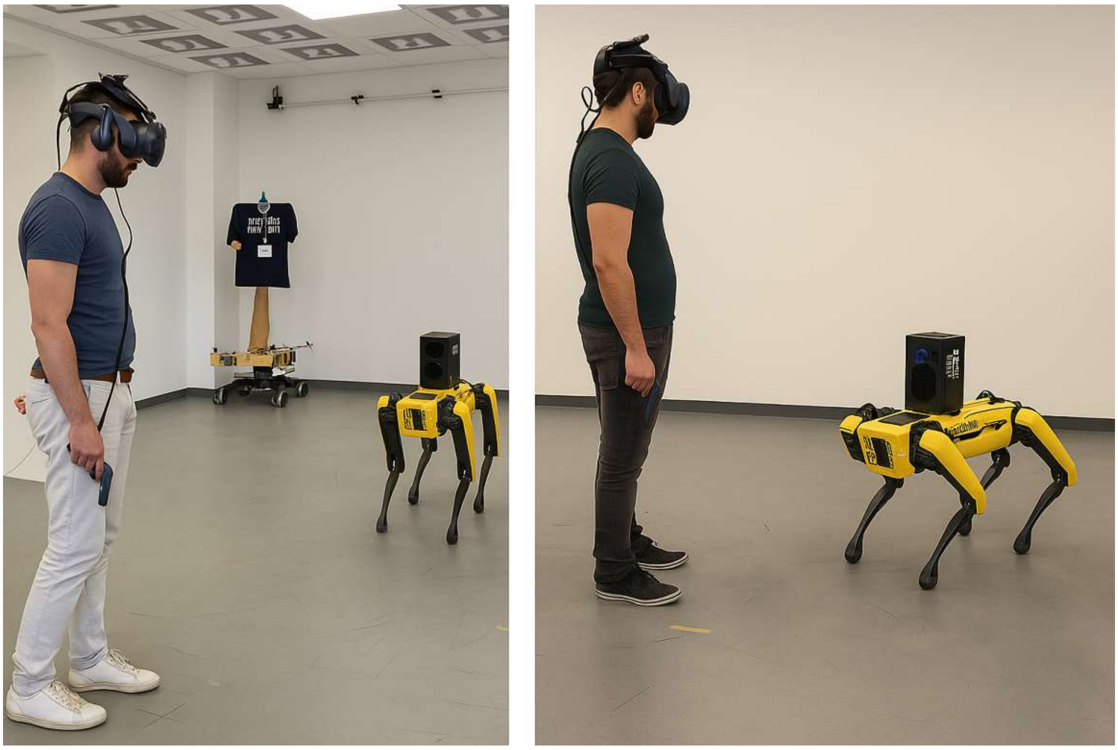

Figure 4.1: Left - Battery stored in a belt pocket. Right - Battery is securely mounted on the users clothing.

The VR environment was developed in Unity3D (version 2021.3.25f1) and designed to simulate a small forest scene, featuring trees, rocks, and ambient forest sounds. The rocks were placed as obstacles for the users in such a way as to guide them through the environment while preventing them from colliding with the Spot robot throughout the navigation process, as well as waypoints for the Spot robot since the smells were placed next to those objects, as can be seen in Figure 4.2. A large rock was placed in the middle, under which the Spot robot started at the beginning of the study, while four small rocks were placed 2 meters from the center of the workspace in each direction.

Figure 4.2: Smell was released near designated small rocks in the environment, with the Spot robot stopping and facing the user before scent emission.

In addition, the tree line was intentionally placed this way, as this prevented users from going further than the 5m×5m real-life workspace. Although users were thoroughly monitored during the experiment to make sure that they were as safe as possible anyway and, for example, to allow them to walk as freely as possible without endangering them, it was a great way to visually tell users that they have reached the end of the room without interrupting their VR experience.

Ambient forest sounds were continuously played in the background to mask any auditory signals that could reveal the timing of the scent release.

4.3 Procedure

Before the experiment began, each participant was welcomed, informed about the general concept of the study, and briefed about safety regulations, such as the fact that Spot moves through the room but is programmed to walk around users if necessary, safely. They were then asked to sign a consent form, which they all did. Afterwards, they completed a demographic questionnaire and filled out the pre-experiment Virtual Reality Sickness Questionnaire (VRSQ) to establish a good baseline for physical well-being and sensitivity to VR and smell exposure. Participants were then equipped with the HTC Vive Pro Eye Headset and wireless adapter to perform a short VR training. They entered the virtual forest environment and familiarized themselves with walking in VR as well as with the visual elements and obstacles. This phase ensured that participants were comfortable with the interface, movement mechanics, and the immersive VR experience before the actual experiment began. The main experiment consisted of three blocks, each corresponding to one of the smell intensity conditions, described in Section 4.1. During each of those blocks, participants completed the navigation task by locating three predefined scent goals where they performed the smelling. The specific positions of the goals were unknown to participants beforehand. As previously outlined, Spot autonomously navigated to each goal, rotated to face the user, and triggered the corresponding scent at the assigned intensity when the user approached. Participants then confirmed scent detection by pressing a button on the back of the VR controller or were prompted to proceed if no detection occurred within the time limit.

Throughout the session, participants were closely monitored to ensure their safety, particularly as they moved freely within the 5m×5m physical space. The spot robot was programmed to avoid close-range collisions with participants, or other objects, for that matter. It actively rerouted its path around users when they were in its path between one Spot goal and the next, without making physical contact.

After each block, which consisted of recognizing three smells at the same intensity, resulting in a total of nine smell interactions per participant, participants filled out a brief post-block questionnaire, assessing perceived scent intensity, recognition, and confidence in detection. While participants completed the digital survey, which was administered using Google Forms, the room was aired out for at least five minutes before beginning the following condition. The reasoning for that was to diminish any residual odors from the previous block and to minimize odor adaptation from users [BBEL71].

This procedure was repeated for the remaining two intensity conditions. Finally, upon completion of all three blocks, participants completed a final post-experiment questionnaire, which included repeated VRSQ questions and open-ended feedback prompts. At the end of the session, participants were debriefed on the purpose and goals of the study, as well as on potential future applications for such mobile scent systems. They were encouraged to share any final thoughts or observations they might have made.

In the following image, Figure 4.3, the procedure is visualized as a flowchart.

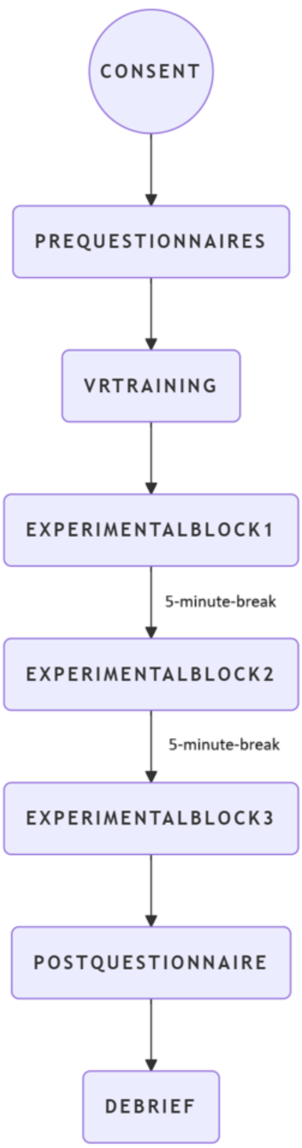

Figure 4.3: Overview of the study procedure, including training, three scent intensity blocks, 5-minute breaks between experimental blocks, final questionnaires, and the debrief.

Each session lasted approximately 45 minutes per participant.

4.4 Data Collection and Metrics

To evaluate the feasibility and effectiveness of the mobile olfactory VR system, multiple data sources were collected throughout the study, which can be seen in Figure 4.4. By continuously recording the position and orientation of both Spot and the participant in the virtual environment at 90Hz, and combining this with subjective self-report measures, a comprehensive understanding of the user interactions and perceptions was obtained.

Metric	Description	Source
Detection Time	Time from scent trigger to user confirmation	System logs
Recognition Accuracy	Correctness of scent identification	Post-block form
Perceived Intensity	User-rated strength of scent	Post-block form
Confidence Level	Self-reported certainty in recognition	VRSQ form
VR Sickness (VRSQ)	Pre/post physical symptoms	Unity + Python log

Figure 4.4: Overview of the collected evaluation metrics, their descriptions, and respective data sources.

Different subjective measurements have been collected, one of them being the smell detection time. For each of the three experimental blocks, the time it took participants to detect a smell was recorded. The time measurement began when the Spot robot triggered the scent and ended when the participant pressed the designated button on the VR controller to confirm the detection of the odor. If a scent was not identified within 20 seconds by the user, a timeout was logged, and the experiment moved forward to the next step of the procedure.

In addition, participants were asked to identify the perceived scent via an open-ended text field in the questionnaire. This enabled the analysis of recognition accuracy for each smell type across different intensities and smell types, providing great insight into how reliably distinct smells could be identified in a VR setting. Furthermore, participants completed a brief post-block questionnaire after every one of the three blocks, where they rated the perceived intensity of the scents and indicated their confidence level in identifying the smells. These metrics help to determine how well users can distinguish between low, medium, and high-intensity settings and how sure they feel about their ability to smell the correct odors.

To ensure that users would always feel safe and comfortable, they were monitored throughout the whole study. Nevertheless, to analyse if the time in the VR environment would have any impact on participants, they were asked to fill out a VRSQ [KPCC18] before and after the experiment. This measured symptoms such as eye strain, dizziness, or disorientation, helping to assess the impact of olfactory stimuli and mobile robotic interaction on VR sickness. VRSQ scores were then computed considering the delta score from the pre-VRSQ scores.

In the post-experiment questionnaire, data were collected by asking users the following subjective questions: "How much did you trust the VR system's ability to simulate smells accurately? (1 - Did not trust at all, 7 - Trusted very much)"; "How far were you (in cm) from the smell source during the experiment?". Participants were also encouraged to leave open comments to provide qualitative feedback on usability and the perceived realism of the system.

In parallel to the subjective data, system-level logs were automatically recorded. These included timestamps of scent release, positional tracking of both the robot and the user, the distance to the scent source at the time of emission, and timeout events. These objective metrics allowed cross-validation of self-reported responses with the actual behavior.

4.5 Results

To analyze the collected data, non-parametric statistical methods were applied, as the majority of dependent variables did not meet the assumption of normality. This was confirmed using the Shapiro-Wilk test. For interval-scaled measurements such as smell detection time, an Aligned Rank Transform (ART) ANOVA test [WFGH11] was conducted, treating Smell Intensity and Smell Type as within-subject factors. Post-hoc comparisons were performed using contrast tests based on the ART-ANOVA framework [EKHW21]. For ordinal data and Likert-type responses, including the VRSQ scores, perceived intensity ratings, and confidence levels, a Friedman ANOVA was used, with the experimental block as the within-subject factor. Here, each participant completed three experimental blocks, one for each smell intensity (low, medium, high), allowing for the within-subject comparison across the conditions. When significant effects were found, follow-up pairwise comparisons were conducted using Conover's test with appropriate adjustments.

4.5.1 Time and Trajectories

There was no significant effect of block order ($\chi^2(2) = 4.00,\ p = 0.13$) or Smell intensity ($\chi^2(2) = 0.57,\ p = 0.75$) on the overall duration of a trial. On average, each block lasted approximately 211±99 sec.

Participants generally stayed within the boundaries of the 5m×5m tracked space, and Spots movement accuracy was continuously logged and compared to the coordinates of each scent goal. Figure 4.5 below shows aggregated trajectories of both the Spot robot and participants, revealing clearly visible clusters at (0, 2), (−2, 0), and (0, −2), which correspond to the scent goal locations where Spot released the odors. The figure also illustrates how participants navigated the virtual forest environment while avoiding central obstacles and the origin zone. To assess the precision of Spot's positioning during scent delivery, we compared its final pose with the target locations. On average, Spot reached the scent goals with a positional deviation of M=10.87cm (SD=7.92cm) and an orientation deviation of M=3.76° (SD=6.12°). Across all trials, the robot consistently approached the goal from the correct direction and triggered the scent within a 75cm radius of the user. To assess how accurately Spot reached the designated scent goal locations, we analyzed its final position and orientation relative to the predefined targets. On average, Spot stopped with a positional offset of M = 10.32 cm (SD = 8.51 cm) and an orientation difference of M = 3.11° (SD = 8.61°) compared to the intended Smell Goal alignment, confirming its consistent and safe alignment, facing the user for each scent emission.

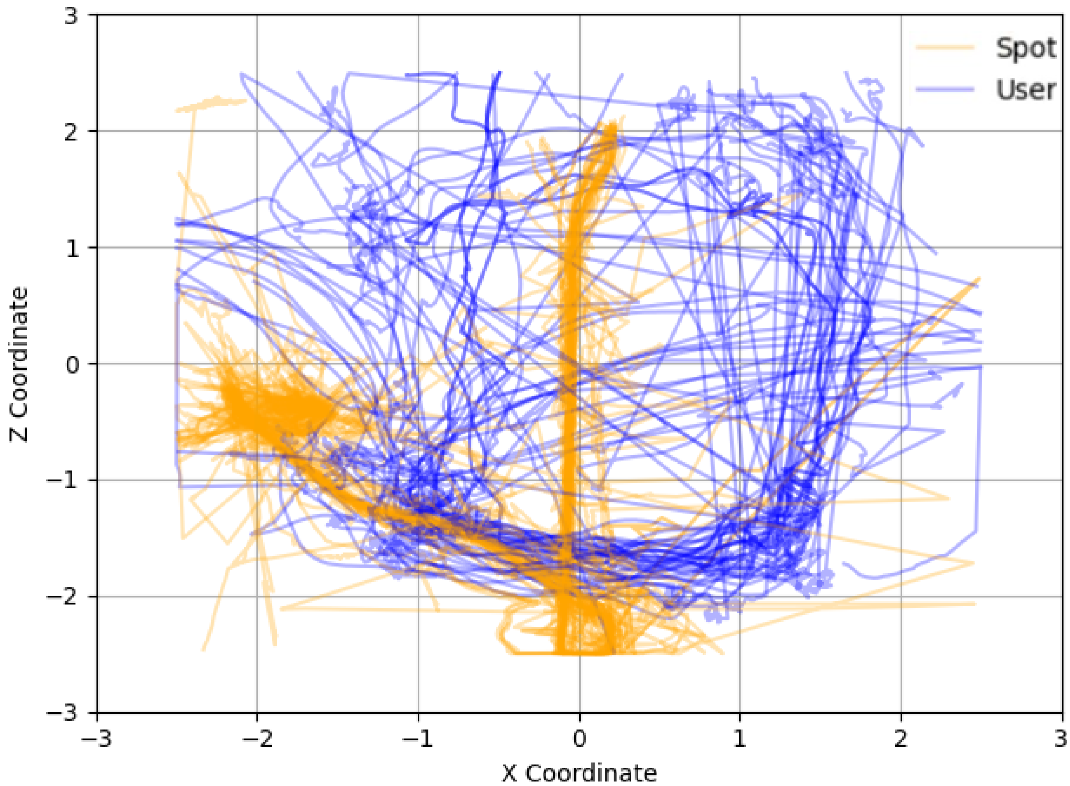

Figure 4.5: Combined movement paths of Spot (orange) and the user (blue) within the workspace throughout the study

4.5.2 Smell Perception

Figure 4.6 visualizes the average time and standard deviation for participants to detect a smell during each trial, grouped by Smell Intensity and Smell Type. An ART-ANOVA revealed a significant main effect for Smell Intensity $F(2, 99.57) = 9.94$, $p < .001$, $\eta_p^2 = .16$

as well as for the Smell Type $F(2, 99.05) = 8.62$, $p < .001$, $\eta_p^2 = .14$. However, no significant interaction effect between the two factors was observed, $F(4, 99.63) = 0.53$, $p = .54$, indicating that the effect of smell intensity on detection time was consistent across all smell types, and vice versa. Therefore, the two factors did not influence each other's impact on detection performance. Post-hoc comparisons indicated that the high intensity led to the fastest detection time ($M = 7.67$, $SD = 2.80$), followed by the medium intensity ($M = 8.90$, $SD = 3.05$) and the low intensity ($M = 10.47$, $SD = 4.40$), which resulted in the slowest detection overall. The difference between low and medium intensity, however, was not statistically significant. Regarding scent types, Flower smells were associated with the longest detection time ($M = 10.16$, $SD = 3.39$), compared to Grass ($M = 8.80$, $SD = 3.83$), and Wood ($M = 8.06$, $SD = 3.47$), which were detected faster. Beyond that, there was no statistically noteworthy detection time difference between Wood and Grass.

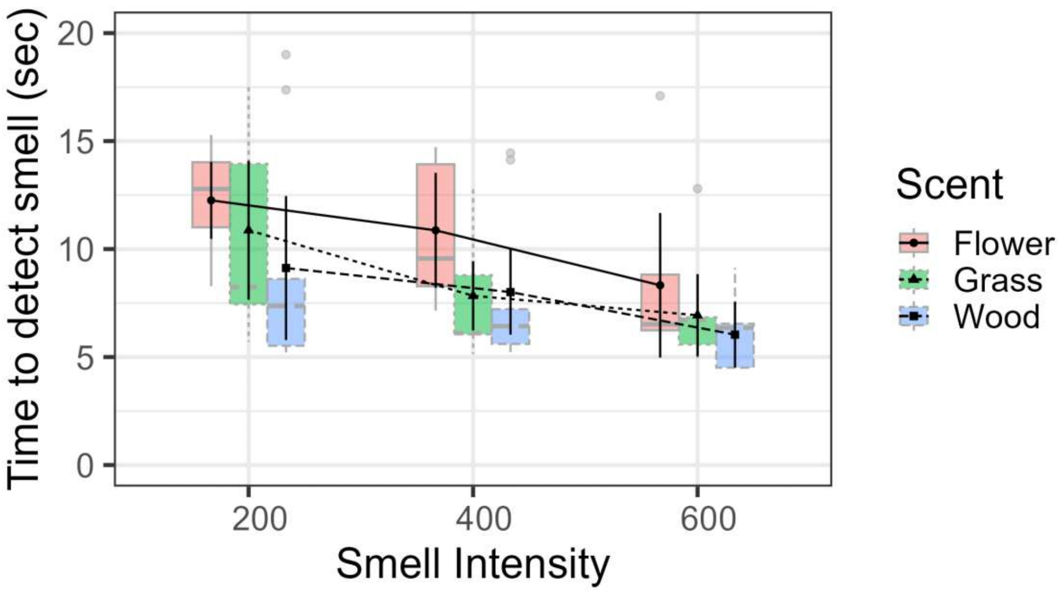

Figure 4.6: A Boxplot visualizing the mean and standard deviation of smell detection times, grouped by scent intensity levels (200, 400, 600) and scent type. Colors indicate scent type: red for Flower, green for Grass, and blue for Wood.

Despite these measurable differences in detection speed, the subjective perception of scent intensity did not show any significant variation across the multiple conditions. Users did not report any effects of the different smell intensities. A Friedman ANOVA therefore showed no main effect of intensity levels on perceived strength of users ($\chi^2(2) = 2.22$, $p = 0.33$), since the users rated all intensities similarly:

- Low (200): M = 5.14, SD = 1.09
- Medium (400): M = 5.04, SD = 1.46
- High (600): M = 4.85, SD = 1.91

This suggests that participants were not consistently able to distinguish between intensities on a subjective level, despite objective differences in detection times.

Participants were also asked to describe the smells as a free-text answer after the experiment. The responses were sanitized for analysis by applying lowercase formatting, removing plural/singular inconsistencies, correcting typos, and excluding generic filler terms. Figure 4.7 shows the word clouds that have been generated for each of the three scents. Across all experiments, the most commonly mentioned scent-related words were: "flowers" (5 mentions), "wood" (4 mentions), "forest" (3 mentions), "grass" (3 mentions), and "roses" (2 mentions).

Figure 4.7: Word clouds illustrating participant responses to the free-text question on perceived smells for each scent type "Please describe the smells you experienced?". From left to right: Flower, Grass, and Wood. Larger and more centered words indicate higher mention frequency across participants.

4.5.3 Questionnaires

To evaluate the subjective experience of the participants, questionnaire data were collected before, during, and after the experiment. The VRSQ was administered before and after the three individual experimental blocks to assess any physical discomfort or symptoms such as disorientation ($\chi^2(2) = 6.25,\ p = 0.51$) or oculomotor strain ($\chi^2(2) = 1.00,\ p = 0.60$). A Friedman NOVA did not reveal any significant effect across the blocks ($\chi^2(2) = 1.80,\ p = 0.40$), suggesting that no substantial increase in symptoms was due to the mobile scent device and VR.

In addition, at the end of the experiment, users were asked to estimate how far away the smell was displayed. Users reported that the distance between them and the Spot robot with the smell was about 108±63 cm, whereas the actual distance was 150 cm.

Table 4.1 summarizes the average scores per block.

Table 4.1: Average VRSQ scores per block, reported separately for the disorientation, oculomotor, and total subscales.

	Disorientation	**Oculomotor**	**Total**
Block 1	5.23±11.45	5.14±10.26	6.19±10.55
Block 2	6.14±10.92	7.73±10.05	8.44±9.57
Block 3	6.94±11.42	8.33±11.23	7.73±10.43

Additionally, as a response to the question "How much did you trust the VR system's ability to simulate smells accurately?", participants were asked to rate their confidence in scent recognition on a 7-point Likert scale after each block. A score of 5.21±1.47 on the 7-point Likert scale was evaluated. Similarly, to the question "How much did you trust Spot Robot for walking safely in the workspace?", participants reported a score of 5.23±1.21 on a 7-Likert scale. While slight trends suggested higher confidence ratings for more intense scent conditions, no statistically significant difference across blocks was found.

4.5.4 Post-Experiment Feedback and Additional Observations

Most participants described the VR experience as something pleasant, enjoyable, and refreshing, particularly those who were using VR for the first time. The experience was perceived as something new and left a positive impression overall (user 1). The environment itself was considered visually pleasing, although slightly simplistic in its design (users 2 and 3). The ambient soundscape, which included bird sounds, contributed to immersion. Nevertheless, some users noted that they could still hear the robot, which was slightly disruptive and occasionally broke their sense of immersion (users 2, 4, 6). Several participants reported being able to perceive the scents that were deployed by the smell sensor and that they generally found them pleasant, even if the specific smells were not always easy to identify for the users (users 10, 11, 13). Suggestions for improvement included using more recognizable or stronger scents, such as lavender or bakery aromas (user 5). One user noted that one scent was much stronger than the other smells (user 11). One participant also questioned why blue smoke was used and reported difficulty understanding the spatial relationship to the robot, which users could not locate spatially, since it was not visible through the headset (user 6).

CHAPTER 5

Discussion

This chapter discusses the key findings of the evaluation in light of the initial research questions and hypotheses. It reflects on how the system performed in terms of smell detection, recognition, and user comfort, and explores potential reasons behind differences observed across conditions. Design implications, technical insights, and directions for future work are derived from both quantitative results and qualitative feedback.

5.1 Reflections on Study and Hypotheses

This study aimed to investigate the feasibility, reliability, and user perception of a mobile scent delivery system embedded in a spatial VR environment. Four core hypotheses were tested, each addressing a different aspect of system performance and human perception. These were evaluated based on the statistical analyses outlined in Chapter section 4.5 and are interpreted below in terms of both quantitative results and qualitative observations.

The first hypothesis (H1) proposed that higher smell intensities would lead to faster detection. This was confirmed by a significant main effect of scent intensity on detection time, as shown by the ART-ANOVA in Figure 4.6 and discussed in subsection 4.5.2. Users reacted more quickly to stronger smells, consistent with prior findings that higher molecular concentrations accelerate olfactory detection [LHK+24]. This result validates the technical ability of the system to modulate perception through intensity control reliably, and it highlights intensity as a crucial parameter for time-sensitive scent design.

The second hypothesis (H2) suggested that different smell types would result in different detection times, assuming that certain smells are more immediately recognizable than others. This was partially supported, as again can be seen in Figure 4.6. While detection times did differ across scents, with “Wood” being detected more quickly than “Rose” or “Wet Ground,” these differences were not always statistically significant. Qualitative comments suggested possible causes, including that users found some smells artificial or difficult to describe, while others evoked stronger emotional associations. Interestingly, negative associations seemed to increase detection speed, as evidenced by the “Wood” smell. In contrast, pleasant or ambiguous smells like “Rose” were sometimes missed or confused, resulting in a longer time to detect the smell. Since the “Wood” scent drew more negative feedback and was described as uncomfortable, along with intense, spicy, or woody, participants would not want to be exposed to it for extended periods and therefore may have subconsciously prioritized its detection to avoid prolonged exposure. These associations are further illustrated in Figure 4.7, which shows participant word associations for each scent type, revealing common descriptors and emotional connotations. This could also explain why it was the fastest to detect, as prior research noticed that a negative or unpleasant olfactory experience could influence the perception and attention of users [BB17]. Additionally, the speed at which users recognize a smell is known to improve when the scent is familiar or easier to identify [PD20]. Due to “Wet Ground” being more easily identified than the other two smells by the users, this could explain the faster detection time. Nevertheless, this suggests that both emotional valence and perceptual clarity affect olfactory responsiveness in VR. Finally, it is important to note that the physical distance between the user and the Spot robot may also have influenced perception. In this study, only one fixed distance, which was approximately 75cm, was tested, leaving open questions about how proximity affects intensity perception and response times.

The third hypothesis (H3) assumed that higher smell intensity would also lead to stronger perceived smell strength. However, this was not supported. While the detection time varied across intensity levels, with higher intensities leading to faster detections, which also can be seen in Figure 4.6, participants rated the intensity levels as relatively similar across all blocks. This discrepancy highlights that users did not consciously perceive higher-intensity scents as stronger, despite their quicker reactions. One possible explanation is that the differences were not significant enough to be consciously distinguished, or that users adapted quickly to the smells. It may also reflect a ceiling effect, where participants have already perceived the lowest intensity as sufficiently strong, making further increases feel negligible. Additionally, it should be noted that intensity perception was only assessed after each block and based on a limited number of trials. This suggests that participants may have either learned or adjusted their perception over time, or lacked sufficient repeated comparisons to notice differences, particularly when users experienced different intensity orders, which likely led to divergent subjective learning perceptions across participants. This finding suggests that increasing intensity alone does not necessarily translate into a more substantial subjective experience, which is a valuable insight for the design of future multi-sensory systems.

The fourth hypothesis (H4) proposed that mobile scent delivery would not increase VR sickness symptoms. This was confirmed, as discussed in subsection 4.5.3, and as can be seen in Table 4.1. VRSQ scores remained stable across all interaction blocks, and no significant discomfort was reported. Participants reported feeling safe and unaffected, with the experience not interfering with their overall comfort or daily well-being. This suggests that integrating a moving robot with synchronized scent emission can be done safely in immersive environments. The system did not introduce any additional strain beyond the base VR experience, even though users were walking and turning in a spatially active scenario. This confirms the system's suitability for extended real-time applications. However, it must be acknowledged that users were exposed to the system for only a short period. The absence of symptoms may therefore be partly due to the limited exposure duration, meaning that systems involving longer user experiences still require further investigation to understand potential long-term effects.

These outcomes underscore the complexity of multi-sensory interaction. While the system reliably delivered scent and enhanced timing accuracy, not all perceptual outcomes, namely the users perceived intensity ratings and their recognition accuracy, aligned with the technical parameters. The divergence between objective detection and subjective evaluation, especially regarding perceived intensity, highlights the need for careful calibration and individualized tuning in future designs. Such tuning should consider individual factors, including users olfactory sensitivity, emotional associations with specific scents, prior scent familiarity, effects of VR sickness or motion sensitivity in larger user experiences, and susceptibility to sensory or motion-related discomfort in VR environments.

A summary of the tested hypotheses and the observed outcomes can be seen in Table 5.1.

Table 5.1: Overview of tested hypotheses, their rationale, and observed outcomes

Hypothesis	Description / Rationale	Observed Outcome
H1	Higher smell delivery intensities would lead to faster detection times, due to higher concentrations of scent molecules.	**Confirmed.** Detection times significantly decreased with higher intensity across all scents.
H2	Different smell types would result in varying detection times, based on how easily they were recognized.	**Partially supported.** Wood was identified faster than Rose or Wet Ground, but results were inconsistent due to individual variation.
H3	Higher smell intensities would lead to stronger perceived smell strength.	**Not supported.** Despite faster detection, subjective ratings of intensity did not increase significantly.
H4	Olfactory stimuli would not significantly increase VR sickness symptoms.	**Confirmed.** VRSQ scores remained stable; no notable discomfort was reported.

Beyond the hypothesis-level findings, this study also provides broader insights into the design and application of mobile olfactory systems in VR:

- The combination of trajectory recording, synchronized robot movement, and condition-based scent emission proved technically robust and flexible, operating under real-time constraints without causing sensory conflict.

- The study demonstrated that smell can be introduced at precise moments during spatial navigation, without confusing users or increasing simulator sickness, making it suitable for dynamic interaction scenarios.
- Participant feedback suggested that emotional and semantic associations of smells may have influenced recognition and detection. Some scents were identified more quickly or confidently, possibly due to prior familiarity or stronger emotional responses. While these impressions were not quantitatively confirmed, they point to the potential value of personalization or adaptive scent selection in future systems.

Ultimately, this research demonstrates that mobile olfactory systems are not only technically viable but also perceived as meaningful and non-intrusive in immersive VR settings.

Taken together, the findings highlight mobile scent delivery as a promising component of immersive system design, particularly when carefully adapted to spatial and user constraints.

5.2 Design Implications

The findings of this study offer several design implications for future implementations of mobile scent delivery in immersive environments. First, the successful synchronization between robot movement and scent emission underlines the potential of integrating olfactory interaction into real-time VR experiences. The system's ability to trigger smells precisely and reliably during user navigation confirms that spatial scent cues can be introduced without overwhelming or confusing users. This opens up design opportunities for enhancing presence, guiding attention, or marking transitions in interactive scenarios.

Notably, the results also highlight the feasibility of large-scale mobile scent systems that can dynamically accompany users across space. Unlike stationary emitters, a mobile platform enables scent delivery that flexibly adapts to the users position and movement, making it suitable for expansive, walkable environments such as room-scale VR installations, location-based storytelling, exhibitions, or therapeutic scenarios. Since the system does not require fixed wall-mounted emitters, permanent wiring, scent tubing, or room-specific tracking setups, it can be easily deployed across various venues or temporary installations. This portability not only broadens the range of possible applications but also emphasizes the value of mobile scent systems as flexible and immersive tools, enabling them to overcome the spatial constraints of static setups.

Moreover, the study highlights the importance of emotional and semantic associations with specific smells. These associations affected recognition speed and subjective comfort, even when the technical intensity was held constant. Designers of future systems should therefore not only focus on the chemical properties of smell, such as molecule concentration or intensity, but also consider the social, emotional, and contextual meanings users attach to certain scents. Adaptive scent selection or user-specific profiles could help accommodate individual preferences and avoid discomfort from ambiguous or negatively perceived odors.

Another key implication concerns the autonomy and behavioral coordination of the robot. To support user trust and avoid confusion, the robot's movement and orientation changes should occur smoothly and predictably, aligning with user expectations and the narrative or the existing interaction flow. In the current system, Spot moves between predefined Smell Zones triggered manually or via script. However, future iterations could benefit from greater autonomy, such as gaze-based or intent-driven predictions that allow the robot to anticipate user behavior and deliver scents just before the user reaches a point of interaction. This would minimize delays and create a more seamless, immersive experience.

Safety considerations are also essential when designing mobile olfactory systems. To avoid collisions or interruptions in presence, future systems could dynamically restrict the robot's access to user-only zones or implement proximity-based logic to adjust its path. This spatial coordination is especially relevant in multi-user settings, where multiple users or robots may share the same environment. Supporting individualized scent scheduling and positioning can help prevent cross-contamination and improve user-specific interactions.

Finally, the modularity and mobility of the system open up promising application areas such as location-based entertainment, education, storytelling, or rehabilitation. In scenarios where workspace constraints limit physical locomotion, scent-triggered cues could serve as natural, immersive redirection mechanisms. For instance, by introducing or removing certain smells, users could be guided toward or away from specific areas without breaking immersion. Similarly, a single mobile scent unit could be shared among multiple rooms or users, enabling flexible deployment without the need for stationary infrastructure. Taken together, these insights position mobile scent delivery systems not just as technical tools but as powerful experiential components. Their ability to influence perception, behavior, and memory through subtle yet context-sensitive cues offers exciting opportunities for immersive system design, particularly when adapted to the spatial logic and sensory expectations of different users and applications.

5.3 Limitations

As with any research prototype that integrates a diversity of tools, plugins, and technologies, including real-time robotics and multi-sensory interaction, several technical, practical, and perceptual challenges emerged during development, deployment, and testing. While the system functioned reliably and fulfilled its core objectives, several important limitations are worth acknowledging when interpreting the results or planning future improvements.

One central challenge concerned the inherent complexity of olfactory stimuli. Unlike visual or auditory output, scent dispersion is influenced by airflow, the shape of the room, user movement, and the delay from the generator until the scent reaches the nose. Although the intensity could be adjusted via parameter settings in Unity, precise timing and localization of smell release were more challenging to control. Smells could linger in the room longer than intended, occasionally interfering with follow-up interactions. This issue required careful ventilation and timing between sessions, especially during repeated trials, and limited the speed and replicability of test runs. However, this limitation is common to most scent-based systems and not specific to the hardware used.

In total, the integration and control of the Olorama scent generator worked reliably in most cases but required thoughtful coordination to ensure meaningful scent delivery. While not a major technical hurdle, its physical placement and interaction timing still required careful alignment with the user's position and the robot's movement to avoid premature or delayed perception.

A further limitation was the mounting and tracking setup. The HTC Vive Tracker used to measure the robot's proximity to the user's head-mounted display was not fixed in a dedicated holder but instead taped onto the robot's surface. Although this approach worked throughout the study, it introduced potential for minor misalignment. The position of the tracker, as well as the one of the Olorama scent device and the other tools that were used, remained constant throughout the study, making any shift impossible. Nevertheless, a firmer mount would improve positional accuracy and system robustness in future setups.

From a software perspective, the evaluation was limited to a single 5m×5m forest scene. While the environment was carefully designed to reflect a natural setting and worked well for the purpose of the study, it did not allow testing more complex or varied spatial-smell relationships. Dynamic transitions between scenes or zone-based storytelling were not implemented. As a result, it might be difficult to generalize and compare the results to other virtual worlds or applications. Additionally, the study focused on one specific interaction type involving detection and recognition, and did not explore alternative use cases or task types such as affective responses, exploration behavior, or narrative immersion.

Another limitation relates to the use of a within-subjects design, in which each participant experiences all experimental conditions. While this approach improves statistical power and allows for controlling individual differences in factors such as smell sensitivity, VR experience, or reaction speed, it may introduce potential carryover effects. Participants might become more accustomed to the scent stimuli or anticipate the procedure, which could affect detection or recognition performance. To mitigate such risks, future studies should consider incorporating counterbalancing techniques or varying condition orders more rigorously. Furthermore, the study did not include a control condition without smell, which would have helped isolate the specific contribution of olfactory input to the observed outcomes. Likewise, additional outcome variables such as presence, emotional response, or perceived immersion were not assessed systematically and could provide more nuanced insights in future evaluations. Future work could also compare olfactory cues with other sensory modalities, such as visual markers or specialized audio, and examine behavioral aspects like users exploration patterns or time spent near scented zones, further enriching the understanding of the role of scent in guiding attention and shaping interaction.

Finally, although the robot–scent coordination was technically stable, the Spot itself remained audible during operation. Despite participants wearing headphones, the robot's mechanical movements were still noticeable. This did not lead to discomfort or break presence according to participants' feedback, but it may affect immersion in future scenarios where audio-olfactory synchronization is critical. Reducing system noise or better masking it could be considered in future iterations. Future iterations may focus on using rubber foot pads to reduce the impact noise and the vibration of the robot. In terms of evaluation, this thesis included measurements of detection time, intensity perception, and recognition accuracy. However, due to the limited sample size and the relatively constrained environment, the results should be interpreted with care. Some perceptual responses varied depending on user proximity, walking speed, or scent familiarity. Larger-scale or more ecologically diverse studies would help verify how consistent these results are across settings and user groups.

Summarized, these limitations do not undermine the technical success of the system but rather highlight areas for future refinement. Most of them offer practical guidance for scaling and adapting the system beyond this proof-of-concept prototype and into more robust or applied scenarios.

CHAPTER 6

Conclusion and Future Work

This thesis presented a mobile olfactory display system designed for large-scale immersive VR environments. The system integrates a Boston Dynamics Spot robot, an Olorama scent generator, a Vive Tracker, and a custom Unity-based interface. Together, these components enabled location-specific scent delivery by synchronizing robot navigation with user interactions in VR. A Python-based server was developed to receive real-time commands from Unity, sending movement instructions to the robot via TCP and triggering scent emission via UDP. The Vive Tracker mounted on the robot allowed the system to measure the distance to the users head-mounted display, providing a spatial reference for scent activation. This approach eliminated the need for wearable scent hardware and instead allowed for a more ambient and natural integration of smell into the VR experience by using a mobile robot to deliver odors directly to the intended location.

The system was tested through a controlled user study in a 5×5 meter virtual forest environment. Participants encountered three olfactory interaction points, where the robot stopped and released specific scents when the user approached. A visual cue indicated the active interaction zone, and participants confirmed detection through a controller. Results showed that smell delivery could be executed reliably and was generally well-perceived across different users. Importantly, most participants reported no discomfort or disruption to their sense of presence, and they were able to detect, recognize, and respond to the scent cues, suggesting that the system succeeded in introducing olfactory interaction without breaking immersion.

These results underline that robotic scent delivery is not only technically feasible but also well-received by users in immersive, mobile VR settings. By enabling proximity-dependent scent triggering without any wearable device, the system offers a new design direction for multi-sensory interaction that supports user mobility and natural behavior. This represents a promising alternative to fixed or body-worn olfactory displays, especially in scenarios where space, motion, and autonomy are central.

At the same time, several limitations and open questions suggest directions for future development. While the system worked reliably, it was limited to a single environment and a predefined interaction structure. Future studies could explore more complex or varied scenes, incorporate multiple rooms or story-driven layouts, and test how scent perception holds up under different pacing or environmental conditions. Another promising path is improving the robot's autonomy, such as by, for instance, using gaze-based prediction or behavior modeling to trigger scent emission more dynamically and reduce manual intervention. Similarly, adapting the robot's path in real-time to avoid user-robot collisions or to guide user flow more naturally could improve safety and fluidity, especially in multi-user scenarios.

Additional technical refinements may further enhance the system. For instance, reducing the mechanical noise of the robot through foot padding or better masking could support stronger audio-olfactory synchronization. A more stable mounting solution for tracking hardware would improve positional accuracy. From a perceptual standpoint, incorporating user-specific scent preferences or adaptive delivery based on previous responses might increase comfort and personalization. Lastly, evaluation metrics could be expanded in future iterations to explore long-term memory effects, cross-modal associations, or learning outcomes supported by scent-enhanced VR.

In summary, this work offers a proof-of-concept system that demonstrates the feasibility and potential of robotic scent delivery in VR. It contributes a technically robust, perceptually subtle, and easily extensible platform for exploring large-scale olfactory interaction. While still at an early stage, the approach lays important groundwork for future applications in storytelling, training, education, rehabilitation, or entertainment, especially where immersive, hands-free, and spatially aware scent delivery could add value.

Ultimately, this study lays the foundation for future systems that deliver scent dynamically and non-intrusively in large-scale virtual environments. It is paving the way for shared, hands-free olfactory experiences that enhance immersion without relying on wearable hardware, with future work moving towards more adaptive and immersive multi-sensory experiences.

Overview of Generative AI Tools Used

To support the writing process, I used a few generative AI tools in a helpful but limited way. Perplexity AI helped me search for academic papers and get an overview of related work. I used Grammarly to check my grammar and style, and ChatGPT to help with rewording, editing, and making some parts easier to read, as well as to draw up mockup images. I made all final content and decisions.

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Bibliography

[AAS20] Yewande Akinola, Oluwatoyin Agbonifo, and Oluwafemi Sarumi. Virtual Reality as a tool for learning: The past, present and the prospect. *Journal of Applied Learning & Teaching*, 3, August 2020.

[ABE+22] Nicholas S. Archer, Andrew Bluff, Andrew Eddy, Chreshall K. Nikhil, Nick Hazell, Damian Frank, and Andrew Johnston. Odour enhances the sense of presence in a virtual reality environment. *PLOS ONE*, 17(3):e0265039, March 2022. Publisher: Public Library of Science.

[AHD+18] Judith Amores, Javier Hernandez, Artem Dementyev, Xiqing Wang, and Pattie Maes. BioEssence: A Wearable Olfactory Display that Monitors Cardio-respiratory Information to Support Mental Wellbeing. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 5131–5134, July 2018. ISSN: 1558-4615.

[AM17] Judith Amores and Pattie Maes. Essence: Olfactory Interfaces for Unconscious Influence of Mood and Cognitive Performance. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 28–34, New York, NY, USA, 2017. Association for Computing Machinery.

[BB17] Oliver Baus and Stéphane Bouchard. Exposure to an unpleasant odour increases the sense of Presence in virtual reality. *Virtual Reality*, 21(2):59–74, June 2017. Publisher: Springer Science and Business Media LLC.

[BBEL71] B. Berglund, U. Berglund, T. Engen, and T. Lindvall. The effect of adaptation on odor detection. *Perception & Psychophysics*, 9(5):435–438, September 1971.

[BP21] Sanne Boesveldt and Valentina Parma. The importance of the olfactory system in human well-being, through nutrition and social behavior. *Cell and Tissue Research*, 383(1):559–567, January 2021.

[Bro10] Jennifer C. Brookes. Science is perception: what can our sense of smell tell us about ourselves and the world around us? *Philosophical* *transactions. Series A, Mathematical, physical, and engineering sciences*, 368(1924):3491–3502, August 2010.

[CF23] Sarah Cormiea and Jason Fischer. Odor discrimination is immune to the effects of verbal labels. *Scientific Reports*, 13(1):1742, January 2023.

[DHR17] David Dobbelstein, Steffen Herrdum, and Enrico Rukzio. inScent: a wearable olfactory display as an amplification for mobile notifications. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers*, pages 130–137, Maui Hawaii, September 2017. ACM.

[DMP+21] Nicolò Dozio, Emanuela Maggioni, Dario Pittera, Alberto Gallace, and Marianna Obrist. May I Smell Your Attention: Exploration of Smell and Sound for Visuospatial Attention in Virtual Reality. *Frontiers in Psychology*, 12, July 2021. Publisher: Frontiers.

[DPGMD+22] Marcelo De Paiva Guimarães, James Miranda Martins, Diego Roberto Colombo Dias, Rita De Fátima Rodrigues Guimarães, and Bruno Barberi Gnecco. An olfactory display for virtual reality glasses. *Multimedia Systems*, 28(5):1573–1583, October 2022.

[DVO16] Dmitrijs Dmitrenko, Chi Thanh Vi, and Marianna Obrist. A Comparison of Scent-Delivery Devices and Their Meaningful Use for In-Car Olfactory Interaction. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 23–26, Ann Arbor MI USA, October 2016. ACM.

[DWH+99] H.Q. Dinh, N. Walker, L.F. Hodges, Chang Song, and A. Kobayashi. Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In *Proceedings IEEE Virtual Reality (Cat. No. 99CB36316)*, pages 222–228, March 1999. ISSN: 1087-8270.

[EKHW21] Lisa A. Elkin, Matthew Kay, James J. Higgins, and Jacob O. Wobbrock. An Aligned Rank Transform Procedure for Multifactor Contrast Tests. In *The 34th Annual ACM Symposium on User Interface Software and Technology*, UIST '21, pages 754–768, New York, NY, USA, 2021. Association for Computing Machinery.

[Gui19] Erico Guizzo. By leaps and bounds: An exclusive look at how Boston dynamics is redefining robot agility. *IEEE Spectrum*, 56(12):34–39, December 2019. Conference Name: IEEE Spectrum.

[HHSR98] Hunter Hoffman, Ari Hollander, K. Schroder, and S. Rousseau. Physically touching and tasting virtual objects enhances the realism of virtual experiences. *Virtual Reality*, 3:226–234, December 1998.

[HKC+23] Sun A Han, Jin Kook Kim, Do-Yeon Cho, Zara M. Patel, and Chae-Seo Rhee. The Olfactory System: Basic Anatomy and Physiology for General Otorhinolaryngologists. *Clinical and Experimental Otorhinolaryngology*, 16(4):308–316, November 2023.

[Hol23] Shirley Holt. Virtual reality, augmented reality and mixed reality: For astronaut mental health; and space tourism, education and outreach. *Acta Astronautica*, 203:436–446, February 2023.

[HSB04] Rachel Herz, Corrente Schankler, and Sophia Beland. Olfaction, Emotion and Associative Learning: Effects on Motivated Behavior. *Motivation and Emotion*, 28:363–383, December 2004.

[IBM+14] Matthieu Ischer, Naëm Baron, Christophe Mermoud, Isabelle Cayeux, Christelle Porcherot, David Sander, and Sylvain Delplanque. How incorporation of scents could enhance immersive virtual experiences. *Frontiers in Psychology*, 5, 2014.

[KGS+24] Elizabeth D. Kirby, Melissa J. Glenn, Noah J. Sandstrom, Christina L. Williams, Elizabeth D. Kirby, Melissa J. Glenn, Noah J. Sandstrom, and Christina L. Williams. 8.3 The Olfactory System - Introduction to Behavioral Neuroscience | OpenStax, November 2024. Book Title: Introduction to Behavioral Neuroscience Publisher: OpenStax.

[KPCC18] Hyun K. Kim, Jaehyun Park, Yeongcheol Choi, and Mungyeong Choe. Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment. *Applied Ergonomics*, 69:66–73, May 2018.

[LHK+24] Maxence Lalis, Matej Hladiš, Samar Abi Khalil, Loïc Briand, Sébastien Fiorucci, and Jérémie Topin. M2OR: a database of olfactory receptor–odorant pairs for understanding the molecular mechanisms of olfaction. *Nucleic Acids Research*, 52(D1):D1370–D1379, January 2024.

[Lin98] Roger W. A. Linden. *The Scientific Basis of Eating: Taste and Smell, Salivation, Mastication and Swallowing, and Their Dysfunctions*. Karger Medical and Scientific Publishers, 1998. Google-Books-ID: VItrjPNGdVMC.

[LJW20] Danyang Li, Jiafeng Jia, and Xiaochun Wang. Unpleasant Food Odors Modulate the Processing of Facial Expressions: An Event-Related Potential Study. *Frontiers in Neuroscience*, 14, 2020.

[LYZ+23] Yiming Liu, Chun Ki Yiu, Zhao Zhao, Wooyoung Park, Rui Shi, Xingcan Huang, Yuyang Zeng, Kuan Wang, Tsz Hung Wong, Shengxin Jia, Jingkun Zhou, Zhan Gao, Ling Zhao, Kuanming Yao, Jian Li, Chuanlu Sha, Yuyu Gao, Guangyao Zhao, Ya Huang, Dengfeng Li, Qinglei Guo, Yuhang Li, and Xinge Yu. Soft, miniaturized, wireless olfactory interface for virtual reality. *Nature Communications*, 14(1):2297, May 2023. Publisher: Nature Publishing Group.

[MSR06] Alan Mackay-Sim and Jean-Pierre Royet. Structure and Function of the Olfactory System. In Christos Pantelis, David Castle, and Warrick J. Brewer, editors, *Olfaction and the Brain*, pages 3–27. Cambridge University Press, Cambridge, 2006.

[NM07] Takamichi Nakamoto and Hai Pham Dinh Minh. Improvement of olfactory display using solenoid valves. In *2007 IEEE Virtual Reality Conference*, pages 179–186, Charlotte, NC, USA, 2007. IEEE.

[PBH17] J. Paluchová, J. Berčík, and E. Horská. 2. The sense of smell. In Angel A. Carbonell-Barrachina, editor, *Sensory and aroma marketing*, pages 27–60. Brill | Wageningen Academic, May 2017.

[PD20] Susan Persky and Alexander P. Dolwick. Olfactory Perception and Presence in a Virtual Reality Food Environment. *Frontiers in Virtual Reality*, 1, September 2020. Publisher: Frontiers.

[SBB16] Berenice Serrano, Rosa M. Baños, and Cristina Botella. Virtual reality and stimulation of touch and smell for inducing relaxation: A randomized controlled trial. *Computers in Human Behavior*, 55:1–8, February 2016.

[SH21] Rachel S. Herz. Olfactory Virtual Reality: A New Frontier in the Treatment and Prevention of Posttraumatic Stress Disorder. *Brain Sciences*, 11(8):1070, August 2021.

[SLW11] Kai Song, Qi Liu, and Qi Wang. Olfaction and Hearing Based Mobile Robot Navigation for Odor/Sound Source Search. *Sensors*, 11(2):2129–2154, February 2011. Number: 2 Publisher: Molecular Diversity Preservation International.

[SMB+13] C. Sezille, B. Messaoudi, A. Bertrand, P. Joussain, M. Thévenet, and M. Bensafi. A portable experimental apparatus for human olfactory fMRI experiments. *Journal of Neuroscience Methods*, 218(1):29–38, August 2013.

[SSdM92] D. G. Smith, L. Standing, and A. de Man. Verbal memory elicited by ambient odor. *Perceptual and Motor Skills*, 74(2):339–343, April 1992.

[TLD+07] R. Tortell, D. Luigi, A. Dozois, Sean Bouchard, Jacquelyn Morie, and D. Ilan. The effects of scent and game play experience on memory of a virtual environment. *Virtual Reality*, 11:61–68, March 2007.

[VBMRS14] Carlos Velasco, Diana Balboa, Fernando Marmolejo-Ramos, and Charles Spence. Crossmodal effect of music and odor pleasantness on olfactory quality perception. *Frontiers in Psychology*, 5, November 2014. Publisher: Frontiers.

[WFGH11] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 143–146, New York, NY, USA, 2011. Association for Computing Machinery.

[YKN+04] Y. Yanagida, S. Kawato, H. Noma, A. Tomono, and N. Tesutani. Projection based olfactory display with nose tracking. In *IEEE Virtual Reality 2004*, pages 43–50, March 2004. ISSN: 1087-8270.

[YYT+06] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose. Wearable Olfactory Display: Using Odor in Outdoor Environment. In *IEEE Virtual Reality Conference (VR 2006)*, pages 199–206, March 2006. ISSN: 2375-5334.

[ZZAL25] Leijing Zhou, Yiqing Zhang, Xin An, and Junxian Li. E-scent Coach: A Wearable Olfactory System to Guide Deep Breathing Synchronized with Yoga Postures. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 1–14, Bordeaux/Talence France, March 2025. ACM.

Appendix

Demographic Survey

User ID (filled by experimenter): ______________________________

1. Age
How old are you?

____

2. Gender
What is your gender?

- ◯ Female
- ◯ Male
- ◯ Prefer not to say
- ◯ Other: ____________

3. Do you have allergies or sensitivities to scents?

- ◯ Yes
- ◯ No
- ◯ Not sure

4. Previous Experience in Virtual Reality (VR)
What is your level of experience with VR?

- ◯ None (today is the first time)
- ◯ Tried once
- ◯ Novice
- ◯ Occasional user
- ◯ Monthly user (at least once per month)
- ◯ Weekly user (at least once per week)
- ◯ Daily user

5. Sense of Smell
How would you rate your sense of smell?

- ◯ Very Poor
- ◯ Poor
- ◯ Average
- ◯ Good
- ◯ Excellent

6. Previous Experience with Smell Detection Technologies
Have you ever used or worked with smell detection technologies before? (e.g., digital scent technology, olfactory displays)

- ◯ Yes
- ◯ No
- ◯ Not sure

7. Identifying different smells

Please rate your agreement with the following statement: I am confident in being able to correctly identify specific smells.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

Post Block Questionnaire

User ID (filled by experimenter): ____________________

Block (filled by experimenter): **1 2 3**

Symptoms (rated on a 4-point scale):

Symptom	Not at all	Mild	Moderate	Severe
General Discomfort	◯	◯	◯	◯
Fatigue	◯	◯	◯	◯
Eyestrain	◯	◯	◯	◯
Difficulty focusing (visually)*	◯	◯	◯	◯
Headache	◯	◯	◯	◯
Fullness of the head*	◯	◯	◯	◯
Dizziness with eyes closed	◯	◯	◯	◯
Vertigo*	◯	◯	◯	◯

Participants rated their current symptoms after each interaction block.

Term Definitions:

- *** Difficulty focusing (visually)** – Challenges in maintaining clear and sharp visual focus, difficulty in adjusting focus, or the inability to concentrate visually.
- *** Fullness of the head** – A sensation of pressure or heaviness in the head.
- *** Vertigo** – Experienced as loss of orientation with respect to vertical upright, e.g., the perception of spinning or rotational movement, even when stationary.

How intense were the smells during the trials?

1	2	3	4	5	6	7
Not intense at all						Very Intense

Post-Experiment Questionnaire

User ID (filled by experimenter): ______________________________

1. Please describe the smells you experienced during the study:

____

____

____

2. How far were you (in cm) from the smell source during the experiment?

____

3. I was confident in detecting smells in VR environments correctly.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

4. How much did you trust the VR system's ability to simulate smells accurately?

1	2	3	4	5	6	7
Did not trust at all						Trust very much

5. Additional comments to the experiment:

____

____

____