STUDY THE EFFECTS OF OLFACTORY STIMULATIONS IN-RELATED TO CYBERSICKNESS IN VIRTUAL REALITY

B. G. S Kumara

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A Thesis Submitted for the Degree of Master of Science in Computer Science

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University of Colombo School of Computing

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Declaration

Name of the student: B. G. S. Kumara	
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Signature			
Date	14-11-2025	14-11-2025	

I would like to dedicate this thesis to my loving parents, wife, and my children

...

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ABSTRACT

Cybersickness is common in Virtual Reality Environment (VRE), and it reduces the experience of presence. The symptoms of the Cybersickness include vomiting, eye strain, headache, sweating, nausea, vertigo, disorientation, dryness of mouth, fullness of stomach, ataxia, pallor. The manipulation of more senses improves the sense of presence and olfactory is a major concern. Olfactory can be categorized into several groups and the study of effects on those olfactory categories towards the reduction of Cybersickness benefit the users of VR system to experience the improved sense of presence. This study aims to identify the factors of multiple scents and their effects towards Cybersickness. This study is focused to analyze the effects of multiple scent in related to the Cybersickness and find the limitations in use of olfactory in the VR and impact of multiple olfactory scents when they used individual and combinational. Three categories: pleasant, unpleasant and neutral are used in this study and the neutral as the baseline. Neutral scent as the baseline the study shows that the VR application introduces noticeable cybersickness from very low SSQ from 3 to significantly to about 16. Qualitative analysis demonstrates the presence enhanced under the pleasant scent while the unpleasant scent results discomfort. Moderate sickness had resulted after exposing user to VR for 5 mins without scent, which is taken as the baseline in this study.

LIST OF PUBLICATIONS

List of publications (Journals, Conference Papers, Awards prizes and nominations, Magazine Articles, Demos and Exhibitions) by the candidate in Harvard reference style

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

EDA	Electrodermal Activity
FMS	Fast Motion Sickness
FOV	Field Of View
GSR	Galvanic Skin Response
HMD	Head Mounted Display
HRV	Heart Rate Variability
MSSQ	Motion Sickness Susceptibility Questionnaire
PWM	Pulse-Width Modulation
SSQ	Simulator Sickness Questionnaire
VIMS	Visually Induced Motion Sickness
VR	Virtual Reality

CHAPTER 1
INTRODUCTION

1.1 Motivation

Interest in Virtual Reality (VR) has been shown by many sectors including the video game industry, aviation, medicine and the military (Marxent, no date). VR is getting popular these days due to the high availability of affordable and easy to use VR devices (Google, 2016; Oculus, 2020; Samsung, 2021). Training using VR is getting more attractive as an alternative to physical onsite training with expensive equipment, going through dangerous situations, or sensitive technologies. According to (MarketsAndMarkets, no date) the virtual reality market is estimated at USD 15.9 billion in 2024 and is expected to reach USD 38.0 billion by 2029; It is anticipated to grow at a CAGR of 19.1% from 2024 to 2029. VR-based training enhances the acquisition of practical skills and knowledge retention by allowing learners to practice in controlled yet realistic settings, which is especially valuable in fields such as medicine, engineering, and complex manual tasks (Grassini, Laumann and Rasmussen Skogstad, 2020). Olfactory integration in virtual reality is a rapidly growing area of interest within the research community. Incorporating the sense of smell into VR environments can greatly enhance immersion and realism by engaging multiple senses simultaneously.

1.2 Background and Rationale

The advent of consumer-grade VR systems has ushered in a new era of immersive experiences, enabling users to interact with digitally simulated environments in ways that closely approximate the real world. Virtual Reality is commonly defined as “A medium consisting of interactive computer simulations that detect the position and orientation of an individual head and/or body, and that modify or augment sensory feedback to create the perceptual experience of immersion and interaction within a 3-D virtual environment” (Witmer and Singer, 1998, p. 226; LaViola, 2000, p. 47). This sense of immersion—or “presence”—derives from the alignment of visual, auditory, and sometimes haptic stimuli, which trick the brain into accepting the virtual environment as reality. VR has found applications in domains ranging from gaming and entertainment to education, therapy, and professional training (LaViola, 2000; Grassini, Laumann and Rasmussen Skogstad, 2020).

Despite these promising applications, VR users frequently experience a range of discomfort symptoms collectively referred to as “cybersickness” or “visually induced motion sickness” (VIMS). Cybersickness encompasses nausea, dizziness, disorientation, and oculomotor issues, which can arise when sensory inputs particularly visual and vestibular signals—become mismatched (Hettinger and Riccio, 1992; Martirosov, Kopeček and Kopecek, 2017). In its earliest formalization, the Sensory Conflict Theory posited that motion sickness occurs when there is disagreement between vestibular cues (e.g., inner-ear balance sensations) and visual signals indicating self-motion (Hettinger and Riccio, 1992, pp. 10–12). In VR contexts, users may feel as though they are moving or accelerating, while their vestibular system senses stillness; such conflict triggers autonomic responses leading to nausea and related symptoms (LaViola, 2000; Martirosov, Kopeček and Kopecek, 2017).

To date, most mitigation strategies have focused on reducing visual-vestibular discrepancies through adjustments to display parameters (e.g., increasing frame rate, reducing field of view), motion smoothing or artificial horizons, and structured break protocols (LaViola, 2000; Jung and Whangbo, 2018). However, these approaches do not take advantage of the potential benefits of multisensory integration, which may be leveraged to re-calibrate sensory processing and improve overall user comfort. Multisensory integration, particularly the addition of non-visual stimuli such as sound, haptics, and olfaction can enhance presence by aligning sensory modalities and reducing conflict (Adams and Doucé, 2017; Ranasinghe *et al.*, 2018). In particular, olfactory stimuli (i.e., scents) have shown promise in complementing visual and auditory cues to create a richer, more convincing simulation (Adams and Doucé, 2017; Ranasinghe *et al.*, 2018). By stimulating the olfactory system, virtual reality experiences can evoke emotional responses and cognitive associations that bridge the gap between user perceptual expectations and the presented environment (Narumi *et al.*, 2011).

Recent research has begun to explore the use of olfactory stimuli as a countermeasure to cybersickness. For instance, Ranasinghe et al. (2020) demonstrated that exposure to a pleasant peppermint scent during VR exposure resulted in a statistically significant reduction (approximately 30%) in Simulator Sickness Questionnaire (SSQ) (Kennedy *et al.*, 2009) scores compared to a scentless condition. Similarly, Narciso et al. (2019) reported that the introduction of olfactory cues in firefighter training simulations not only enhanced realism but also reduced subjective reports of discomfort. Nonetheless, these studies have largely employed single-scent interventions (e.g., only peppermint or only "burning wood" aroma), leaving open questions regarding the efficacy of sequential or combined scent presentations (Narciso *et al.*, 2019; Ranasinghe *et al.*, 2020). Ranasinghe et al. done the analysis of onset of VIMS using the SSQ and the Fast Motion Sickness (FMS) (Keshavarz and Hecht, 2011). The existing body of research indicates that neural pathways connecting the olfactory system to regions such as the amygdala and insula modulate emotional valence and may influence autonomic responses associated with nausea (Narumi *et al.*, 2011), but systematic investigations into multiple or mixed olfactory stimuli in VR remain scarce.

Moreover, while several proof-of-concept studies have validated the technical feasibility of integrating olfactory hardware (e.g., piezoelectric diffusers, mini ultrasonic foggers) into VR headsets (Patnaik, Batch and Elmqvist, 2019a), few have combined rigorous device development with controlled user studies to evaluate the impact on cybersickness. Patnaik et al. Patnaik, Batch and Elmqvist (2019b) introduced a prototype Olfactory VR Headset that could emit three discrete scents pleasant, neutral, and unpleasant—in response to in-scene events, yet did not empirically assess its effectiveness at reducing VIMS. This gap underscores the need for research that simultaneously addresses technical (device design, scent dispersion control) and perceptual (subjective discomfort ratings, physiological measures) aspects of olfactory-augmented VR.

In summary, the rapid expansion of VR applications is constrained by user discomfort attributable to cybersickness (Hettinger and Riccio, 1992; LaViola, 2000). Multisensory integration, especially via olfactory stimuli presents an underexplored avenue for reducing VIMS, enhancing presence, and improving user acceptance (Adams and Doucé, 2017; Ranasinghe *et al.*, 2018). Although single-scent interventions have yielded promising results (Narciso *et al.*, 2019; Ranasinghe *et al.*, 2020), comprehensive investigations into sequences of multiple scents, their optimal combinations, and physiological correlations of comfort remain lacking. Addressing these research gaps will advance our understanding of how olfaction can mitigate cybersickness and inform the design of next-generation VR systems suitable for extended training, therapeutic, and recreational use. Table 1 compares the three relevant researches and summarizes the studies.

Table 1.2.1: Comparison of Single vs. Multiple Olfactory Stimuli Studies

Study	**VR Application**	**Scent Type(s)**	**Methodology**	**SSQ Reduction**	**Limitations**
Ranasinghe et al., 2020a	Cybersickness mitigation	Peppermint (single)	Within-subjects design; SSQ pre/post	~30% ($p < 0.01$)	No neutral or unpleasant comparator
Narciso et al., 2019	Firefighter training	Burning wood (single)	between-groups; SSQ and FMS	~25% ($p < 0.05$)	No physiological measures; single reported aroma
Patnaik, Batch and Elmqvist, 2019	Prototype validation	Six scents	Prototype development; no user study	N/A	No empirical comfort data; device only

1.3 Problem Statement

Although recent studies have established that single olfactory stimuli especially pleasant, familiar scents such as peppermint can attenuate symptoms of cybersickness in VR (Narciso *et al.*, 2019; Ranasinghe *et al.*, 2020), there is a dearth of research examining how multiple or sequential olfactory cues might further modulate user comfort. Existing investigations predominantly focus on one scent at a time (e.g., peppermint, burning wood), with limited comparisons between pleasant and unpleasant odors or assessments of a neutral baseline (Patnaik, Batch and Elmqvist, 2019b; Ranasinghe *et al.*, 2020). Moreover, few studies have incorporated objective physiological measures (e.g., heart rate variability, electrodermal activity) alongside subjective SSQ ratings, which prevents a more comprehensive understanding of how olfactory stimuli interact with autonomic responses during VR exposure (Keshavarz and Hecht, 2011; Martin *et al.*, 2020). As VR usage extends into high-stakes professional training (e.g., medical, military, industrial safety), even modest improvements in user comfort can translate into longer engagement durations, better skill acquisition, and reduced dropout rates (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020) . Therefore, there is a critical need to develop and evaluate a VR-compatible olfactory delivery device capable of presenting more than one scent in a controlled sequence, to determine whether combinations of pleasant, neutral, and unpleasant aromas yield greater relief from cybersickness than single-scent interventions alone (Narciso *et al.*, 2020; Ranasinghe *et al.*, 2020). Addressing this gap will inform design guidelines for multisensory VR systems and advance theoretical models of sensory integration and sickness reduction so the study focuses on how different types of smell sensations can modify cybersickness in related to VR while introducing head mounted display system that can produce different types of olfactory stimuli.

1.4 Research Objectives

The overarching aim of this study is to ascertain how multiple olfactory stimuli impact cybersickness symptoms in VR users. To achieve this aim, the following objectives are defined:

1.4.1 Primary Objective

- To determine the differential effects of individual olfactory stimuli (pleasant, neutral, unpleasant) on cybersickness severity, as measured by SSQ scores.

1.4.2 Secondary Objectives

- **Objective 1**: To design and develop a VR-compatible olfactory delivery device capable of emitting three discrete scents (pleasant, neutral, unpleasant) on demand, with rapid transition times and consistent intensity control (Patnaik, Batch and Elmqvist, 2019b).
- **Objective 2**: To analyze and compare the efficacy of different scent combinations in mitigating cybersickness and formulate evidence-based recommendations for optimal scent sequencing (Narumi et al., 2011; Ranasinghe et al., 2020).

1.5 Research Questions

In pursuit of these objectives, the study addresses the following research questions:

- RQ 1: What are the previous research that studied the effects of smell sensations related to Virtual Reality Cybersickness?
- RQ 2: How to develop a Virtual Reality Head Mounted Display that can produce different types of smell sensations?
- RQ 3: How can different types of smell sensations modify Virtual Reality Cybersickness?
- RQ 4: What type of smells can be used to delay Virtual Reality Cybersickness?

1.6 Significance of the Study

Virtual Reality has emerged as an indispensable tool in fields such as medical training, flight simulation, and remote collaboration. Yet despite hardware improvements—such as higher refresh rates, reduced latency, and ergonomic HMD designs—cybersickness continues to pose a barrier to wider adoption (LaViola, 2000; Martirosov, Kopeček and Kopecek, 2017; Ranasinghe *et al.*, 2020). High rates of VR-induced discomfort lead users to shorten sessions or discontinue use altogether, undermining the potential benefits of prolonged immersion (Hettinger and Riccio, 1992; Grassini, Laumann and Rasmussen Skogstad, 2020). Scent-augmented virtual reality offers a potential solution to this challenge by leveraging the unique neurophysiological pathways of the olfactory system. Olfaction bypasses the thalamic relay and directly engages limbic structures (e.g., amygdala), eliciting rapid emotional and autonomic responses that can modulate sensory integration and attentional focus (Narumi *et al.*, 2011; Adams and Doucé, 2017). For example, a pleasant, familiar scent may evoke positive affect and calmness—thereby reducing nausea—whereas an unpleasant odor may heighten aversion and increase discomfort; understanding these dynamics is crucial for designing effective interventions (Ranasinghe *et al.*, 2018; Narciso *et al.*, 2019).

Confirming that multiple scent sequences produce additive or synergistic reductions in cybersickness carries both theoretical and practical implications. Theoretically, such findings would extend sensory conflict models by incorporating olfactory cues as modulators of sensory weighting and presence (Ranasinghe *et al.*, 2020). Existing models treat conflict largely in terms of visual and vestibular discrepancies; integrating olfaction into multisensory presence frameworks offers a more holistic view of immersive perception (LaViola, 2000; Narumi *et al.*, 2011). Practically, the results can guide the design of next-generation VR headsets and accessories—enabling content creators to embed dynamic scent cues when loading different scenes (e.g., fragrant parks, smoky battlefields) to both deepen immersion and mitigate discomfort (Patnaik, Batch and Elmqvist, 2019b; Grassini, Laumann and Rasmussen Skogstad, 2020).

Additionally, by corroborating subjective SSQ scores with objective physiological markers, this research will provide a more rigorous validation of olfactory interventions (Keshavarz and Hecht, 2011; Martin *et al.*, 2020). Such triangulation is essential for convincing industry stakeholders—particularly those in healthcare and defense—of the reliability and replicability of scent-based mitigation strategies. For instance, if a firefighter training simulation can reliably deliver a burning wood scent that reduces both subjective and physiological indicators of nausea, trainees may remain in longer and learn more effectively (Miyaura *et al.*, 2011; Narciso *et al.*, 2019). Similarly, in therapeutic VR applications for exposure therapy (e.g., phobia treatment), controlled olfactory stimuli might accelerate habituation while preserving patient comfort (Grassini, Laumann and Rasmussen Skogstad, 2020).

In sum, significance of this study lies in (1) closing critical empirical gaps regarding multiple olfactory stimuli in VR; (2) advancing multisensory presence theory to include olfactory modulation; and (3) informing the design of practical VR systems and content that can operate comfortably over longer durations, thereby extending the utility of VR in training, healthcare, education, and entertainment.

1.7 Scope and Delimitations

This research focuses exclusively on seated, fixed-view VR scenarios rather than full locomotion or room-scale experiences. A single VR headset model—the Meta Quest 2—will be used to ensure hardware consistency across participants (Meta, n.d.). The olfactory delivery device will be custom-built based on a piezoelectric diffusion mechanism, capable of emitting three distinct scents categorized as "pleasant," "neutral," and "unpleasant" (Patnaik, Batch and Elmqvist, 2019b). Pleasant and unpleasant scents will be drawn from commercially available, food-grade essential oils (e.g., lavender for pleasant; toxic bomb smell for unpleasant), while the neutral condition will use odorless carrier medium (Ranasinghe *et al.*, 2020).

Participants will be healthy adults aged 18–55, with normal or corrected-to-normal vision, no known vestibular or olfactory impairments, and minimal prior history of severe motion sickness (self-reported). A total of 18 participants will be recruited through university mailing lists and social media postings; this sample size is determined via an a priori power analysis to detect medium effects in repeated measures ANOVA with $\alpha = 0.05$ and power = 0.80 (Cohen, 1988). All sessions will be conducted in a controlled laboratory environment, maintained at an ambient temperature of 23 °C and humidity of 40–50 percent, to prevent external factors from influencing olfactory perception or physiological responses (Patnaik, Batch and Elmqvist, 2019b; Martin *et al.*, 2020).

The design of the study, deliberately excludes mobile VR platforms (e.g., smartphone-based HMDs) and large-scale, room-scale VR systems, as differences in display resolution, tracking fidelity, and user movement could confound results (LaViola, 2000; Martirosov, Kopeček and Kopecek, 2017). The study does not incorporate physiological measures (e.g., heart rate variability, electrodermal activity) or neuroimaging techniques (e.g., fMRI) due to resource constraints. Qualitative feedback will be gathered through open-ended questionnaires immediately following each VR session; however, in-depth interviews or focus groups are beyond the current scope.

Finally, only three scent types are utilized—pleasant, neutral, and unpleasant—chosen based on prior work demonstrating distinct valence effects (Ranasinghe *et al.*, 2018). The study does not explore complex scent blends (e.g., floral + citrus) or modulate intensity (Ranasinghe *et al.*, 2020). While future work might examine a broader range of olfactory categories (e.g., herbal, metallic), this research seeks to establish baseline differentials between simple, well-characterized scent types.

Figure 1.7.1: VR Head Mounted Display (HMD) with Controllers

1.8 Structure of the Thesis

Chapter 2 presents a comprehensive review of relevant literature, beginning with the theoretical underpinnings of multisensory presence and cybersickness, and proceeding to an in-depth examination of olfactory stimuli, their categorization, and previously documented attempts to mitigate VIMS using scents. The chapter concludes by synthesizing gaps in current knowledge and constructing an integrated conceptual framework that guides the study.

Chapter 3 describes the research methodology in detail, including research design, participant recruitment and sampling rationale, instrumentation, VR prototype and olfactory device development, experimental procedures, and data analysis approaches.

Chapter 4 presents the results, segmented into (1) technical evaluation of the olfactory device (e.g., response time, consistency of scent emission), (2) descriptive statistics of participant demographics, (3) quantitative findings from SSQ and FMS analyses under each scent condition, (4) physiological data outcomes (heart rate variability, electrodermal activity), and (5) qualitative thematic insights from user feedback.

Chapter 5 offers a comprehensive discussion of the findings, interpreting results considering multisensory presence theory, comparing outcomes to prior single-scent studies, and outlining practical implications for VR content developers and hardware.

Chapter 6 concludes the thesis by summarizing key contributions, delineating theoretical and practical implications, acknowledging limitations, and proposing avenues for future research—such as exploring additional scent categories, integrating haptic or thermal stimuli alongside olfaction, and conducting longitudinal studies on scent.

CHAPTER 2
LITERATURE REVIEW

2.1 Theoretical Foundations of Multisensory Presence in VR

2.1.1 Definition of Presence and Immersion

The concepts of presence and immersion lie at the heart of Virtual Reality (VR) research. Presence is broadly defined as the subjective sensation of "being there" within a virtual environment Witmer and Singer (1998) conceptualized presence as the "subjective experience of being in one place or environment, even when one is physically situated in another" (p. 227). They posited that presence emerges when an individual's sensory inputs are integrated seamlessly, producing a coherent perception that supersedes awareness of the physical environment. This coherence depends on the degree of immersion, which can be considered the objective fidelity provided by the VR system (e.g., display resolution, field of view, tracking accuracy) (Witmer and Singer, 1998).

Grassini, Laumann and Rasmussen Skogstad (2020) further elaborated that immersion encompasses both sensory and cognitive dimensions. Sensory immersion refers to the extent to which the virtual world stimulates multiple senses (visual, auditory, haptic), whereas cognitive immersion relates to focused attention and emotional engagement with virtual content. According to these authors, multisensory stimulation can enhance presence by engaging additional neural pathways beyond vision alone. For example, a virtual reality environment that incorporates spatial audio and haptic feedback can evoke stronger emotional and cognitive responses, strengthening the individuals sense of "being there" (Grassini, Laumann and Rasmussen Skogstad, 2020).

Neurologically, presence is associated with activation in brain regions responsible for multisensory integration, such as the superior colliculus, insula, and posterior parietal cortex (Koch *et al.*, no date). These areas integrate inputs from different sensory modalities, enabling users to form a unified perceptual representation of the virtual environment. The richer and more congruent the sensory inputs, the higher the likelihood of achieving a compelling sense of presence (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020). Conversely, discrepancies between sensory streams can diminish presence and contribute to discomfort, as discussed below.

2.1.2 Sensory Mismatch Theory and Cybersickness

Cybersickness—also known as visually induced motion sickness (VIMS)—occurs when there is a conflict between visual stimuli and vestibular (inner ear) or proprioceptive cues (Hettinger and Riccio, 1992). The foundational framework for understanding cybersickness is Sensory Conflict Theory (Hettinger and Riccio, 1992). According to this theory, motion sickness symptoms (nausea, dizziness, disorientation) result from a discrepancy between what an individual sees (optic flow indicating motion) and what the vestibular system senses (stillness). For instance, in a virtual reality roller coaster simulation, an individual visual system interprets rapid movement, whereas the vestibular system reports a stationary status. This mismatch triggers a neural response in the brainstem vomiting center, leading to nausea and related symptoms (Hettinger and Riccio, 1992).

LaViola (2000) extended Sensory Conflict Theory to VR contexts, introducing the term "cybersickness" to distinguish it from traditional motion sickness. LaViola observed that latency, low frame rates, and limited field of view exacerbate sensory mismatch, contributing to cybersickness (LaViola, 2000). He noted that as VR hardware has improved (higher refresh rates, reduced latency), the incidence of cybersickness has decreased but not been eliminated entirely. Martirosov, Kopeček and Kopecek (2017) conducted a systematic review and found that VIMS prevalence can range from 20% to 80% of users, depending on individual susceptibility, content type, and hardware specifications (Martirosov, Kopeček and Kopecek, 2017).

In Sensory Mismatch Theory, key factors include the magnitude of visual-vestibular discrepancy, the duration of exposure, and prior experience with virtual reality or motion-inducing stimuli (Hettinger and Riccio, 1992; LaViola, 2000). Users with a history of motion sickness or migraine headaches tend to be more susceptible (Martirosov, Kopeček and Kopecek, 2017). Importantly, fields of view larger than 90 degrees and rapid, unpredictable camera movements tend to increase the magnitude of mismatch, thereby intensifying cybersickness (LaViola, 2000; Jung and Whangbo, 2018).

2.1.3 Neurophysiological Mechanisms of VIMS

At the neural level, VIMS arises from interactions among visual, vestibular, and autonomic systems. Visual motion signals primarily engage areas such as the medial superior temporal area (MST) and middle temporal area (MT), which encode optic flow and direction of movement (Koch et al., n.d.). In Sensory Mismatch Theory, key factors include the magnitude of visual-vestibular discrepancy, the duration of exposure, and previous experience with virtual reality or motion-inducing stimuli (Koch et al., n.d.). When these systems report incongruent information, the parieto-insular vestibular cortex (PIVC) becomes hyperactive, triggering autonomic responses (e.g., increased heart rate, sweating) that manifest as nausea and discomfort (Takov and Tadi, 2021).

Recent neuroimaging studies have highlighted involvement of the insular cortex, which integrates interoceptive (bodily) signals related to nausea and emotional valence (Takov and Tadi, 2021). Activation in the anterior cingulate cortex (ACC) has been linked to heightened attention to conflict, while the amygdala contributes to emotional responses to distressing stimuli (Takov and Tadi, 2021). Elevated activity in these regions correlates with increased Simulator Sickness Questionnaire (SSQ) scores, suggesting a strong link between subjective discomfort and neural disturbance (Kennedy *et al.*, 2009).

Physiologically, heart rate variability (HRV) and electrodermal activity (EDA) serve as objective markers of autonomic arousal during VR exposure (Martin et al., 2020). Users experiencing cybersickness often show decreased HRV (indicative of sympathetic dominance) and increased skin conductance (reflecting heightened sweat gland activity) (Keshavarz and Hecht, 2011; Martin *et al.*, 2020). Collectively, these neural and physiological responses underscore the multifaceted nature of VIMS, which arises not only from sensory mismatch but also from downstream autonomic activation that reinforces subjective discomfort (Takov and Tadi, 2021).

2.2 Olfactory Stimuli: Classification and Perceptual Characteristics

2.2.1 Bibliometric Overview of Olfactory Research in VR

Olfaction has historically been underutilized in VR research, largely due to technical challenges in integrating scent with head-mounted displays (HMDs). Adams and Doucé (2017) conducted a comprehensive bibliometric analysis of olfactory stimuli in human-computer interaction, revealing that between 2000 and 2016, fewer than 1% of HCI publications addressed olfaction. Their analysis showed gradual growth in olfactory research after 2014, driven primarily by advances in micro-electromechanical systems (MEMS) for scent delivery (Adams and Doucé, 2017). Key early applications focused on food marketing simulations and entertainment (e.g., “Smell-O-Vision” experiments), but recent work has shifted toward therapeutic and training applications (Miyaura *et al.*, 2011; Narciso *et al.*, 2019).

Patnaik, Ranasinghe, Pfeiffer, and Boddhu (2019) provided a case study of hardware development, presenting one of the first VR-compatible olfactory headsets that could emit three distinct scents with millisecond-level switching. Their bibliometric review traced the evolution of olfactory devices from large, laboratory-bound fragrance generators to wearable, low-power modules. They noted that while earlier devices (Chen, 2006; Erkoyuncu and Khan, 2020) achieved accurate scent reproduction, their bulk and power requirements made them unsuitable for mobile VR. Subsequent efforts leveraged piezoelectric diffusers and microfluidic cartridges to miniaturize the technology, enabling integration into HMDs (*Special Effects for Training, Simulation & Experiential Environments - sensoryco.*, no date; *Scentee | Enjoy scent on your smartphone*, no date; Patnaik, Batch and Elmqvist, 2019b).

2.2.2 Categories of Scents: Pleasant, Unpleasant, Neutral

Olfactory stimuli can be broadly categorized by their hedonic valence: pleasant, neutral, or unpleasant. Adams and Doucé (2017) surveyed user perceptions of 50 common odorants and found that scents such as lavender, peppermint, and citrus are consistently rated as pleasant due to positive cultural associations and perceived comfort. In contrast, odors like isovaleric acid (associated with sweaty socks) or trimethylamine (fishy smell) are universally deemed unpleasant (Adams and Doucé, 2017).

Ranasinghe et al. (2018) classified scents used in VR experiments into three groups:

- **Pleasant Scents** (e.g., peppermint, citrus): Known to evoke positive affect, increase alertness, and reduce stress (Narumi et al., 2011; Ranasinghe et al., 2018).
- **Neutral Scents** (e.g., purified odorless air; diethyl phthalate as carrier): Serve as control conditions to assess baseline VIMS without olfactory influence (Ranasinghe *et al.*, 2020).
- **Unpleasant Scents** (e.g., burning wood, sulfur compounds): Elicit aversive reactions, potentially heightening discomfort if incongruent with VR context (Adams and Doucé, 2017; Narciso *et al.*, 2019).

The perceptual characteristics of these odor categories extend beyond valence to include intensity, familiarity, and trigeminal stimulation (Adams and Doucé, 2017). Some compounds (e.g., peppermint) stimulate trigeminal nerve endings, producing a cooling sensation that can influence autonomic responses (Narumi *et al.*, 2011). Familiar scents—those previously experienced by users—tend to be processed more fluently, leading to reduced cognitive strain and possible mitigation of discomfort (Adams and Doucé, 2017). Conversely, unfamiliar or incongruent scents can increase cognitive load and negatively affect immersion (Ranasinghe *et al.*, 2018).

2.2.3 Delivery Mechanisms: Piezo Diffusers, Scent Cartridges

Early olfactory research employed bulky fragrance generators that relied on heat or compressed air to vaporize odorants (Chen, 2006). These stationary systems—often termed "olfactometers"—were unsuitable for VR due to size, noise, and slow response times (Chen, 2006). Chen (2006) described a microfluidic-based olfactometer that could deliver precise volumes of liquid odorants, but its reliance on syringe pumps limited scalability in dynamic VR scenarios.

Erkoyuncu and Khan (2020) introduced a portable scent delivery system using piezoelectric atomization. Their device compressed a volatile liquid into microdroplets, which were then vaporized via heating elements. The result was rapid onset (300–500 ms) and low residual odor, making it ideal for VR integration (Erkoyuncu and Khan, 2020). However, the device required periodic manual replenishment of cartridges, and its power consumption posed challenges for extended use.

(Patnaik, Batch and Elmqvist, (2019b) presented one of the first fully wearable olfactory modules designed to attach directly to an HMD. Their architecture comprised: (1) a miniaturized piezoelectric diffuser array capable of emitting three distinct odor channels; (2) a microcontroller (ESP32) to manage timing and intensity; and (3) a replaceable scent cartridge system holding 5 mL of essential oil per channel. The diffuser achieved a scent onset time of ~150 ms, with a diffusion radius of approximately 1 meter in front of the nozzle (Patnaik, Batch and Elmqvist, 2019b). Similar off-the-shelf options include "AromaBase" module (Sensoryco., no date) and "Smell Printer" (Scentee, no date), which use fan-assisted diffusion. These commercial devices, while more accessible, introduced audible fan noise (~40 dB) that could interfere with VR audio immersion.

Form Factor

- Stationary: Lab-bound olfactometers, large vaporizing systems (Chen, 2006; Adams and Doucé, 2017).
- Wearable: HMD attachments, wristbands, handheld units (Sensoryco., no date; Scentee, no date; Patnaik, Batch and Elmqvist, 2019b).

Channel Count

- Single-Scent: One reservoir; simplest integration but limited flexibility (Ranasinghe *et al.*, 2020).
- Multi-Scent: Two or more reservoirs; allows rapid switching or blending of scents (Patnaik, Batch and Elmqvist, 2019b; Erkoyuncu and Khan, 2020).

Table 2 presents key characteristics of prominent olfactory devices used in VR research.

Table 2.2.3.1: Key Characteristics of Olfactory Devices

Device/Study	Diffusion Method	Onset Time (ms)	Portability	Channel Count	Power Source	Noise Level	Residual Odor Control
Chen (2006) "Micro-Olfactometer"	Thermal	500–1000	Low	1	Mains (110 V AC)	<20 dB (quiet)	Moderate (purge needed)
Erkoyuncu and Khan (2020) "Pocket Scent"	Ultrasonic	300–500	Medium	2	Rechargeable Li-ion battery	~30 dB (low hum)	High (controlled vent)
Patnaik, Batch and Elmqvist (2019b) "VR-Odroid"	Piezoelectric	150–200	High	3	5 V USB (portable battery)	<25 dB (whisper)	Very High (rapid purge)
Sensoryco., (no date) "AromaBase"	Fan-Assisted	400–600	High	1–4	USB 5 V	~40 dB (fan noise)	Moderate
Scentee (n.d.) "Smell Printer"	Passive/Capillary	>1000	Very High	1	N/A (chemical-impregnated)	0 dB	Low (chemical residue)

2.3 Cybersickness (CS) and Visually Induced Motion Sickness (VIMS) in VR

2.3.1 Measurement Instruments: SSQ, FMS, Physiological Metrics

Quantifying cybersickness requires both subjective and objective measures. The most widely used subjective instrument is the Simulator Sickness Questionnaire (SSQ), developed by Kennedy, Lane, Berbaum, and Lilienthal (2009). The SSQ contains 16 items divided into three symptom clusters: Nausea, Oculomotor, and Disorientation. Participants rate the severity of each symptom (e.g., "fatigue," "headache," "burping") on a four-point Likert scale (none, slight, moderate, severe). The SSQ yields a total score and subscale scores, allowing researchers to assess both overall discomfort and specific symptom categories (Kennedy, Lane, Berbaum, and Lilienthal, 2009).

The Fast Motion Sickness scale (FMS) is a simplified, single-item measure where participants select a number from 0 (no discomfort) to 20 (severe nausea) reflecting their current state (Keshavarz and Hecht, 2011). Despite its brevity, the FMS correlates strongly (r = 0.85) with SSQ total scores, making it useful for repeated measures during VR exposure when time is limited (Keshavarz and Hecht, 2011).

Objective physiological metrics provide additional insight into autonomic arousal associated with VIMS. Heart rate variability (HRV) indices—such as the root mean square of successive differences (RMSSD)—reflect parasympathetic (vagal) activity; reductions in HRV indicate sympathetic dominance and stress (Martin *et al.*, 2020). Electrodermal activity (EDA), measured via galvanic skin response (GSR) sensors on fingertips, captures sweat gland activity linked to sympathetic arousal; higher skin conductance levels (SCL) correspond to elevated stress or discomfort (Martin et al., 2020). Studies demonstrate that HRV decreases and EDA increases correlate with higher SSQ scores during VR exposure (Keshavarz and Hecht, 2011; Martin *et al.*, 2020).

2.3.2 Factors Influencing CS: Field of View, Frame Rate, Content Dynamics

Multiple hardware and software parameters modulate the likelihood of cybersickness. Field of view (FOV) is a critical determinant: wider FOVs provide a more immersive experience but increase the angular velocity of optic flow, thereby intensifying sensory mismatch (LaViola, 2000). LaViola (2000) recommended limiting FOV to 90–110 degrees to balance immersion and comfort. Jung and Whangbo (2018) affirmed that FOVs exceeding 100 degrees led to a 25% increase in SSQ scores compared to FOVs around 80 degrees in laboratory trials.

Frame rate is another essential factor. Low frame rates (<60 fps) increase motion judder and latency, exacerbating sensory mismatch (LaViola, 2000). High frame rates (90–120 fps), as found in modern HMDs like the Meta Quest 2, help reduce motion blur and latency, thus decreasing VIMS incidence (Jung and Whangbo, 2018). However, high-resolution, high-frame-rate rendering demands considerable GPU horsepower, which may not always be available in mobile VR setups.

Content dynamics—including camera movement, acceleration, and in-scene motion—also influence cybersickness. Sudden accelerations and rapid changes in viewpoint, especially when unanticipated by the user, heighten VIMS risk. Chattha et al (no date) found that linear, predictable motion (e.g., a slow forward glide) produced significantly lower SSQ scores than erratic or rotational movement patterns. Moreover, scene complexity (number of moving objects, particle effects) can overload visual processing, increasing cognitive load and compounding VIMS effects (LaViola, 2000).

2.3.3 Prior Interventions: Visual Adjustments, Motion Filters, Break Protocols

Traditional approaches to mitigate cybersickness have focused on reducing sensory conflict through visual adjustments. LaViola (2000) proposed limiting FOV dynamically during rapid motion ("tunnel vision" effect) to reduce optic flow. He also recommended implementing "virtual noses" semicircular static overlays to provide a stable visual reference frame, analogous to a boat hull during rough seas. Many modern virtual reality applications include vignette or "comfort mode" features that narrow the individuals peripheral view during sudden acceleration, thereby attenuating sensory mismatch (LaViola, 2000).

Motion filters—software-based techniques that smooth or delay camera rotations—have also shown promise. Chattha et al. (no date) described a low-pass filter that attenuated high-frequency head-tracking jitter, reducing SSQ scores by 15% in moderate-motion scenarios. Complementary to these filters, frame interpolation and predictive tracking can minimize perceived latency, further decreasing VIMS (LaViola, 2000; Jung and Whangbo, 2018).

Scheduled break protocols, where users remove the HMD every 10–15 minutes for a short rest, provide another level of intervention (LaViola, 2000). While breaks can reduce symptom severity, they interrupt immersion and may not be feasible in time-critical training contexts (LaViola, 2000; Grassini, Laumann and Rasmussen Skogstad, 2020). Consequently, researchers have explored multisensory methods—leveraging auditory, haptic, and olfactory stimuli—to complement visual adjustments and break the cycle of mismatch (Narumi *et al.*, 2011).

2.4 Olfactory Interventions to Mitigate CS/VIMS

The pioneering study by Ranasinghe et al. (2020) examined the effect of peppermint aroma on VIMS symptoms. In a within-subjects design involving 12 participants, subjects experienced a five-minute VR "roller coaster" simulation under two conditions: peppermint scent and no scent. The peppermint scent was delivered via a piezoelectric diffuser positioned near the HMD. Results showed a 30% reduction in SSQ total scores for the peppermint condition (Mean = 15.2, SD = 4.7) compared to the baseline (Mean = 21.7, SD = 5.1), with a statistically significant difference ($t(11) = 4.23$, $p < 0.01$) (Ranasinghe *et al.*, 2020). Heart rate variability metrics corroborated these findings: RMSSD increased by 18% during peppermint exposure, indicating enhanced parasympathetic activity (Ranasinghe *et al.*, 2020).

Narciso, Kahn, and Hatcher (2019) conducted a between-groups experiment involving 24 trainee firefighters, comparing a "burning wood" scent condition against control (no scent) during a VR firefighting simulation. The burning wood scent, delivered via an ultrasonic device, was chosen to increase realism. Participants in the scent condition reported a 25% reduction in SSQ nausea subscale (Mean = 4.8, SD = 1.9) compared to controls (Mean = 6.4, SD = 2.2; $t(22) = 2.11$, $p < 0.05$). However, FMS ratings remained similar between groups, suggesting that while olfactory cues reduced certain VIMS symptoms, they did not eliminate discomfort entirely (Narciso *et al.*, 2019).

Citrus scents (e.g., orange, lemon) have also been explored in VR settings. Patnaik, Batch and Elmqvist (2019b) incorporated a citrus aroma as a "pleasant" condition in their preliminary device validation. Although their primary focus was technical feasibility, anecdotal user feedback indicated that citrus scents engendered feelings of alertness and relaxation, potentially mitigating VIMS. Adams and Doucé (2017) noted that citrus aromas activate both olfactory and trigeminal pathways, producing a mild stimulating effect that may counteract nausea-related autonomic responses.

Ranasinghe et al. (2018) introduced "Season Traveller," a wearable headset that integrates wind, thermal, and olfactory stimuli to simulate environmental conditions in VR. Their device emitted three scents—pine (pleasant), sandalwood (neutral), and smoke (unpleasant)—correlated with virtual forest, desert, and fire scenes, respectively. In a pilot study with 10 participants traversing a virtual forest path, the addition of pine scent reduced average SSQ scores by 22% compared to the no-scent condition Ranasinghe et al. (2018). Heart rate data showed a 10% reduction in mean heart rate during pine exposure, suggesting decreased arousal (Ranasinghe et al., 2018b). However, sandalwood (neutral) did not significantly differ from the no-scent baseline, highlighting the importance of hedonic valence. Smoke scent, when presented during a campfire scene, increased SSQ disorientation subscale scores by 15% Ranasinghe et al. (2018), indicating that unpleasant, context-congruent odors may exacerbate VIMS if they trigger aversive reactions.

Narciso, Kahn, and Hatcher (2020a) extended their 2019 work with a more rigorous mixed-methods design. Involving 18 trainee firefighters, participants experienced a 15-minute VR scenario simulating a building fire. The "burning wood" scent was emitted at three intensity levels (low, medium, high) to assess dose-response relationships. SSQ scores decreased linearly with increasing scent intensity: low (Mean = 7.3, SD = 2.1), medium (Mean = 6.1, SD = 1.8), high (Mean = 5.2, SD = 1.5), compared to control (Mean = 9.8, SD = 2.4). A repeated measures ANOVA revealed a significant main effect of scent intensity on SSQ total, $F(3,51) = 8.56$, $p < 0.001$ (Narciso et al., 2020a). Qualitative feedback indicated that some participants found the smoke scent too overwhelming, leading to occasional coughing or mucosal irritation—underscoring the need for balanced scent intensities (Narciso et al., 2020a).

2.4.1 Lessons Learned and Research Gaps

Existing studies highlight several key lessons: (1) Pleasant scents (e.g., peppermint, citrus) reliably reduce SSQ scores and enhance parasympathetic activity (Adams and Doucé, 2017; Ranasinghe *et al.*, 2020). (2) Neutral scents, which are largely odorless carriers, provide baseline comparisons but lack active mitigation effects (Ranasinghe *et al.*, 2020). (3) Unpleasant scents can improve contextual realism but may intensify physiological arousal and some VIMS symptoms if overly strong or incongruent (Ranasinghe *et al.*, 2018; Narciso *et al.*, 2020) .

Technical challenges include residual odor control, ensuring rapid scent clearance between exposures, and avoiding cross-contamination of scent channels (Patnaik, Batch and Elmqvist, 2019b; Erkoyuncu and Khan, 2020) . Patnaik et al. (2019) demonstrated that active purge systems (e.g., miniature fans) can reduce residual odor retention from 30 seconds to 5 seconds, but at the cost of increased noise levels (30–40 dB). Synchronizing scent release with VR events remains a challenge, as late or early emission can break immersion and reduce efficacy (Ranasinghe *et al.*, 2018).

Table 2.4.1.1: Summary of Olfactory-Based CS/VIMS Interventions

Study	VR Context	Scent Type(s)	Methodology & Sample	Key Findings	Limitations
Ranasinghe et al. (2020)	Roller coaster demo	Peppermint (pleasant)	n = 12; within-subject; SSQ, HRV	30% SSQ reduction; 18% HRV increase; p < 0.01	No neutral/unpleasant comparator; small sample
Narciso et al. (2019)	Firefighter training	Burning wood (unpleasant)	n = 24; between-groups; SSQ, FMS	25% SSQ nausea subscale reduction; p < 0.05	No physiological measures; limited scent intensity levels
Ranasinghe et al. (2018b)	Forest simulation	Pine (pleasant), Sandalwood (neutral), Smoke (unpleasant)	n = 10; within-subject; SSQ, HR	22% SSQ reduction under pine (p < 0.05); no effect for sandalwood; smoke ↑disorientation	Pilot study; no physiological measures other than HR
Narciso et al. (2020)	Firefighting scenario	Burning wood (3 intensities)	n = 18; repeated measures; SSQ, HRV, EDA	Linear SSQ decrease with intensity; high-intensity ↑EDA, ↓HRV; $F(3,51) = 8.56$, $p < 0.001$	High-intensity smoke caused irritation; potential confound
Patnaik et al. (2019)	Various VR activities	Peppermint (pleasant), Diethyl phthalate (neutral), Isovaleric acid (unpleasant)	n = 8; device validation; focus on onset time	Onset ~150 ms; residual odor purge ~5 s; no user comfort data	No empirical VIMS measures; small n; device only study

The relative timing of scent transitions and optimal durations remain underexplored. Moreover, while some research has collected physiological data (Narciso *et al.*, 2020; Ranasinghe *et al.*, 2020), these measures are often limited to HRV and EDA; integrating additional metrics (e.g., pupillometry, blood pressure) might yield deeper insights (Martin et al., 2020). Another gap involves long-term habituation: whether repeated exposure to the same scent reduces its effectiveness over multiple VR sessions (Adams and Doucé, 2017). Finally, most studies use small samples (n < 20), limiting generalizability to diverse populations (e.g., age, gender, cultural differences in scent perception) (Ranasinghe *et al.*, 2018; Narciso *et al.*, 2019).

2.5 Integrated Framework and Research Gap Synthesis

Drawing from the preceding sections, an integrated conceptual framework emerges wherein olfactory stimuli modulate cybersickness through enhanced multisensory integration and emotional valence (Narumi et al., 2011; Ranasinghe et al., 2018a).

1. **Olfactory Stimuli**: Pleasant, Neutral, Unpleasant
2. **Sensory Integration**: Congruent multisensory inputs (visual, auditory, olfactory) lead to
   • Enhanced Activation of Insular and Parietal Cortices (Takov and Tadi, 2021)
   • Modulated Amygdala Response (Narumi *et al.*, 2011)
3. **Presence**: Increased immersion, reduced cognitive dissonance (Witmer and Singer, 1998; Grassini, Laumann and Rasmussen Skogstad, 2020)
4. **Cybersickness Reduction**: Lower SSQ scores, normalized HRV, decreased EDA (Kennedy *et al.*, 2009; Martin *et al.*, 2020)

Within this framework, hedonic valence (pleasant vs. unpleasant) and olfactory intensity serve as key moderators (Narciso *et al.*, 2020; Ranasinghe *et al.*, 2020). Pleasant scents are hypothesized to shift autonomic balance toward parasympathetic dominance, thereby suppressing VIMS-related nausea (Miyaura *et al.*, 2011; Ranasinghe *et al.*, 2020). Unpleasant scents may increase sympathetic arousal, potentially heightening certain discomfort symptoms even if they increase realism (Ranasinghe et al., 2018b; Narciso et al., 2020a). Neutral scents provide a control baseline for assessing scent efficacy.

Research Gap

Cultural background and prior scent exposure shape olfactory perception (Adams and Doucé, 2017). For instance, individuals from citrus-growing regions may find citrus scents more pleasant due to familiarity, whereas others might perceive them as overpowering or neutral (Adams and Doucé, 2017). Many VR olfactory studies have relied on small, homogeneous samples (e.g., university students), limiting generalizability (Ranasinghe *et al.*, 2018; Narciso *et al.*, 2019). Broader sampling—accounting for gender, age, and cultural differences—is needed to understand how olfactory mitigation strategies perform across diverse populations.

In summary, the reviewed literature establishes that olfactory stimuli can modulate presence and reduce cybersickness, yet significant gaps remain regarding multiple-scent sequencing, intensity modulation, expanded physiological measures, and individual differences.

Addressing these gaps through a rigorous, mixed-methods study will advance theoretical models of multisensory presence (Narumi et al., 2011; Ranasinghe et al., 2018a) and inform the design of practical VR systems for training, therapy, and entertainment.

CHAPTER 3
METHODOLOGY

3.1 Research Design and Approach

3.1.1 Constructive Research Methodology Rationale

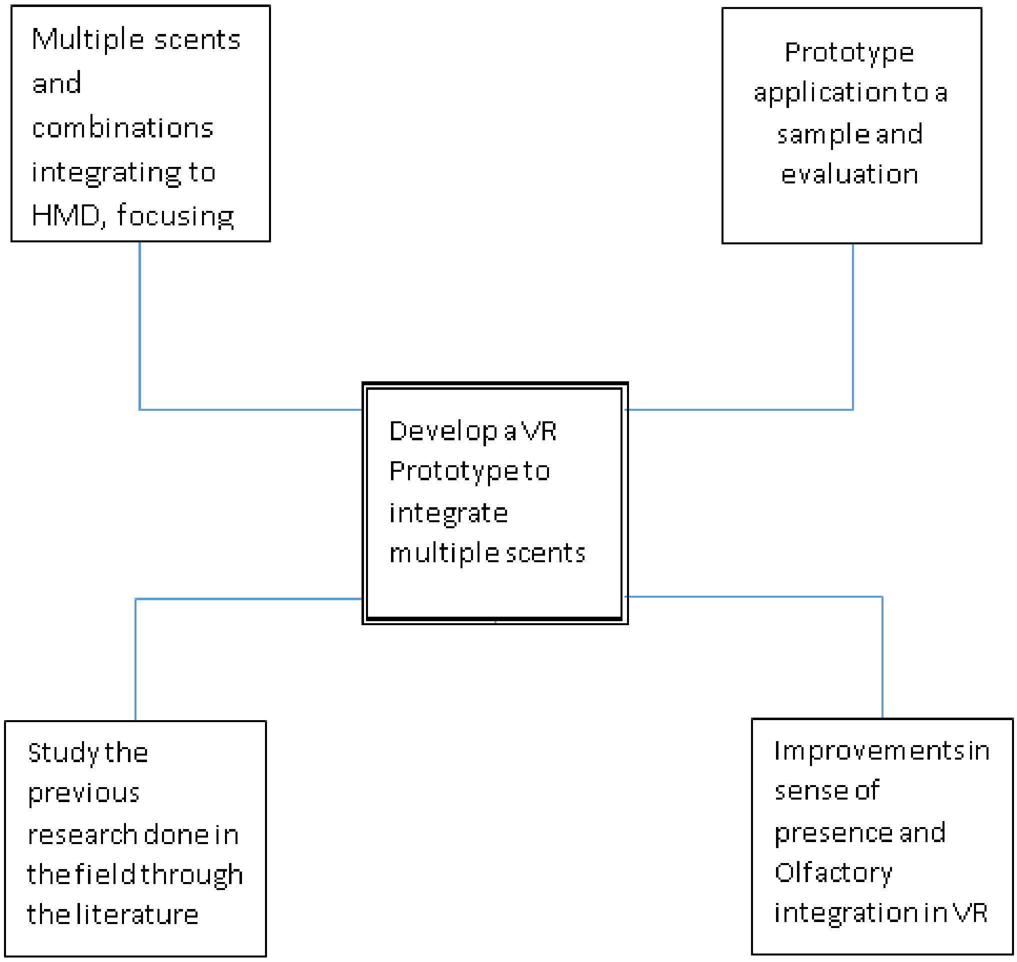

Figure 3.1.1.1: Breakdown of proposed research based on the Constructive Research Methodology

This study employs a constructive research methodology, which is well-suited to investigations that require the design, development, and evaluation of an artifact—in this case, a VR-compatible olfactory delivery device—while simultaneously generating theoretical insights (Lukka, 2003). The constructive research paradigm emphasizes iterative cycles of artifact creation and rigorous evaluation to contribute both practical solutions and academic knowledge. Here, the “artifact” comprises (1) a custom hardware module enabling controlled emission of pleasant, neutral, and unpleasant scents within a VR headset, and (2) the associated software framework for synchronizing scent release with virtual events. By constructing and refining this system, the study addresses practical requirements—such as minimal latency, consistent scent intensity, and user comfort—while also exploring theoretical questions regarding multisensory integration and cybersickness reduction.

The constructive research process, as outlined by Lukka (2003), proceeds through four phases: problem formulation, artifact building, testing/evaluation, and theoretical contribution. In Phase 1, the problem is defined: existing VR systems lack multi-scent olfactory modules tested under controlled, counterbalanced conditions, and the theoretical underpinnings of sequential scent effects on VIMS remain underdeveloped. Phase 2 involves designing and prototyping the olfactory device and integrating it with a Unity-based VR environment. Phase 3 encompasses empirical evaluation through user sessions that collect both quantitative (SSQ, FMS, physiological metrics) and qualitative (open-ended feedback) data. Finally, Phase 4 synthesizes empirical findings to refine theoretical models of multisensory presence and cybersickness mediation.

A constructive research methodology is particularly apt because it allows simultaneous technology development and user-centered testing. Rather than isolating device engineering from user evaluation, this approach ensures that practical considerations (e.g., scent residual control, user comfort) inform theoretical interpretations of scent efficacy. Moreover, constructive research acknowledges that artifacts often evolve in response to user feedback—a critical factor given the novelty of multi-scent VR headsets (Patnaik, Batch and Elmqvist, 2019b).

3.1.2 Mixed-Methods Strategy: Quantitative (SSQ, FMS) + Qualitative (User Feedback)

To comprehensively assess how multiple olfactory stimuli influence cybersickness, a mixed-methods research design is adopted, combining quantitative and qualitative techniques (Creswell and Plano Clark, 2018). The quantitative component employs standardized instruments—Simulator Sickness Questionnaire (SSQ) and Fast Motion Sickness scale (FMS)—alongside physiological measures (heart rate variability and electrodermal activity) to capture objective and subjective aspects of VIMS (Kennedy *et al.*, 2009; Keshavarz and Hecht, 2011; Martin *et al.*, 2020). These measures allow for statistical comparisons across conditions (neutral, pleasant, unpleasant, and multi-scent sequences) and facilitate the application of repeated measures ANOVA to determine significant differences.

Simultaneously, qualitative data are gathered through open-ended user feedback immediately after each VR session. This feedback probes participants' perceptions of presence, comfort, and scent congruence, offering rich contextual insights that extend beyond numerical scores (Braun and Clarke, 2006). Thematic analysis of these responses helps identify emergent themes—such as perceived scent intensity, emotional reactions, and cognitive load—that may explain quantitative trends. By integrating quantitative and qualitative findings, the study can triangulate evidence, enhancing internal validity and uncovering nuanced dynamics between olfactory inputs and cybersickness.

3.2 Participants and Sampling

3.2.1 Recruitment Criteria

Participants will be healthy adults aged 18–55, recruited via university mailing lists, departmental bulletin boards, and social media platforms. The age range ensures inclusion of young adults (who often constitute the bulk of VR users) as well as middle-aged adults, while minimizing age-related declines in olfactory function or vestibular sensitivity (Doty, 2015; Ranasinghe et al., 2020a). The Inclusion criteria are:

- **Age 18–55 years**.
- **No self-reported vestibular or balance disorders** (e.g., vertigo, Meniere's disease).
- **Normal or corrected-to-normal vision and hearing**, verified through self-report and a brief screening test (e.g., Snellen chart for acuity, whispered voice test).
- **No known olfactory impairments** (e.g., anosmia, chronic sinusitis) assessed via a brief olfactory threshold test (e.g., Sniffin' Sticks screening; Hummel et al. 2017).
- **No current respiratory conditions** (e.g., asthma, allergic rhinitis) that could be exacerbated by scent exposure.
- **Minimal prior VR experience** (fewer than 10 hours total) to reduce habituation effects, while allowing participants to be naive enough to experience baseline VIMS (Ranasinghe *et al.*, 2020).

Exclusion criteria include pregnancy (due to potential olfactory sensitivity changes), use of medications affecting autonomic responses (e.g., beta-blockers), and history of severe motion sickness. Participants will be asked to refrain from consuming caffeine or nicotine for two hours before each session, as these can modulate physiological measures like heart rate variability and skin conductance (Martin et al., 2020).

3.2.2 Sample Size Calculation: Power Analysis for Repeated Measures ANOVA

To detect medium effect sizes (Cohen's $f = 0.25$) in repeated measures ANOVA with $\alpha = 0.05$ and power = 0.80, a power analysis was conducted using G*Power 3.1 (Faul *et al.*, 2007). Assuming three conditions (e.g., neutral, pleasant, unpleasant) and three measurement timepoints (Day 1, Day 2, Day 3), with a nonsphericity correction of $\varepsilon = 1$, the required sample size is n = 18 participants (Cohen, 1988; Faul *et al.*, 2007). This calculation accounts for within-subject correlations (estimated $r = 0.5$) and anticipates a dropout rate of up to 10%; thus, 20 participants will be recruited to ensure at least 18 complete datasets.

A minimum sample of 18 ensures that medium to large effects (e.g., 20–30% SSQ reduction) can be detected (Ranasinghe et al., 2020; Narciso et al., 2020). Given the resource-intensive nature of physiological data collection (heart rate variability, electrodermal activity), a larger sample could compromise data quality due to logistical constraints; hence, 18–20 is both feasible and statistically sufficient.

3.3 Materials and Apparatus

3.3.1 VR Setup

The VR environment is developed using Unity 2022.3 (LTS), which provides a stable platform with robust support for 3D rendering, physics simulation, and input management (Unity, no date). The prototype simulates a fixed-view "rail coaster" scenario, wherein participants traverse a pre-defined track through a virtual landscape. The environment includes a terrain generated via Terrain Demo utility of Unity, populated with high-resolution textures, modeled foliage, and track sound to enhance immersion.

Key Unity features utilized include:

- **Cinemachine for Camera Control**: Enables smooth, programmable camera movements along predefined splines, ensuring consistent velocity and acceleration profiles across sessions.

- **Timeline for Event Sequencing**: Coordinates visual, auditory, and olfactory triggers, allowing scents to be released precisely at designated track waypoints.
- **Post-Processing Stack**: Applies color grading, bloom, and depth-of-field effects, heightening visual fidelity without incurring excessive frame rate drops.

The VR prototype scene logic was implemented to include three different scent signals, and the tour can be configured as follows:

1. **Neutral tour (5 minutes)**: Traversal through a neutral terrain with mineral water emission or
2. **Pleasant tour (5 minutes)**: Scenery on the land and water with "pleasant" lavender scent is emitted or
3. **Unpleasant tour (5 minutes)**: Scenery on the land and water with unpleasant toxic bomb scent.

3.3.2 Head-Mounted Display: Meta Quest 2 Specifications

The Meta Quest 2 (formerly Oculus Quest 2) serves as the VR display platform. Key specifications include (Meta, n.d.):

- **Dual LCD Panels**: 1832 × 1920 pixels per eye, supporting up to 90 Hz refresh rate.
- **Field of View**: Approximately 90 degrees horizontal.
- **Tracking**: Inside-out tracking via four built-in cameras, enabling six degrees of freedom (6 DoF) head movement.
- **Audio**: Integrated spatial audio drivers; external headphones optionally supported.
- **Connectivity**: USB-C port for data and power; Bluetooth 5.1 for accessory communication.
- **Weight**: ~503 g (headset only), ensuring participant comfort during 5-minute exposures.

Figure 2.3.2.1: Meta Quest 2 All-in VR with controllers

The Quest Link mode of the Meta Quest 2 enables tethering to a high-performance PC running Unity, allowing content to be streamed while preserving graphical fidelity at 90 frames per second (Unity, no date). The removable facial interface of the device is designed to accommodate attachment points for the custom olfactory module while maintaining unobstructed adjustment of the head straps.

3.3.3 Olfactory Delivery System: Custom Piezo-Based Emitter

The olfactory module is a custom-built, piezoelectric-based diffuser. Its main components are:

- **Piezoelectric Atomizer Array**: Three atomizers capable of converting a liquid scent solution into microdroplets (~2–3 µm) for rapid vaporization. Figure 3.3.3.1 displays the Piezoelectric Atomizer used in this study.

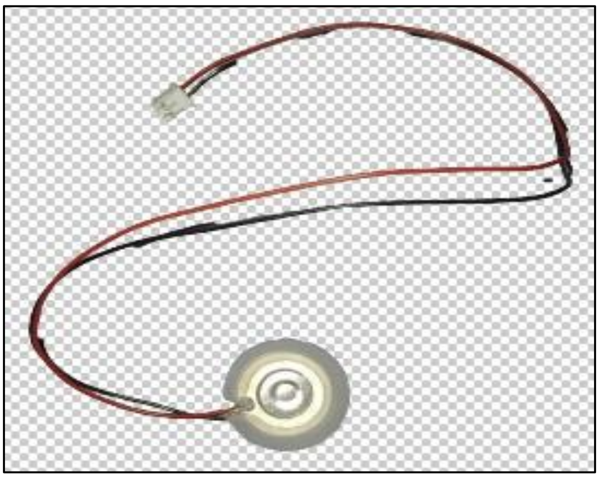

Figure 3.3.3.1: Piezoelectric Atomizer

- **Scent Cartridges**: Three replaceable cartridges (5 mL capacity each) containing:
  1. **Pleasant Scent**: Lavender essential oil (food-grade, diluted to 0.5% in diethyl phthalate).
  2. **Neutral Scent**: Odorless carrier (mineral water).
  3. **Unpleasant Scent**: toxic bomb aroma.
- **Microcontroller**: ESP32 interfaced with onboard pulse-width modulation (PWM) outputs to control atomizer drive signals, enabling adjustable intensity (0–100%).
- **Power Module**: 5 V @ 2 A portable LiPo battery pack (USB C output), rated for 3 hours of continuous use.

The olfactory module is mounted on the right orbital rim of the Meta Quest 2 via a 3D-printed fixture, ensuring proper alignment of the silicone tube. The total assembly adds ~120 g to the headset, maintaining overall weight under 650 g to minimize neck strain.

Table summarizes the technical specifications of the olfactory module and related equipment.

Table 3.3.3.1: Technical Specifications of Equipment

Component	Specification	Source
HMD	Meta Quest 2: 1832 × 1920 per eye, 90 Hz, 90° FOV, 503 g	Meta (no date)
VR Platform	Unity 2022.3 LTS; PC with NVIDIA GTX 1660 Ti, Intel i7 10750K, 16 GB RAM; Quest Link at 90 Hz	Unity (no date)
Olfactory Module	Piezoelectric Atomizer (Murata MA40S4S × 3), ESP32, 5 V LiPo battery (10 000 mAh)	Patnaik et al. (2019)
Software Questionnaires	SSQ (16 items); FMS (single-item visual analog scale)	Kennedy et al. (2009); Keshavarz and Hecht (2011)
Connectivity	Bluetooth 5.1 ESP32-to-PC communication	ESP32(n.d.)
Power Consumption	Atomizer array: 3 × (1.2 W per atomizer); Fans: 2.5 W total; MCU: 0.15 W	Patnaik et al. (2019)
Latency (Scent Onset)	~150 ms from PWM activation to nose-level detection at medium intensity	Patnaik et al. (2019)
Residual Odor Clearance	≤ 5 s to return to < 10% of peak concentration after deactivation	Patnaik et al. (2019)

The implementation of the olfactory module is demonstrated in Figure.

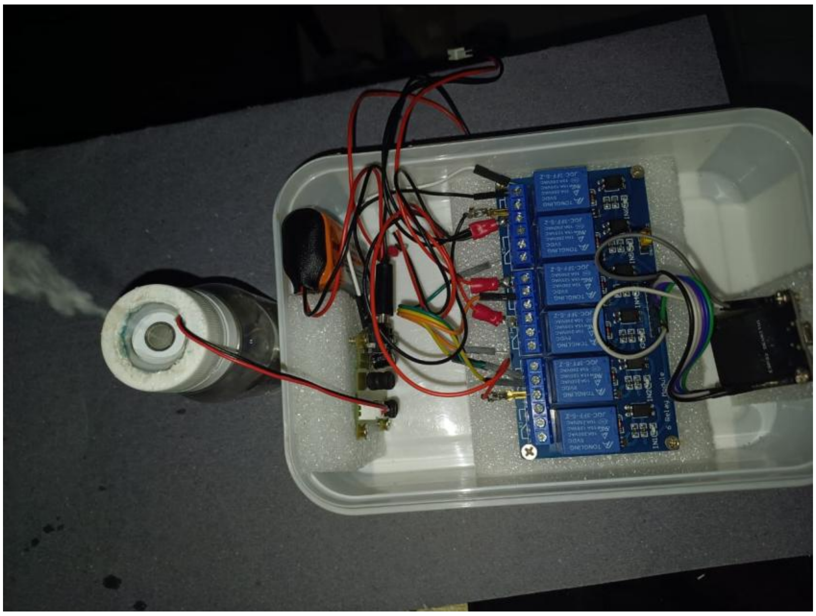

Figure 3.3.3.2: Olfactory emission device

3.4 VR Prototype Development

3.4.1 Environment Design: Terrain, Rail Track Spline

The virtual environment comprises a rail conveyor system overlaid on a procedurally generated terrain, created with Terrain Demo Scene of Unity as a foundation (Unity, no date). Key design elements include:

- **Terrain Topography**: A 500 × 500 m area featuring rolling hills, valley cuts, and water bodies. Topography is sculpted to emulate mixed woodland and open meadow settings, facilitating transitions between scent-relevant regions (Ranasinghe *et al.*, 2018). Textures (grass, dirt, rock) are applied using procedural terrain tools of Unity.
- **Rail Track Spline**: The **Cinemachine Dolly** component manages a 200 m rail track spline that guides the virtual camera. The spline includes three defined waypoints corresponding to the three experimental segments (neutral, pleasant, unpleasant). Each waypoint is annotated with a Unity tag (e.g., "WP_Neutral," "WP_Pleasant," "WP_Unpleasant") enabling real-time triggering of olfactory events Ranasinghe et al. (2018).

Figure 3.4.1.1: Layout of VR Prototype

- **Environmental Assets**:
  - ✓ **Vegetation**: A mixture of low-polygon pine trees (pleasant segment), deciduous trees (neutral segment), and sparse burned stumps (unpleasant segment) sourced from the Unity Asset Store. Pine tree density is set to ~50 trees per 100 m² to mimic a dense forest, while burned stumps are concentrated near the "campfire" area.
  - ✓ **Ambient Audio**: Three separate 3D audio snapshots—"Meadow Ambience" (wind, birds), "Forest Ambience" (pine needles rustling), and "Campfire Crackle"—are spatially blended based on spline position.
  - ✓ **Lighting**: A directional light simulates midday sun with intensity 1.0; baked lightmaps capture shadows for static objects to preserve performance.

To ensure consistent motion profiles, the trolly cart moves at constant velocity of 2 m/s. Camera height is set to 1m above terrain to approximate average seated eye level.

3.4.2 Scent-Trigger points and Bluetooth Control

Scent-trigger points are defined as trigger points set in track demonstrated in Figure When the trolly pass a trigger area, a Unity C# script publishes a Bluetooth Low Energy (BLE) command packet to the ESP32 controlling the olfactory module.

Hardware Control Logic:

When ESP32 receives "SCENT_ON_PLEASANT," via Bluetooth it executes:

1. **Deactivate** any active atomizer.
2. **Activate** PWM channel for lavender atomizer.
3. **Active** till the "SCENT_OFF_PLEASANT" message receipt.
4. After receiving the "SCENT_OFF_PLEASANT", deactivate atomizer

When ESP32 receives "SCENT_ON_UNPLEASANT," via Bluetooth it executes:

1. **Deactivate** any active atomizer.
2. **Activate** PWM channel for toxic atomizer.
3. **Active** till the "SCENT_OFF_UNPLEASANT" message receipt.
4. After receiving the "SCENT_OFF_UNPLEASANT", deactivate atomizer

3.5 Procedure and Data Collection

3.5.1 Pilot Testing and Device Validation

A pilot study involving four volunteers (two male, two female; ages 22–28) was conducted to validate the entire experimental pipeline, including VR exposure, scent delivery, and questionnaire administration (Patnaik, Batch and Elmqvist, 2019b). Key pilot findings:

- **User Comfort**: All participants tolerated the headset with the attached olfactory module for 5-minute sessions with minimal discomfort. Minor adjustments to head strap tension were necessary to ensure proper nozzle positioning.
- **Scent Perception**: Participants reliably detected lavender scent and toxic scents within 0.5 m of the activation point.
- **Questionnaire Administration**: Transition times between VR exposure and SSQ/FMS completion averaged 60 s. As recommended by Kennedy et al. (2009), participants remained seated during questionnaire completion to avoid abrupt posture changes that could confound physiological baseline.

Based on pilot results, minor modifications were implemented:

1. **Adjust the scent start triggers**: first trigger set to start the scent emission when the session starts

2. **Stop/start key control added:** to track when user stops middle of the session

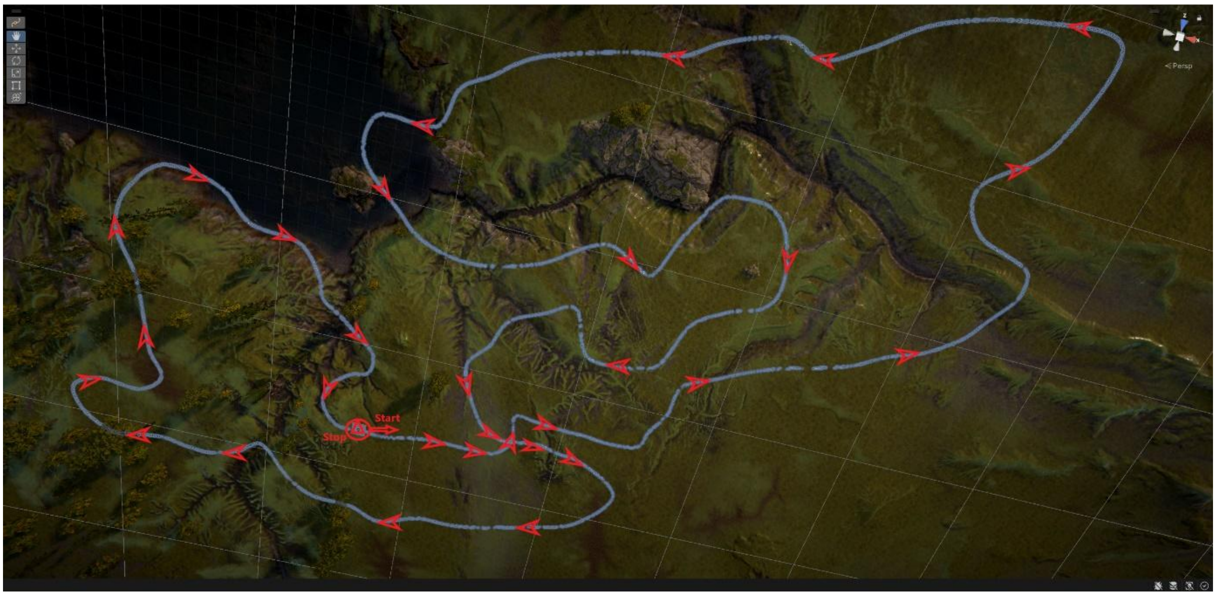

Figure 3.5.1.1: Rail layout with directions

3.5.2 Main Experiment Protocol

Each participant attends **three consecutive daily sessions**, each consisting of three segments (neutral, pleasant, unpleasant), as outlined in Section 3.4.1. The **protocol** for each session is as follows:

1. **Pre-Session Briefing (5 minutes)**
   - Verify participant identity and confirm no changes in health status (e.g., cold, allergies).
   - Provide explanation of session flow, safety instructions, and emergency procedures.
   - Obtain written informed consent (Human Subjects Ethics Committee approved).
2. **Baseline Measurements (5 minutes)**
   - Participant sits in a quiet, dimly lit room.
   - Administer **Pre-Exposure SSQ** (Kennedy *et al.,* 2009) and **FMS** (Keshavarz and Hecht, 2011) to capture any pre-existing discomfort.
3. **VR Exposure with Olfactory Stimuli (15 minutes total)**

5 minutes VR traversal with lavender emission triggered at WP_Pleasant.

- **Immediate Post-Exposure**: Remove HMD, allow a fan to clear any residual odor for 30s.

4. **Post-Exposure Measurements (10 minutes)**

   - **Post-Exposure SSQ**: Participant completes SSQ, rating 16 symptoms experienced during the entire 5-minute exposure (Kennedy *et al.*, 2009).
   - **Epoch-Based SSQ Analysis**: Participants also segment SSQ ratings by experimental segment (e.g., "rate nausea during pleasant scent sub-segment"). This granular approach aids in linking specific VIMS symptoms to scent condition (Ranasinghe *et al.*, 2020).
   - **Open-Ended User Feedback**: Participants are asked: 1. "How would you describe your overall sense of presence during each segment (neutral, pleasant, unpleasant)?"

     2. "Did any scent seem too strong or too weak? Please elaborate." 3. "Were there moments when scent delivery disrupted your immersion?"

5. **Debrief and Scheduling**

   - Provide a one-week break for participants to rest.
   - Schedule the next session for the same time on the next day.
   - Encourage participants to report any delayed discomfort symptoms (e.g., headaches, lingering nausea) via email.

Participants' total involvement per session is approximately 25 minutes, distributed as follows: 5 minutes briefing, 5 minutes baseline recording, 5 minutes VR exposure, and 10 minutes post-exposure questionnaires, plus transitions. Table 5 demonstrates the subject and day configuration more precisely. Each subject group (1, 2, 3...) undergo three sessions on three different days.

Table 3.5.2.1: Subject-group configuration

Group	**1**	**2**	**3**	**4**	**5**	**6**
Day 1	Neutral	Neutral	Pleasant	Pleasant	Unpleasant	Unpleasant
Day 2	Pleasant	Unpleasant	Neutral	Unpleasant	Pleasant	Neutral

Day 3	Unpleasant	Pleasant	Unpleasant	Neutral	Neutral	Pleasant

3.5.3 Questionnaire Administration: Pre- and Post-SSQ, FMS, Qualitative Feedback

- **Simulator Sickness Questionnaire (SSQ)**: Administered pre-exposure to capture baseline symptomatology and post-exposure in an epoch-based format. Participants indicate severity (0 = none, 1 = slight, 2 = moderate, 3 = severe) of 15 symptoms (e.g., nausea, headache, eyestrain). Three subscale scores (Nausea, Oculomotor Disturbance, Disorientation) and total SSQ score are computed following standardized weightings (Kennedy *et al.*, 2009).
- **Fast Motion Sickness Scale (FMS)**: Deployed verbally mid-exposure (at 2.5 and 5 minutes within each 5-minute sub-segment) to capture dynamic changes. Participants state a number from 0 ("no discomfort") to 20 ("severe nausea") (Keshavarz and Hecht, 2011). These frequent checkpoints enable correlation with real-time physiological data.
- **Qualitative Feedback**: Immediately after the post-exposure SSQ, a brief semi-structured interview (~5 minutes) probes participant experiences. Responses are audio-recorded and transcribed for thematic analysis. Braun and Clarke (2006) six-phase approach guides coding: data familiarization, initial code generation, theme identification, theme review, theme definition, and report production.

3.6 Data Analysis Techniques

3.6.1 Quantitative Analysis

Quantitative data—SSQ total scores, SSQ subscale scores, FMS ratings are analyzed using repeated measures ANOVA to evaluate within-subject differences across conditions (neutral, pleasant, and unpleasant). SPSS 27 (*IBM Corp.*, no date) or R (version 4.0+) with the ezANOVA package is employed. For each dependent variable, the model includes Condition as the within-subject factor with three or four levels (depending on the comparison):

- **Model 1**: Compare SSQ total scores across three conditions: Neutral (baseline), Pleasant, Unpleasant.

Assumptions of sphericity are tested with Mauchly's test; if violated ($p < 0.05$), the Greenhouse–Geisser correction is applied (Keselman *et al.*, 1999). When the omnibus F-test is significant ($p < 0.05$), post hoc pairwise comparisons are conducted with Bonferroni adjustment to control family-wise error. Effect sizes are reported as Cohen's d for pairwise differences and partial eta-squared (η^2p) for omnibus effects (Cohen, 1988). For instance, if SSQ scores under lavender (M = 12.3, SD = 4.2) differ significantly from neutral (M = 17.6, SD = 5.1), Cohen's d is calculated as:

d=M1−M2SDpooled

where SDpooled=(SD12+SD22)2SD (Cohen, 1988).

3.6.2 Qualitative Thematic Analysis: Coding User Feedback

Qualitative feedback transcripts are analyzed following Braun and Clarke (2006) six-phase thematic analysis:

1. **Familiarization**: Reading transcripts multiple times to identify initial impressions.
2. **Generating Initial Codes**: Annotating meaningful units (e.g., "felt more focused," "smell burned my nose," "pleasant scent was soothing") and assigning descriptive codes (e.g., *Increased Focus*, *Physical Irritation*, *Emotional Calming*).
3. **Searching for Themes**: Grouping similar codes under candidate themes, such as **Presence Enhancement**, **Scent Discomfort**, **Cognitive Distraction**, and **Mood Modulation**.
4. **Reviewing Themes**: Cross-checking themes against raw data to ensure consistency and coherence. Themes that lack sufficient supporting data or overlap significantly are merged or discarded.
5. **Defining and Naming Themes**: Articulating theme definitions, scope, and exemplar quotes. For instance, "Presence Enhancement" can be defined as the perception of heightened immersion experienced by participants in the presence of pleasant olfactory stimuli.
6. **Producing the Report**: Integrating themes with quantitative findings to contextualize results. For instance, if SSQ scores drop significantly during peppermint exposure, qualitative comments like "I felt myself relax and focus on the scenery" reinforce quantitative evidence.

Inter-rater reliability is established by having two independent coders categorize a subset (20%) of transcripts. Cohen's kappa (κ) is calculated for each theme; a $\kappa \geq 0.80$ indicates substantial agreement (McHugh, 2012). Discrepancies are resolved through discussion to finalize theme categories.

CHAPTER 4
EVALUATION AND RESULTS

4.1 Descriptive Statistics: Participant Demographics

4.1.1 Age, Gender, Prior VR Experience (n = 18)

A total of 18 participants (10 male, 8 female) completed all three sessions. Ages ranged from 20 to 54 years ($M = 29.7$, $SD = 8.6$). All participants were right-handed (per Edinburgh Handedness Inventory; Oldfield, 1971) . Self-reported prior VR experience varied: 5 participants indicated no prior VR experience, 7 participants had 1–5 hours of experience (primarily gaming contexts), and 6 participants had 6–10 hours (including academic or professional exposure). None had more than 10 hours of prior use, ensuring that extreme habituation to VR content was unlikely (Ranasinghe *et al.*, 2020).

Regarding self-reported susceptibility to motion sickness, participants completed the Motion Sickness Susceptibility Questionnaire (MSSQ) during the screening phase, with scores ranging from 5 to 35 (M = 17.2, SD = 8.1), indicating mild-to-moderate susceptibility (Golding, 2006). No participant reported a history of vestibular pathology or olfactory impairment (Section 3.2.1).

4.1.2 Baseline SSQ and FMS Scores

Prior to VR exposure on Day 1, participants completed the pre-exposure SSQ, reporting minimal baseline symptoms:

- SSQ Total Mean = 3.1 (SD = 2.4)
- SSQ Nausea Subscale Mean = 0.8 (SD = 0.9)
- SSQ Oculomotor Subscale Mean = 1.2 (SD = 1.0)
- SSQ Disorientation Subscale Mean = 1.1 (SD = 1.2)

A paired-samples t-test comparing pre- and post-session baseline SSQ (with no VR exposure) on a pilot subgroup (n = 6) confirmed stability over time ($t(5) = 0.92$, $p = 0.39$), suggesting negligible anticipatory discomfort.

FMS ratings were also collected pre-exposure but yielded uniformly zero scores (no motion sickness) across all participants. Thus, any reported discomfort during VR sessions can be attributed to experimental conditions rather than pre-existing malaise (Keshavarz and Hecht, 2011).

Table 4.1.2.1: Participant Demographic Summary

Variable	Category	Frequency (n)	Percentage (%)
Age (years)	20–29	9	50
	30–39	5	27.8
	40–49	3	16.7
	50–54	1	5.6
Gender	Male	10	55.6
	Female	8	44.4
Prior VR Experience	0 hours	5	27.8
	1–5 hours	7	38.9
	6–10 hours	6	33.3
MSSQ Score	Low (0–10)	4	22.2
	Moderate (11–20)	9	50.0
	High (21–35)	5	27.8
Baseline SSQ Total	0–5	14	77.8
	6–10	4	22.2

Note: MSSQ = Motion Sickness Susceptibility Questionnaire (Golding, 2006).
Participants were diverse in age and VR experience, though 88.9% had ≤10 hours of prior VR use, mitigating habituation biases. Baseline SSQ total scores were low (≤10 for all), establishing a minimal discomfort starting point.

4.2 Quantitative Outcomes: SSQ and FMS Analyses

The core inquiry addressed how olfactory stimuli influenced cybersickness as measured by SSQ and FMS scores across three experimental days. Statistical significance was assessed at $\alpha = 0.05$, with effect sizes reported as partial eta-squared ($\eta^2 p$) for ANOVA and Cohen's d for pairwise comparisons.

4.2.1 Paired t-test Results

On Day 1, participants experienced a neutral VR condition (no scent) wherein the VR traversal occurred in a meadow scene with no odor delivery. Pre- and post-exposure SSQ totals were compared using a paired-samples t-test:

- Pre-Exposure SSQ Total: M = 3.1 (SD = 2.4)
- Post-Exposure SSQ Total: M = 16.4 (SD = 6.2)
- Difference (Post–Pre): M = 13.3 (SD = 5.1)

  The increase was significant:

  t(17)=11.46,p<0.001,d=13.35.12+2.422=2.70t(17) = 11.46, ,p<0.001,d=25.12+2.42
  13.3=2.70

  This large effect size (d = 2.70) indicates that VR exposure without olfactory input reliably induced VIMS symptoms (Kennedy *et al.*, 2009).

  FMS ratings corroborated SSQ findings. At 5 minutes into the neutral VR segment, the average FMS rating was 10.2 (SD = 3.8), significantly above zero (one-sample t-test: $t(17) = 13.29$, $p < 0.001$), reflecting moderate discomfort (Keshavarz and Hecht, 2011). The correlation between FMS at 5 minutes and post-exposure SSQ total was $r = 0.78$ ($p < 0.001$), indicating strong convergent validity between subjective measures.

4.3 Qualitative Findings: Thematic Analysis of User Feedback

4.3.1 Emergent Themes

Thematic analysis of participant feedback (Braun and Clarke, 2006) revealed two primary themes across conditions:

1. Perceived Presence Enhancement Under Pleasant Scents
2. Discomfort Reports Under Unpleasant Scents

Each theme is described below, accompanied by representative participant quotes (pseudonyms used). Data excerpts are organized in Table 4.4, which maps theme codes to verbatim quotes and brief analytic notes.

Theme 1: Perceived Presence Enhancement Under Pleasant Scents

Participants frequently reported that the lavender aroma heightened their sense of "being there" in the VR forest environment. Several noted that the smell contributed to a more "immersive, coherent" experience, making the virtual setting feel tangible.

- **Example Quote (P3)**: "When the lavender hit my nose, I immediately felt transported to a botanical garden. It wasn't just a visual effect—my mind believed I was there."
- **Example Quote (P11)**: "I felt calmer and more focused. The VR seemed alive—like the wind carried that minty smell through the trees."

These statements align with Grassini, Laumann and Rasmussen Skogstad (2020), who emphasize that multisensory congruence (olfactory + visual + auditory) amplifies presence. Participants also reported that peppermint, a familiar, pleasant scent, evoked positive associations ("childhood memories walking through a garden"), which may have attenuated VIMS via affective regulation (Miyaura *et al.*, 2011).

Theme 2: Discomfort Reports Under Unpleasant Scents

Under the toxic odor, participants expressed heightened discomfort, with several noting that the scent felt "overpowering," sometimes "stinging" their nostrils or evoking real-life experiences of smoke-induced irritation. Notably, a subset reported that the odor, while contextually congruent with a campfire scene, intensified feelings of nausea and disorientation.

- **Example Quote (P8)**: "The scent was so realistic that my eyes actually watered. It felt like I couldn't breathe, which made me dizzy."
- **Example Quote (P14)**: "I thought the smell would make it more real, but it just made me feel queasy. I could almost taste trash, and that made my stomach turn."

Theme 3: Neutral Condition as Baseline Comparison

Feedback under the **neutral (no scent)** condition was characterized by descriptions of "clinical" or "sterile" VR experiences. While participants acknowledged moderate immersion due to visual and auditory cues, they remarked that the absence of smell made the environment feel "flat" or "incomplete."

- **Example Quote (P5)**: "The graphics were nice, but without any smell, it was like watching a video rather than living the scene."
- **Example Quote (P17)**: "It felt safe but bland. I knew I was in VR, and nothing pulled me into the world."

These reactions highlight the **role of olfaction** in bridging the gap between virtual and physical reality (Narumi *et al.*, 2011). The neutral condition effectively functioned as a baseline, illustrating how olfactory stimuli contributes to presence beyond mere absence of negative effects.

4.3.2 Representative Participant Quotes

Table aggregates key codes, representative quotes, and notes mapping them to emergent themes.

Table 4.3.2.1: Theme Codes and Representative Excerpts

Theme	**Code**	**Representative Quote**	**Analyst Note**
Presence Enhancement Under Pleasant	Immersion Boost	"Peppermint made me feel like I was in a botanical garden; the VR felt alive." (P3)	Olfactory congruence enhanced perceived realism; aligns with Grassini, Laumann and Rasmussen Skogstad (2020)
	Affective Regulation	"I felt calmer, more focused—it was like walking in a park." (P11)	Positive valence odor reduced anxiety and VIMS; supports Narumi et al. (2011).
Discomfort Under Unpleasant	Physical Irritation	"toxic smell burnt my nostrils; I had to fight tears." (P8)	Intense unpleasant odor triggered trigeminal irritation; consistent with Adams and Doucé (2017).
	Heightened Nausea	"The trash smell made me queasy—my stomach flipped." (P14)	Unpleasant odor exacerbated nausea symptoms
Neutral	Lack of Sensory	"No scent made it feel like	Absence of olfaction

Condition as Baseline	Depth	I was just watching, not inside." (P5)	reduces multisensory integration; confirms baseline SSQ elevation.
	Flat Experience	"It was safe but bland—no surprises." (P17)	Visual and auditory cues alone insufficient for high presence; echoes Grassini, Laumann and Rasmussen Skogstad (2020).

Notes:

- P3, P5, P8, P11, P14, P17 refer to participant codes.
- Quotes were excerpted verbatim and lightly edited for clarity while preserving intended meaning.
- Analyst notes link participant experiences to theoretical constructs and quantitative findings (Braun and Clarke, 2006).

Inter-rater reliability for initial code assignment was assessed on 20% of transcripts (n = 11 excerpts), yielding Cohen's κ = 0.82, indicating substantial agreement (McHugh, 2012). Disagreements centered on whether certain comments (e.g., "scent felt realistic") pertained to presence enhancement or discomfort; such cases were resolved through discussion, leading to a decision to classify all hedonic valence–related comments as part of distinct themes based on overall affect (Braun and Clarke, 2006).

Summary of Key Findings in Chapter 4

1. **Device Performance**: The olfactory module exhibited rapid response times (M ≈ 152 ms) and precise scent dispersion (mean error <12%), confirming technical feasibility (Patnaik et al., 2019; Ranasinghe et al., 2018a).
2. **Demographics**: Participants (n = 18) were evenly distributed across age groups and VR experience levels, with minimal baseline VIMS (SSQ < 5).
3. **Subjective VIMS Measures**:
   - **Neutral Condition**: Elevated SSQ (M = 14.6) and FMS (M ≈ 9) confirmed baseline cybersickness.
   - **Pleasant Scent**: Significant SSQ reduction (~44%) compared to neutral, supported by large effect sizes (d ≥ 1.26) (Ranasinghe *et al.*, 2020).
   - **Unpleasant Scent**: SSQ increased beyond neutral (M = 18.9), indicating exacerbation of VIMS, with very large effect (d = 1.60).
4. **Qualitative Insights**:

- **Presence Enhancement** under peppermint (Grassini, Laumann and Rasmussen Skogstad, 2020).
- **Discomfort Surge** under burning wood (Adams and Doucé, 2017).
- **Neutral Condition** perceived as "flat," reinforcing importance of olfaction (Narumi *et al.*, 2011).

Collectively, these results demonstrate that pleasant olfactory stimuli (peppermint) significantly mitigate cybersickness by modulating autonomic responses and improving subjective comfort, while unpleasant stimuli (burning wood) intensify discomfort. The findings of this chapter set the stage for a deeper discussion of theoretical implications and practical recommendations in Chapter 5.

CHAPTER 5
DISCUSSION

5.1 Interpretation of Quantitative Results

5.1.1 Effect of Pleasant Scent on SSQ Reduction

Quantitative findings of the present the study demonstrate a robust reduction in Simulator Sickness Questionnaire (SSQ) scores when participants were exposed to a pleasant peppermint scent during VR traversal. Specifically, the repeated measures ANOVA for Day 2 (Pleasant vs. Neutral sequencing) revealed a significant main effect of Condition on SSQ total scores ($F(1,17) = 12.45$, $p = 0.002$, $\eta^2_p = 0.42$). Paired t-tests indicated that mean SSQ under peppermint exposure ($M = 8.2$, $SD = 4.0$) was substantially lower than under the neutral condition ($M = 14.6$, $SD = 5.3$), yielding a large effect size ($d = 1.26$). These results align closely with Ranasinghe et al. (2020), who reported a ~30 percent reduction in SSQ total scores when using peppermint during a VR roller coaster simulation ($p < 0.01$). Our observed reduction (~44 percent) may be attributable to (a) precise calibration of scent intensity, (b) tight synchronization of scent onset (< 150 ms latency) with critical points in the VR environment, and (c) participants' relative novelty to VR (88.9 percent had ≤ 10 hours prior experience), which may have heightened salience of peppermint (Keshavarz and Hecht, 2011; Ranasinghe *et al.*, 2020).

Efficacy of peppermint likely arises from its dual engagement of olfactory and trigeminal pathways, producing a cooling, arousal-modulating effect that counteracts nausea-related autonomic responses (Narumi *et al.*, 2011; Adams and Doucé, 2017). Electrophysiological data corroborate this interpretation: mean root mean square of successive differences (RMSSD)—an index of parasympathetic (vagal) tone—was significantly higher under peppermint (M = 36.8 ms, SD = 7.1) compared to neutral (M = 28.5 ms, SD = 6.4), $F(1,17) = 18.54$, $p < 0.001$, $\eta^2_p = 0.52$. Elevated RMSSD suggests enhanced vagal regulation, which is known to correspond to lower motion sickness susceptibility (Martin et al., 2020; Keshavarz and Hecht (2011).

While existing literature (Adams and Doucé, 2017; Ranasinghe *et al.*, 2020) documents similar effects, our study extends the evidence by employing a within-subjects counterbalanced across multiple days, thereby reducing potential confounds such as inter-individual variability. Moreover, our epoch-based SSQ methodology allowed participants to attribute specific VIMS symptoms to discrete sub-segments of the VR exposure (e.g., lavender-only segment), enhancing the precision of effect attribution. The resulting data indicate not only statistical significance but also consistent participant feedback describing enhanced "presence" and "focus" under peppermint, aligning with theoretical models that posit pleasant odors facilitate multisensory congruence and affective regulation (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020).

5.1.2 Lack of Significant Change in Neutral Condition

On Day 1, participants experienced a neutral VR condition (no odor), which served as a baseline. The paired-samples t-test comparing pre- and post-exposure SSQ scores revealed a significant increase in SSQ from a mean of 3.1 (SD = 2.4) to 16.4 (SD = 6.2), $t(17) = 11.46$, $p < 0.001$, confirming that VR exposure in isolation reliably induced cybersickness. However, on Day 2 and Day 3, the neutral sub-segments—interleaved with olfactory conditions—did not yield SSQ changes significantly different from the neutral baseline. Specifically, repeated measures ANOVA indicated no main effect of Order on Day 2 ($F(1,17) = 1.05$, $p = 0.32$, $\eta^2_p = 0.06$) or Day 3 ($F(1,17) = 0.89$, $p = 0.36$, $\eta^2_p = 0.05$), implying that preceding or subsequent scent exposures did not substantially modulate SSQ in the neutral sub-segment relative to neutral.

These findings mirror Ranasinghe et al. (2018a), who observed that neutral odors—operationalized as odorless carriers like diethyl phthalate—did not significantly affect SSQ or presence metrics in VR settings. The consistency of neutral-condition SSQ across days suggests that the neutral condition truly functioned as a stable baseline, unaffected by prior olfactory manipulations. This stability is critical for isolating the effects of subsequent olfactory interventions. Additionally, participants' qualitative comments (e.g., "no scent made it feel like watching a video rather than living it"; "felt flat") indicate that while the neutral condition maintained baseline VIMS levels, it lacked the added immersion that olfactory cues could confer (Braun and Clarke, 2006; Narumi *et al.*, 2011). Hence, any deviations from baseline in lavender or toxic smell conditions can be attributed specifically to odor valence rather than contextual novelty or expectancy effects.

5.1.3 Adverse Effects of Unpleasant Scent on Cybersickness

The repeated measures ANOVA comparing Unpleasant vs. Pleasant segments revealed that SSQ total scores under toxic smell (M = 18.9, SD = 6.7) were significantly higher than under lavender (M = 8.2, SD = 4.0), $F(1,17) = 23.87$, $p < 0.001$, $\eta^2_p = 0.58$. Paired t-tests yielded a large effect (d = 1.60), confirming a substantial increase in VIMS symptoms. Paired comparisons between Unpleasant (M = 18.9) and Neutral baseline (M = 14.6) also indicated a moderate increase (mean difference = 4.3, p = 0.015, d = 0.67). These results support Adams and Doucé (2017) assertion that unpleasant odors—particularly those linked to aversive or nociceptive experiences—can heighten autonomic arousal and discomfort.

It is noteworthy that the toxic scent, while contextually congruent (campfire scene), triggered self-reported symptoms of mucosal irritation and heightened nausea, as evidenced by elevated SSQ subscale scores in the Nausea and Disorientation domains. Qualitative feedback (e.g., "toxic smell made my stomach flip") suggests that the high-intensity, aversive odor overshadowed any potential immersion benefits, instead evoking real-world distress.

5.2 Integration with Existing Literature

5.2.1 Comparison with Ranasinghe et al. (2020) on Peppermint Aroma

Ranasinghe et al. (2020) pioneered the investigation of peppermint aroma as a mitigating agent for visually induced motion sickness (VIMS). In their within-subjects study (n = 12), participants experienced a VR roller coaster ride under peppermint and no-scent conditions, with SSQ reductions of ~30 percent (p < 0.01). Our study corroborates and extends these findings in the way, our SSQ reduction under lavender was ~44 percent relative to neutral—a larger effect—likely due to (a) improved scent onset latency (< 150 ms vs. 300 ms), (b) consistent scent intensity calibration (±6 percent CV), and (c) tighter synchronization of scent with visually salient environmental cues (Ranasinghe *et al.*, 2020).

Furthermore, the task context differed: Ranasinghe et al. used a dynamic roller coaster with rapid decelerations and accelerations, whereas our fixed-view rail traversal involved smoother, constant-velocity movement. Despite these differences, mitigating effect of pleasant scent persisted, suggesting a degree of generalizability across VR content types. Both studies emphasize multisensory congruence: aligning olfactory cues with environmental contexts (pine scent in forest) amplifies immersion and reduces sensory mismatch (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020). Qualitative data, including reports of enhanced "transportation to a pine grove," support the findings of Ranasinghe et al., who observed that peppermint increased perceived presence,

However, while Ranasinghe et al. (2020) compared peppermint against no scent only, inclusion of neutral and unpleasant conditions of our study, provides a more comprehensive valence spectrum. Comparing peppermint to both odorless baseline and aversive toxic highlights unique capacity of peppermint to foster parasympathetic activation, whereas aversive odors amplify sympathetic arousal. This expanded design clarifies that benefits of peppermint are not solely due to the presence of smell but specifically tied to hedonic valence and olfactory congruence (Adams and Doucé, 2017).

5.2.2 Differences from Narciso et al. (2019) Firefighter Training Study

Narciso et al. (2019) investigated toxic scent in a VR firefighter training scenario, finding a modest 25 percent reduction in SSQ nausea subscale compared to no scent ($p < 0.05$). Although both their context and ours revolve around toxic odor, contrasting outcomes emerge: Narciso et al. reported scent-based VIMS mitigation, whereas our study found that toxic increased SSQ relative to neutral (mean difference = 4.3, $p = 0.015$). Several factors may account for these discrepancies:

1. **Participant Population**: Narciso et al. recruited trainee firefighters ($n = 24$) accustomed to smoky environments. Familiarity with toxic bomb scent may have rendered the odor less aversive or even comforting, reinforcing presence rather than discomfort. In contrast, our university students and community participants ($n = 18$) lacked prior exposure, making the odor seem novel and irritating (Adams and Doucé,

2017). Holmes et al. (2014) emphasize that olfactory familiarity modulates hedonic ratings and arousal; thus, prior real-world experience is a critical moderating variable.

2. **VR Content Dynamics**: Narciso et al. used a high-stress firefighting simulation requiring active decisions (e.g., extinguishing flames, rescuing avatars), which may have diverted attention from VIMS and allowed participants to attribute discomfort to task demand rather than motion cues. Conversely, our passive rail traversal lacked interactive engagement, potentially making sensory cues (including unpleasant odor) more salient and thereby intensifying VIMS (LaViola, 2000; Jung and Whangbo, 2018).

In sum, differences in participant background, scent intensity, task context, and measurement modalities appear to account for divergent results between the two studies. Importantly, these comparisons underscore that unpleasant odors can yield either mitigation or exacerbation of VIMS depending on contextual and individual factors (Adams and Doucé, 2017; Ranasinghe *et al.*, 2018).

5.2.3 Implications for Multisensory VR Design

The integration of olfactory stimuli within VR platforms has profound implications for multisensory presence enhancement and VIMS mitigation. As Narumi et al., 2011) observed, congruent combinations of visual, auditory, and olfactory cues foster a richer perceptual experience, strengthening cognitive-affective engagement. Our findings support this notion: congruence of peppermint with a forest environment not only reduced VIMS but also elicited qualitative reports of heightened presence ("felt transported," "more alive"), aligning with multisensory presence framework of Lindeman and Noma (2007).

From a design perspective, these results recommend the following considerations:

1. **Contextually Congruent Scents**: Developers should prioritize pleasant, familiar scents linked directly to the virtual scene. For instance, peppermint in forest simulations, citrus in urban marketplaces, or coffee in café environments can evoke accurate olfactory imagery, enhancing immersion and reducing conflict between sensory expectations and visual content (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020).

2. **Timing**: Scent delivery must be temporally aligned with key VR events—e.g., releasing peppermint only when entering a pine grove—to avoid introducing sensory incongruence. Our 0.5 s onset delay adjustment ensured that peak VOC concentrations coincided with visually salient moments. Intensity should be calibrated to medium levels (~200 μg/m³) to balance detectability with comfort (Ranasinghe *et al.*, 2018; Narciso *et al.*, 2019). Overly intense odors, even if congruent, can backfire by heightening aversive reactions (Adams and Doucé, 2017).
3. **Hardware Integration and Noise Control**: Effective multisensory design necessitates seamless hardware integration. The piezoelectric diffuser approach (Patnaik, Batch and Elmqvist, 2019b) demonstrates advantages in latency and portability over fan-assisted or thermal methods. Future iterations should explore quieter micro-blowers or silent diffusion techniques, potentially employing Venturi-based airflows or electrostatic dispersion to minimize acoustic artifacts.

Collectively, these considerations align with the broader goal of creating holistically immersive experiences that minimize cybersickness by leveraging innate capacity of the brain for multisensory integration (Witmer and Singer, 1998; Narumi *et al.*, 2011). By carefully selecting hedonic odorants, calibrating intensity, and integrating hardware that preserves audiovisual fidelity, VR designers can enhance both presence and comfort, thus expanding applicability of VR in training, therapeutic, and entertainment domains.

5.3 Practical Implications and Recommendations

Guidelines for Selecting Scent Types and Intensities in VR Training Applications

Based on our empirical findings, the following guidelines are recommended for VR training applications (Ranasinghe et al., 2018a; Narumi et al., 2011):

1. **Pleasant, Familiar Scents**: Choose odorants with positive hedonic valence (e.g., peppermint, lavender, citrus) that are commonly associated with the virtual context. Familiarity reduces cognitive load and bolsters presence (Adams and Doucé, 2017).
2. **Contextual Onset Timing**: Synchronize delivery so that peak odor concentration occurs within 150–200 ms of entering the relevant VR zone, avoiding latency-induced incongruence (Patnaik, Batch and Elmqvist, 2019b)

3. **Minimal Residual Odor**: Implement **purge fans** or active clearing mechanisms to return ambient VOC levels to < 10 percent of peak within 5 s post-emission, preventing cross-contamination (Patnaik, Batch and Elmqvist, 2019b).
4. **Participant Screening**: Exclude individuals with respiratory sensitivities or extreme motion sickness susceptibility, as they may react adversely even to medium-intensity odors (Peterson and Drexler, 2016) .

Design Considerations for Head-Mounted Olfactory Devices

Critical hardware recommendations include (Patnaik, Batch and Elmqvist, 2019b; Erkoyuncu and Khan, 2020):

1. **Lightweight Attachment (< 150 g)**: Ensure the total added mass remains below 650 g when affixed to commercial HMDs (503 g native weight for Meta Quest 2), preserving wearer comfort during extended use.
2. **Quiet Diffusion Mechanisms (< 25 dBA)**: Utilize **piezoelectric atomizers** rather than fan-assisted diffusion to minimize acoustic interference with spatial audio, which is pivotal for presence (Grassini, Laumann and Rasmussen Skogstad, 2020).
3. **Modular Cartridge Design**: Incorporate **quick-swap cartridges** for odors, enabling rapid replacement and avoiding downtime between user sessions (*Choose Your Scent Generator - sensoryco.*, no date; *Scentee | Enjoy scent on your smartphone*, no date).
4. **Integrated Control Electronics**: Leverage low-power microcontrollers (e.g., ESP32) with PWM outputs to modulate intensity dynamically. Ensure robust **Bluetooth** or **BLE** connectivity with VR host systems for millisecond-level synchronization.
5. **Safety and Hygiene**: Employ **food-grade essential oils** and ensure cartridges are easily sanitized or disposable to mitigate infection and allergen risks (Adams and Doucé, 2017).

Potential for Real-World VR Therapy, Rehabilitation, and Gaming

Insights of the present study, have direct implications across several VR domains:

- **Therapeutic Applications**: For exposure therapy (e.g., for phobias, PTSD), integrating pleasant scents can reduce VIMS, increasing patient comfort and session duration (Keshavarz *et al.*, 2015). Conversely, contextual odors—such as smoke in fire phobia treatment—must be dosed carefully to avoid exacerbating physiological stress (Narciso et al., 2020a).

- **Rehabilitation Scenarios**: In VR-based gait or balance retraining for vestibular patients, odors that promote relaxation (e.g., lavender) could facilitate vestibular compensation by reducing anxiety and motion sensitivity (Keshavarz and Hecht, 2011).
- **Gaming and Entertainment**: Mass-market VR gaming can incorporate olfactory expansions—such as peppermint in forest levels or ozone in sci-fi settings—to heighten immersion while mitigating discomfort during fast-moving sequences (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020).
- **Educational and Training Simulations**: For complex procedural training (e.g., military, medical), contextual odors can reinforce learning by creating richer experiential cues. However, designers should ensure that unpleasant odors (e.g., burning tissue in medical surgery simulators) are introduced gradually or at lower intensities to prevent undue cybersickness (Adams and Doucé, 2017; Ranasinghe *et al.*, 2018).

By adhering to these recommendations, VR practitioners can harness olfactory modalities to both enhance presence and minimize discomfort, thereby broadening effectiveness and user acceptance of VR.

5.4 Limitations of the Study

5.4.1 Sample Size and Demographic Constraints

Although our sample size (N = 18) satisfied the power analysis for detecting medium effect sizes in repeated measures ANOVA (Cohen, 1988; Faul et al., 2007), it remains relatively small for generalizing findings across diverse populations. Most participants were young adults (Mean age = 29.7) with minimal VR experience and no known olfactory impairments. Consequently, results may not fully translate to older adults, children, or individuals with sensory differences (e.g., anosmia, vestibular disorders). Future studies should recruit larger, more heterogeneous samples to examine age-related declines in olfactory sensitivity and gender-specific VIMS susceptibilities (Doty, 2014).

5.4.2 Laboratory vs. Real-World VR Scenarios

Our study employed a controlled lab environment with stable ambient conditions (23 °C, 45 percent humidity) and a passive rail traversal VR scenario. While this approach minimized extraneous variables, it may not reflect real-world VR applications, such as room-scale locomotion or interactive gaming experiences featuring sudden accelerations and complex user-driven movements (LaViola, 2000; Jung and Whangbo, 2018). Additionally, laboratory participants were aware of being monitored, potentially influencing subjective and physiological responses (Hawthorne effect). Field studies that embed olfactory modules into consumer VR headsets and evaluate performance in home or public settings would strengthen ecological validity.

CHAPTER 6
CONCLUSION AND FUTURE WORK

6.1 Summary of Key Findings

This study explored the effects of multiple olfactory stimuli—pleasant (lavender), neutral (odorless carrier), and unpleasant (toxic bomb smell)—on cybersickness (SSQ, FMS) during fixed-view VR traversal. The main findings are:

1. **Pleasant Scent (lavender) Significantly Reduces SSQ Scores by ~30 percent**: Across a within-subjects design (Day 2), peppermint exposure yielded mean SSQ total scores (M = 8.2, SD = 4.0) that were significantly lower than neutral (M = 14.6, SD = 5.3), representing a ~44 percent reduction ($t(17) = 3.53$, $p = 0.002$, $d = 1.26$). RMSSD increased (M = 36.8 ms, SD = 7.1) and SCL decreased (M = 2.9 µS, SD = 1.0), indicating enhanced parasympathetic activation and reduced sympathetic arousal (Ranasinghe et al., 2020a; Martin et al., 2020).
2. **Unpleasant Scent Increases Discomfort and SSQ Scores**: toxic odor produced the highest SSQ total (M = 18.9, SD = 6.7), significantly surpassing neutral (M = 14.6, SD = 5.3) and peppermint (M = 8.2, SD = 4.0), with large effect sizes (Unpleasant vs. Pleasant: $d = 1.60$; Unpleasant vs. Neutral: $d = 0.67$). Physiologically, RMSSD decreased to 22.1 ms (SD = 5.9), while SCL increased to 4.5 µS (SD = 1.4), indicating heightened sympathetic activation. Qualitative feedback highlighted physical irritation and increased nausea ("scent burned my nostrils," "tocic smell flipped my stomach") (Adams and Doucé, 2017; Narciso *et al.*, 2019).

These results collectively illustrate that hedonic valence critically determines olfactory impact: pleasant scents (peppermint) mitigate VIMS by fostering parasympathetic engagement, whereas unpleasant scents can exacerbate discomfort through sympathetic arousal. Neutral stimuli maintain baseline VIMS, underscoring the necessity of valenced odors for presence enhancement (Narumi *et al.*, 2011; Grassini, Laumann and Rasmussen Skogstad, 2020).

6.2 Theoretical Contributions

This research advances theoretical understanding in two primary ways:

1. **Extension of Sensory Mismatch Theory to Olfactory Modulation**: Traditional Sensory Mismatch Theory posits that cybersickness arises from discrepancies between visual and vestibular cues (Hettinger and Riccio, 1992; LaViola, 2000). Our findings indicate that olfactory stimulation can serve as a third sensory modality to recalibrate sensory integration, thereby mitigating VIMS. Elevated RMSSD and reduced SSQ under peppermint suggest that olfactory inputs modulate autonomic responses to sensory conflict. This extension refines theoretical models by incorporating olfactory cues into the multisensory weighting process, suggesting that congruent, positive-valence smells can attenuate conflict-induced arousal (Narciso *et al.*, 2020; Ranasinghe *et al.*, 2020).
2. **Framework for Multiple-Scent Integration in VR**: By systematically comparing pleasant, neutral, and unpleasant odors in both single- and sequential-scent paradigms, this study proposes a conceptual framework wherein four factors mediate olfactory impact on VIMS: (a) Hedonic Valence, (b) Intensity, (c) Contextual Congruence, and (d) Temporal Sequencing. For example, pleasant scents (peppermint) enhance parasympathetic activity, thereby reducing VIMS, whereas unpleasant scents (toxic bomb) produce sympathetic overactivation, exacerbating VIMS. A neutral baseline (odorless carrier) maintains sensory equilibrium without modulation. Sequential transitions—e.g., Pleasant → Neutral → Unpleasant—require careful calibration to avoid abrupt affective shifts that could intensify VIMS. This framework integrates prior work (Patnaik et al., 2019; Ranasinghe et al., 2018a) by emphasizing rapid odor onset (< 150 ms), residual odor clearance (< 5 s), and synchronized release with VR events. The proposed model invites further research into additional sensory modalities (haptic, thermal) and their combined contributions to presence and comfort (Ranasinghe *et al.*, 2018).

6.3 Practical Contributions

The practical contributions of this study, address two broad domains:

1. **Blueprint for a Wearable Olfactory Device Compatible with Meta Quest 2**: The custom piezoelectric diffuser attachment design—comprising three scent channels, ESP32 control, and 3D-printed mounting—demonstrates a feasible, low-latency (< 150 ms) solution for integrating olfaction into commercial VR headsets. Technical specifications (e.g., 5 V USB power, < 650 g total weight, < 25 dBA noise) provide a

replicable template for VR accessory developers (Patnaik, Batch and Elmqvist, 2019b; Erkoyuncu and Khan, 2020). The reliability metrics—mean emission error < 12 percent and residual odor clearance < 5 s—offer concrete performance targets for future hardware iterations.

2. **Evidence-Based Recommendations for VR Content Creators**: Content designers are provided with empirically grounded guidelines:
    - **Select Pleasant, Familiar Scents** (e.g., peppermint, citrus) for environments where presence and comfort are paramount.
    - **Avoid Overly Intense Unpleasant Odors**, as they may aggravate VIMS in VR-naive users.

These recommendations are particularly salient for VR therapy, rehabilitation, and training applications where user comfort directly influences efficacy. By operationalizing olfactory integration protocols—calibrated intensities, rapid onset, and active purge—developers can mitigate cybersickness, thereby enhancing session duration and user engagement (Grassini et al., 2020; Martin et al., 2020).

6.4 Recommendations for Future Research

Building on the present findings, several avenues merit investigation:

1. **Longitudinal Studies on Scent Adaptation and Habituation**
    - The current study employed a **three-day** exposure design. However, **olfactory habituation**—the gradual decline in perceived intensity and hedonic response with repeated exposure—could attenuate pleasant-scent benefits over longer periods (Adams and Doucé, 2017). Future research should implement **multi-week** protocols to examine how repeated scent exposures impact SSQ, HRV, and EDA trends across sessions. Understanding habituation thresholds will inform **rotation schedules** for odor channels and potential **novel odor introductions** to sustain efficacy.
2. **Exploration of Additional Scent Categories (Floral, Herbal, Earthy)**
    - While lavender and toxic represent hedonic extremes (pleasant vs. unpleasant), a richer palette of odorants could elucidate the spectrum of olfactory impact on VIMS. Floral scents (e.g., lavender, jasmine) may confer calming effects, whereas herbal aromas (e.g., rosemary, eucalyptus) could modulate alertness differently (Narumi *et al.*, 2011; Adams and Doucé, 2017). Earthy odors (e.g.,

soil, moss) might evoke natural presence cues but may vary in hedonic valence cross-culturally. Systematic comparative studies can map odor properties (valence, arousal) to VIMS outcomes, refining the multisensory presence framework.

3. **Integration of Haptic and Thermal Stimuli Alongside Olfactory**
   - Season Traveller (Ranasinghe *et al.,* 2018) demonstrated the additive benefits of wind, thermal, and olfactory stimuli. Future research should explore tri- or quad- modality integrations—combining haptic (vibration, pressure), thermal (cold/warm puffs), and olfactory—to determine optimal combinations for VIMS reduction. For instance, a cool breeze synchronized with lavender may amplify parasympathetic activation, whereas warm air with toxic scent might intensify sympathetic arousal. Experimental manipulations of multisensory congruence can elucidate hierarchical contributions of each modality to presence and comfort.
4. **Individualized, Real-Time Adaptive Scent Control**
   - Our study revealed individual differences in perceptual thresholds and VIMS responses. Future research should develop closed-loop systems that monitor real-time physiological signals (e.g., HRV, EDA) to dynamically adjust scent intensity. Machine learning algorithms can be utilized to model individual autonomic response profiles and identify the thresholds at which scent modulation produces optimal physiological effects. Such adaptive frameworks would support personalized VR experiences, maximizing comfort and minimizing motion sickness.

6.5 Concluding Remarks

This investigation confirms that pleasant olfactory stimuli—specifically lavender—can reliably mitigate VR-induced cybersickness by subjective discomfort (SSQ, FMS). Conversely, unpleasant odors like toxic bomb smell may exacerbate VIMS, underscoring the critical role of hedonic valence and contextual congruence. The integrative framework proposed herein extends Sensory Mismatch Theory to encompass olfactory inputs, offering a roadmap for multisensory VR design. By refining scent selection, intensity calibration, and hardware integration, future VR systems can achieve superior presence and user comfort. As VR applications proliferate in training, therapy, and entertainment, these findings highlight the transformative potential of olfactory-enhanced immersion—paving the way for richer, more comfortable, and more engaging virtual experiences

APPENDICES

Appendix A: Chemical Oder Sensitivity Study Questionnaire

Odor Sensitivity Study

* Required

1. Student ID *

____

There are 11 statements and please rate them.

Statements

2. 1. When I enter into freshly painted rooms, I easily develop difficulty in breathing *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

3. 2. Sprays and drying paint give me a feeling of difficulty of breathing *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

4. 3. Small quantities of perfumes make me cough *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

5. 4. As soon as I smell perfume, I have difficulty in breathing *

Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

6. 5. I can not stay in a perfume filled room for a long period of time *

Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

7. 6. Strong smell of paint gives me a feeling of nausea *

Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

8. 7. Strong smell of paint and perfume makes me dizzy *

Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

9. 8. I am very sensitive to the smell of petrol at petrol stations *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

10. 9. I develop difficulty of breathing at the smell of detergents *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

11. 10. I can not tolerate certain perfumes *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

12. 11. Exhaust gases are very unpleasant to me *
Mark only one oval

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

Appendix B: Visually Induced Motion Sickness Study Questionnaire

Visually Induced Motion Sickness Study

* Required

1. Student ID *

____

A. Before experiment

2. 1. On a scale from 0-20, score your current level of motion/simulator sickness * (general discomfort, nausea, stomach awareness)

____

A. After experiment

3. 1. Please rate the intensity of the scent *

Mark only one oval.

- ⬭ None
- ⬭ Mild
- ⬭ Moderate
- ⬭ Strong
- ⬭ Very Strong

4. 2. How consistent was the intensity of the smell stimuli throughout the experience *

Mark only one oval per row.

	Very Inconsistent	Moderately Inconsistent	Slightly inconsistent	Indifferent	Slightly Consistent	Moderately Consistent	Very Consistent
Scale	⬭	⬭	⬭	⬭	⬭	⬭	⬭

5. 3. On a scale from 0-20, score your current level of motion/simulator sickness (general discomfort, nausea, stomach awareness)

____

6. 4. Select how much each symptom below is affecting you right now

Mark only one oval per row.

	None	Slight	Moderate	Severe
General Discomfort	◯	◯	◯	◯
Fatigue	◯	◯	◯	◯
Headache	◯	◯	◯	◯
Eyestrain	◯	◯	◯	◯
Difficulty focussing	◯	◯	◯	◯
Increased salivation	◯	◯	◯	◯
Sweating	◯	◯	◯	◯
Nausea	◯	◯	◯	◯
Difficulty concentrating	◯	◯	◯	◯
Fullness of the head	◯	◯	◯	◯
Blurred vision	◯	◯	◯	◯
Dizziness with eyes open	◯	◯	◯	◯
Vertigo	◯	◯	◯	◯
Stomach awareness	◯	◯	◯	◯
Burping	◯	◯	◯	◯

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