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Elevating Virtual Reality Experiences with Olfactory Integration: A Preliminary Review

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Abstract Virtual reality (VR) provides immersive audio-visual experiences but often overlook olfactory senses, which are crucial for human perception and cognition. Smell enhances object recognition, visual spatial attention, and evaluation methods for spatial attention deficits. The sense of smell relies on the olfactory nerve to create a direct link between external stimuli and the limbic system, a brain network involved in regulating emotions such as sadness, anger, joy, and fear, as well as controlling physiological responses like the startle reflex, vocal intonation, pain perception, and memory processes. Artificial intelligence (AI) is essential for integrating odors into VR, enhancing contextual understanding and synchronizing smells with plot developments. Current multi-modal approaches highlight the need for integrated models combining images, texts, and smells. Olfactory cues can enhance memory retention and recall, benefiting educational and training applications. Incorporating scents into immersive technologies creates more realistic and engaging experiences, crucial for fields like healthcare, military training, and education. In this preliminary review, we will explore Olfactory Virtual Reality (OVR) technologies, AI applications, available devices, and future perspectives in the field. Additionally, we will discuss the challenges facing this technology, including issues of delay, size, and the limited range of available odors. A new wearable interface featuring miniaturized odor generators (OGs) and AI algorithms enables rapid responses and low power consumption, achieving latency-free mixed reality. OVR research shows promising applications in treating Post-Traumatic Stress Disorder (PTSD), alleviating anxiety, and enhancing immersion. Recent advancements, such as compact OGs and computer-controlled olfactory stimulation, represent significant progress in multisensory communication technology.

Keywords: Virtual Reality, Artificial Intelligence, Olfactory, Brain–Computer Interface, Olfactory Virtual Realism

1 Introduction

Virtual reality (VR) headsets provide users with immersive audio-visual experiences. This oversight is particularly notable considering VR's broad applications in entertainment, marketing, business, medical treatment, and more realistic, state-of-the-art Virtual Reality/Augmented Reality (VR/AR) advancements [Smith and Mulligan 2021, Appel *et al*. 2021]. However, they often neglect to incorporate olfactory senses, which can offer additional insights into our real-world surroundings [Lyu *et al*. 2023a,b].

The olfactory sense is critical for humans, contributing significantly to the development of object cognition, spatial attention within VR, and thus evaluation methods for patients with spatial attention deficits [Dozio *et al*. 2021, Carrieri *et al*. 2022]. Furthermore, smell influences seasonal and atmospheric perception, as well as the gustatory experience. It significantly modulates behavioral patterns and serves as a pivotal mechanism for survival, facilitating the discernment of potential risks within both sustenance and environmental contexts [Flavián *et al*. 2021]. Mechanistically, our olfactory faculty relies upon the olfactory nerve to establish a direct conduit between external stimuli and the limbic system, a complex network of brain structures implicated in the regulation of affective states, including but not limited to sadness, anger, joy, and fear, alongside mediating physiological responses such as the startle reflex, modulation of vocal intonation, nociception, and mnemonic processes [Liu *et al*. 2023, Gao *et al*. 2021, Thomas-Danguin *et al*. 2014].

Current olfactory research and display development ad-

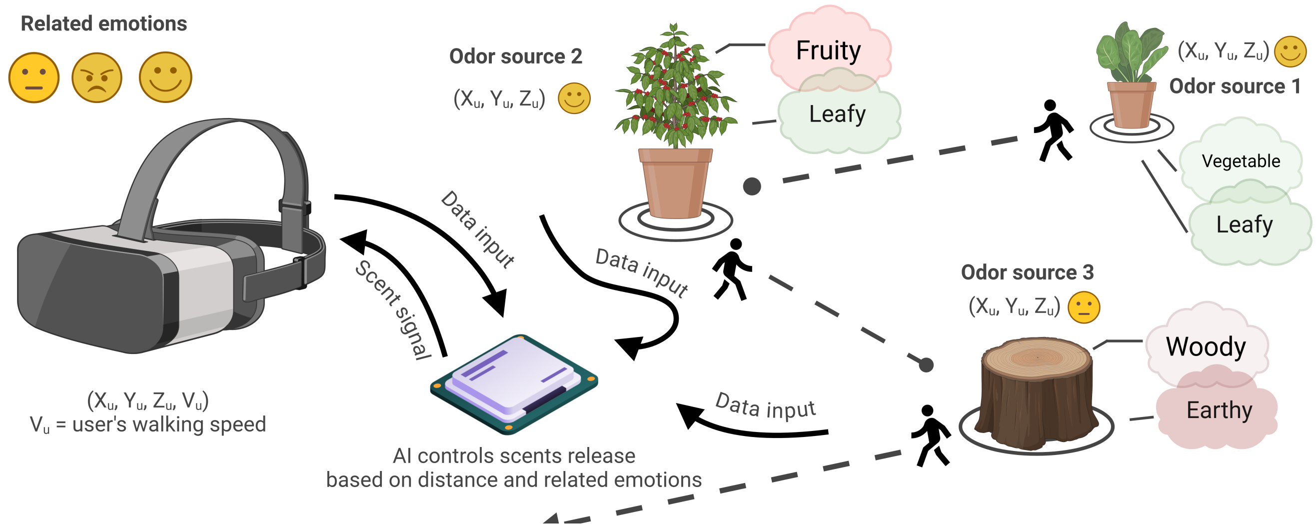

Figure 1. Operating Structure Framework of an OVR Device.

dress as Olfactory Virtual Reality (OVR) various challenges, emphasizing scent's communicative and emotional potentials, its role in multimedia, and therapeutic uses like Post-Traumatic Stress Disorder (PTSD) therapy and stress reduction [S Herz 2021, Kaye 2004]. Some studies focus on scent's ability to enhance the multimedia experience and presence, while others explore its application in training simulations [Patnaik *et al*. 2018, Maggioni *et al*. 2018]. Innovative approaches include miniaturized displays worn like piercings and systems that stimulate the olfactory bulb directly [Wang *et al*. 2020]. Despite these advancements, a key challenge remains in creating technology that enables precise, computer-controlled delivery and measurement of odors in an interactive manner, termed "enactive smelling" [Niedenthal *et al*. 2023].

The use of AI for odor delivery in films, videos and Virtual Environments (VE) is essential for several reasons. It enhances contextual understanding, allowing better synchronization of odors with plot developments [Persky and Dolwick 2020]. Current multi-modal approaches increase computational delay and power consumption, highlighting the need for integrated models that combine images, texts, and smells. Speech recognition and large language models can improve plot comprehension [Zhang *et al*. 2024]. More sophisticated delivery rules are needed to prevent olfactory fatigue and improve user experience. Exploring new odor delivery technologies can advance device design. AI not only aids but also guides future research in synchronizing odors with visuals [Seah *et al*. 2014, Sugimoto *et al*. 2010].

This preliminary review examines the current landscape of research in olfactory virtual reality (OVR) technologies, highlighting key trends, challenges, and future directions (**Figure 1**). Our analysis encompasses advancements in OVR systems, AI-driven applications, available devices, and emerging perspectives within this rapidly evolving field. Recognizing the limited scholarly attention and literature available at this time, our objective is not to produce a systematic review but rather to provide an initial overview that can inform and guide future research in this domain. Specifically, we aim to address the following research questions:

RQ1: How does olfactory perception enrich immersive experiences in VR and other contexts?

RQ2: What technological approaches are used to generate and control olfactory stimuli in OVR?

RQ3: What are the key design considerations for developing OVR devices that can accurately reproduce olfactory experiences?

RQ4: Which AI techniques are used to model and simulate olfactory experiences in immersive technologies?

RQ5: In what ways can the integration of olfactory perception into virtual reality enhance immersive experiences and therapeutic interventions?

This paper is organized as follows: Section 2 examines and discusses the research aimed at addressing the research questions, while Section 3 concludes the paper by highlighting the opportunities and open challenges in this field.

2 Research Questions and Findings

We will discuss the current methodologies utilized to evaluate the reliability of systems based on deep learning models, with a specific focus on OVR. This search was primarily conducted through Google Scholar, using the search terms 'Olfactory' AND 'Virtual Realism,' in combination with keywords like reliability, robustness, resilience, trustworthiness, assurance, verification, validation, assessment, and evaluation. This was supplemented by cross-referencing the citations and references of the identified studies. Due to the relatively limited but technically diverse body of literature in this specialized area, a systematic review was not conducted.

The initial search yielded 88 studies that focused on approaches for assessing the robustness of OVR technology and related areas. Additionally, relevant industry reports and websites were considered, including those from companies such as OVR Technology and OSMO, which employ AI-driven techniques for olfactory perception compression [Lee *et al*. 2023]. Upon closer analysis, several of these studies were found to lack relevance to the specific thematic focus of this preliminary review. Consequently, the scope was narrowed to 38 studies deemed most pertinent. The following subsections systematically address the research questions and synthesize the core findings.

2.1 RQ1: How does olfactory perception enrich immersive experiences in VR and other contexts?

Odor perception is a complex process involving the detection and interpretation of chemical molecules by the olfactory system. Odorants, responsible for smells, are generally volatile, hydrophobic, and have molecular weight below 400 Da, often with a polar functional group to allow interactions such as hydrogen bonding [Berger 2012, Laffort and Gortan 1987]. The human genome contains about 851 olfactory receptor (OR) loci, but only about 396 are functional due to mutations, resulting in genetic variations that cause differences in odor perception among individuals [Verbeurgt *et al*. 2014a]. ORs, located in olfactory sensory neurons (OSNs) [Verbeurgt *et al*. 2014b], activate signaling pathways when stimulated, allowing for the detection of a wide range of odors. The intensity of an odor is related to the number of odorant molecules and the OR response [Malnic *et al*. 1999].

The brain interprets signals from the OSNs and associates them with memories and experiences [Kuhlmann *et al*. 2014], classifying odors into various categories. The relationship between an odorant's chemical structure and its perceived smell is complex, with no clear rules, as structural variations can result in diverse or similar odor profiles [Sharma *et al*. 2021]. The prediction of how pleasant and intense an odor will be has made significant progress; however, this prediction is still not entirely accurate. To enhance these predictions, it is crucial to gather more information on how people perceive a wider variety of odor molecules. This will allow refinement of models and prediction methods, making them more precise and comprehensive [Keller and Vosshall 2016].

The term "umwelt" refers to the subjective experience of each organism with the environment, shaped by its specific sensory organs. In other words, how an organism perceives the world around it depends on the types of sensors and sensory organs it possesses. This highlights the diversity in how different species interact with the environment and how this interaction is crucial for their survival and adaptation [Zavatone-Veth *et al*. 2023]. Despite their significant influence on quality of life, the senses of smell and taste are often underestimated [Doty 2019]. Olfactory disorders are more common and impactful than those related to taste. Many patients who report "taste" problems are experiencing a decrease in olfactory function [Doty *et al*. 1988]. Although not routinely quantitatively assessed in clinical practice, many individuals seek medical help annually due to disorders related to these senses. These disorders not only impair the perception of food flavor and the ability to detect environmental hazards but may also be associated with neurodegenerative diseases like Alzheimer's, increasing the likelihood of mortality in the elderly [Doty 2019].

In a thorough examination of research on ambient scents and their influence on consumer behavior, Morrin and Ratneshwar (2000) conducted an initial study to explore how scent affects brand memory. Their findings suggested that

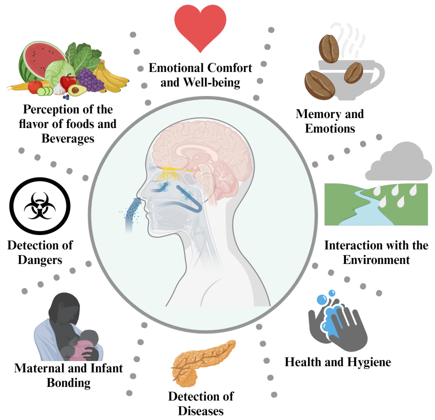

Figure 2. The elements collectively highlight the importance of the sense of smell in various aspects of life, from safety and health to emotional and social interactions.

pleasant ambient scents can capture attention toward brand-related stimuli, although their impact on brand recall was mild and they did not affect brand recognition significantly. Expanding on this investigation, Morrin and Ratneshwar (2003) delved deeper into the connection between ambient scents and brand memory through practical experiments [Morrin and Ratneshwar 2003]. The results revealed that ambient scents not only heightened brand attention but also bolstered brand memory, irrespective of their alignment with the product category. These discoveries hold substantial implications for marketers, indicating that the use of enjoyable ambient scents can effectively elevate brand awareness and recall within retail settings. Furthermore, this research contributes to the broader realm of consumer behavior by shedding light on how cognitive processes, like attention, mediate the influence of ambient scents on brand memory [Morrin and Ratneshwar 2003].

Olfactory perception plays a critical role in enhancing the immersivity of immersive technologies, such as VR and AR. Smell, a sense that allows us to perceive and differentiate numerous airborne environmental chemicals through the nose, is integral to many species' social behaviors, food location, danger detection like fire, predator identification, recognition of toxic compounds, mate selection, and mother-infant recognition [Zarzo 2007]. For humans, olfaction significantly influences well-being by seeking pleasantness and plays a crucial role in eating behavior, food quality perception, and social communication through fragrance (**Figure 2**). By incorporating scents into immersive technologies, developers can craft more realistic and engaging experiences, making users feel as if they are truly part of the environment, whether it's the aroma of fresh pine in a virtual forest or the scent of spices in a digital marketplace [Croy *et al*. 2014].

Furthermore, olfactory cues can significantly enhance memory retention and recall, which is beneficial for educational and training applications within immersive technologies [Dozio *et al*. 2021, Khamsi 2022]. Smell has been a vital part of human evolution and plays an essential role in our day-to-day lives. The ability to sense odors in the environment affects our daily decisions, enabling us to judge the edibility of items of food, avoid environmental hazards, and communicate with others [Stevenson 2010]. A smell or odor can induce strong feelings, alter behavior, and act as a stimulus to the retrieval of autobiographical memory. This capability is particularly valuable in simulations for fields like healthcare, military training, and education, where realistic scenarios can improve learning outcomes and preparedness [Kadohisa 2013]. Overall, integrating olfactory perception into immersive technologies not only enriches the sensory experience but also provides a more comprehensive and impactful way to engage users on multiple levels. Despite being underappreciated and often considered inferior to other human senses, the integration of smell can elevate the immersiveness and effectiveness of these technologies dramatically [Kadohisa 2013].

2.2 RQ2: What technological approaches are used to generate and control olfactory stimuli in OVR?

Scent-focused Extended reality (XR) must address several key areas to create an immersive experience. First, position tracking is crucial for triggering appropriate smells that align with the virtual storytelling, ensuring the system reacts accurately to the user's location in the digital environment [Satava *et al*. 1995]. Second, the production of odorants should involve mixing a finite set of chemicals to produce a wide range of smells, similar to how a printer mixes colors. Third, effective and non-obtrusive storage methods for various scents are essential, considering different potencies and saturations. Finally, the delivery method must account for habituation, where sensitivity to an odor decreases after continuous exposure, ensuring that smells are perceived accurately throughout the experience. These areas collectively enhance the effectiveness and immersion of scent-enhanced virtual experiences [Satava *et al*. 1995]. Scent-focused XR technologies originated in the late 1990s with Myron Krueger, who devised systems to incorporate "telesmell" into battlefield telemedicine. His team developed a headset for olfactory sensations and explored methods for storing and delivering odors [Satava *et al*. 1995, Barfield and Danas 1996]. This groundbreaking work established the basis for future olfactory VR research. Building on this foundation, Jas Brooks from the University of Chicago examined stimulating the trigeminal nerve to simulate temperature changes using odors. His device utilized scents like cayenne pepper and eucalyptol to create sensations of warmth and cold, demonstrating that olfactory stimuli combined with visual VR can evoke tactile responses, which is crucial for immersive experiences [Slater and Sanchez-Vives 2016, Zhu *et al*. 2021].

Despite not achieving commercial success, one of the first efforts to introduce scent was Heilig's (1962) Sensorama simulator. Heilig described it as: "The present invention, generally, relates to simulator apparatus, and more particularly, to apparatus to stimulate the senses of an individual to simulate an actual experience realistically" [Spence *et al*. 2017]. This machine provided users with 3D visuals, scents, stereo sound, wind, and vibrations. One of the few films specifically created for Sensorama depicted a motorcycle ride through Brooklyn. The sense of immersion was enhanced by blowing wind through the user's hair, presenting the city's sounds and smells, and simulating road bumps with a vibrating chair. Olfactory stimulation was also introduced in early cinema with Smell-o-vision, though it met with little success [Spence *et al*. 2017].

VR developers highlight the next step in VR as the integration of the senses, enriching its immersive capabilities [Gromer *et al*. 2018]. Olfactory technology is gaining traction because scent is the 'realest sense' and when combined with vision, produces a 'superadditive effect' [Stewart 2022, Elder and Krishna 2022, Morrin and Ratneshwar 2003]. Olfactory cues also enhance memory recall, aligning with VR and memory research. OVR Technology created a scent mask compatible with VR headsets, simulating hundreds of smells to make virtual environments more realistic. They emphasized the importance of scent in metaverse development. However, consumer responses to olfactory cues in VR, especially in retail contexts, remain unknown [Stewart 2022, Technology 2020].

Investigating olfactory cues' influence on brand responses in VR reveals complexities beyond prior retail research. Psychological mechanisms like scent pleasantness [Spangenberg *et al*. 2005] and ease of processing [Li *et al*. 2008] may not apply to VR, which elicits unique psychological processes such as immersion and flow [Pizzi *et al*. 2020], and demands higher cognitive effort [Cowan *et al*. 2021]. In VR, the realism and enhancement of immersion by scents may matter more than scent pleasantness. This research explores the additive effects of olfactory cues in VR, asking whether these cues improve brand responses (e.g., purchase intentions, online engagement), the psychological processes underlying this relationship, and how VR immersivity moderates these effects [Cowan *et al*. 2021].

This investigation contributes to theory and practice by integrating sensory marketing, immersion, and flow theory to show that olfactory stimuli (ambient or imagined) enhance brand responses. It introduces a novel process where olfactory stimuli in VR increase immersion, fostering a flow state that improves brand responses. Additionally, it reveals that high VR immersivity amplifies the positive impact of olfactory cues on brand responses. Lastly, it guides retailers on utilizing olfactory cues in VR to facilitate positive brand responses, offering a new perspective on the role of system immersivity in this context [Flavián *et al*. 2019].

Research on odor synthesis and detection has traditionally focused on generating chemical molecules for stationary or mobile emission, providing a non-invasive way for users to experience scents as in the real world. Examples include inScent, a wearable device by Dobbelstein et al. [Dobbelstein *et al*. 2017] that adds odors to mobile applications, and Yamada et al.'s wearable olfactory display [Yamada *et al*. 2006] that uses tubes to deliver scents based on the user's location. Other innovations like Bordegoni et al.'s necklace device for museum exhibitions [Bordegoni *et al*. 2019] and Platt's iSmell for associating odors with web content highlight the growing interest in integrating olfactory elements into various contexts [Honaman 2024]. Controlling the spatial and temporal distribution of odors presents another set of challenges. Hasegawa et al.'s Midair [Hasegawa *et al*. 2018] uses electronically steerable ultrasound-driven air flows to manage fragrance distribution, while Tominaga et al.'s "Friend Park" virtual space system [Tominaga *et al.* 2002] provides olfactory experiences tied to specific rooms and objects. Desktop-based displays, such as those by Herrera and McMahan [Herrera and McMahan 2014], and handheld devices like Niedenthal et al.'s olfactory display for the HTC Vive VR system [Niedenthal *et al.* 2023], demonstrate efforts to deliver targeted olfactory stimuli. However, these solutions often face limitations in mobility and comfort, as seen in Micaroni et al.'s bulky headset-mounted display [Micaroni *et al.* 2019].

The human sense of smell is powerful, but its use in human-computer interaction (HCI) is limited. Maggioni and colleagues mapped out an olfactory design space to guide designers' choices when using scents. They identified four key design features: (i) chemical, (ii) emotional, (iii) spatial, and (iv) temporal [Maggioni *et al.* 2020]. Each feature defines a building block for smell-based interaction design, grounded in a review of the relevant scientific literature. The study demonstrates design opportunities in three application cases (one desktop and two virtual reality implementations), highlighting design choices and implementation and evaluation possibilities in using scents. The conclusion discusses how identifying these design features facilitates the healthy growth of this research domain and contributes to an intermediate-level knowledge space, as well as the further challenges the HCI community needs to tackle [Maggioni *et al.* 2020].

Incorporating odors into VR environments can significantly enhance user presence and experience.Baus and Bouchard [2017] found that unpleasant odors strengthen the sense of presence, while Ranasinghe *et al.* [2018] demonstrated the feasibility and effectiveness of integrating thermal, wind, and olfactory stimuli into VR glasses. Covaci et al. [Covaci *et al.* 2019], along with Guedes and Narciso [Narciso *et al.* 2020], showed that olfactory stimuli contribute to user presence in 360° videos. Despite the promising potential of non-chemical implementations, such as stimulating olfactory receptors with electrical pulses, these approaches are currently complex, costly, and invasive [Hariri *et al.* 2016].

2.3 RQ3: What are the key design considerations for developing OVR devices that can accurately reproduce olfactory experiences?

Several olfactory interfaces were developed to enhance user experiences by adding scent-based feedback to visual and auditory cues, leading to more immersive and realistic interactions. One notable application is the development of a soft, miniaturized, wireless olfactory interface for VR [Liu *et al.* 2023], which utilizes a skin-interfaced olfactory feedback systems with wirelessly programmable capabilities. These systems use arrays of flexible and miniaturized odor generators (OGs) to enhance olfactory VR experiences. By adjusting OG heating temperatures, they achieve recognition rates for various smells, demonstrating the potential of this technology. This technology enhances the realism of 4D movie watching, enables smell message delivery, supports medical treatments, and aids in emotion control. Various studies have examined the utilization of olfaction within VR environments [Liu *et al.* 2023].

Nakamoto and Yoshikawa investigated several scents synchronized with scenes from a brief animated film, finding that transitions between contrasting smells were particularly impactful [Nakamoto and Yoshikawa 2006]. Conversely, Jones and colleagues explored the potential of scent-enhanced VR for military training yet observed that additional odors did not significantly enhance participants' immersion during combat gameplay [Jones Moore *et al.* 2004]. Munyan and colleagues evaluated the combination of olfactory stimuli in anxiety-inducing scenarios for exposure therapy, revealing an augmented sense of presence among participants but no measurable increase in anxiety levels [Munyan *et al.* 2016]. Ischer and colleagues developed a 3D immersive environment with precise control over odor dissemination, although the impact of odor on the VR experience was not assessed [Ischer *et al.* 2014].

Additionally, Baus and Bouchard investigated the effects of pleasant and unpleasant scents on participants' sense of presence in a VR setting [Baus and Bouchard 2017]. They found that while exposure to scents unrelated to the virtual environment increased the sense of presence, participants exposed to an unpleasant smell reported a heightened sense of presence compared to those exposed to a pleasant scent, suggesting potential nuances in odor perception and its impact on immersive experiences [Baus and Bouchard 2017]. Another significant application is in the treatment of PTSD and drug addiction [Baus and Bouchard 2010], where VR environments integrated with specific smells are used for therapeutic purposes. Scent exposure therapy, for example, gradually exposes individuals to triggering smells in a controlled setting, helping them manage their conditions. In education and training, olfactory VR simulates various scenarios such as emergency response training, relaxation exercises, and pain distraction, creating more immersive learning experiences by combining smell with visual and auditory cues. Furthermore, olfaction contributes to multi-sensory integration, where the combination of different sensory inputs enhances overall perception.

The OVR Technology Group has been a pioneer in olfactory virtual reality research, focusing on creating practical solutions that enhance user experiences by integrating scent stimuli into VR environments[de Paiva Guimarães *et al.* 2022]. They have developed wearable olfactory displays that seamlessly integrate with virtual reality headset glasses, emitting specific scents based on the virtual content. This allows users to smell corresponding fragrances as they interact with the digital world, providing a more immersive experience. What sets their solution apart is its non-intrusiveness, mobility, and affordability, enabling developers to easily incorporate smell into their VR applications without cumbersome setups or expensive hardware [de Paiva Guimarães *et al.* 2022]. Similarly, the research by Hasegawa et al. [Hasegawa *et al.* 2018] explores an innovative olfactory display called Midair, which controls the spatial distribution of fragrances using electronically steerable ultrasound-driven narrow air flows. By precisely directing these air flows, Midair delivers scents to specific locations within a virtual environment. For instance, if a user interacts with a virtual flower, the system can emit the corresponding floral fragrance. The goal is to enhance immersion by adding scent to the visual and auditory cues in VR [Hasegawa *et al*. 2018].

The integration of olfactory interfaces into VR aims to enhance user experiences by adding scent-based feedback to visual and auditory cues, creating more immersive interactions. However, this technology faces several challenges and limitations. A key issue is the limited range of scents that can be produced, restricting the variety of experiences [Nakamoto and Yoshikawa 2006, Munyan *et al*. 2016, Ischer *et al*. 2014]. Additionally, latency in scent delivery can disrupt synchronization with other stimuli, reducing immersion. User sensitivity to smells varies, with some individuals finding certain scents overwhelming, leading to potential discomfort. Maintenance and refilling of odor generators are cumbersome and costly, posing barriers to widespread adoption [Cowan *et al*. 2023].

Environmental factors, such as air flow and ambient odors, can also affect scent dispersion and perception. Health concerns arise from prolonged exposure to artificial scents, with potential allergies or sensitivities posing risks. Integrating olfactory feedback into VR adds complexity to both hardware and software, increasing development challenges and costs [Tewell and Ranasinghe 2024]. This high cost can limit accessibility and widespread use. Users may also need time to adapt to the new sensory input, requiring a learning curve to interpret olfactory cues within a virtual environment. In conclusion, while olfactory interfaces show great promise for enhancing VR experiences, they must overcome significant challenges related to scent variety, synchronization, user sensitivity, maintenance, environmental factors, health concerns, technical complexity, cost, and user adaptation. Addressing these issues is crucial for the future development and widespread adoption of this innovative technology Cowan *et al*. [2023], Tewell and Ranasinghe [2024].

The study by Yiming, Liu and Collaborators [Liu *et al*. 2024, 2023] addresses key challenges in existing olfactory feedback technologies, such as delays, bulkiness, and limited odor supply. The researchers developed a wearable interface using miniaturized odor generators combined with AI algorithms, achieving millisecond response times, low power consumption, and compact size. This innovation enables seamless, real-time scent experiences in VR and mixed reality (MR), enhancing immersion and realism. The study highlights the critical role of olfaction in human interaction and opens new possibilities for olfactory VR and MR applications in entertainment, education, and medical treatment. But some challanges remain, the miniaturized odor generators (OGs) used in the interface may limit scent variety, restricting the diversity of olfactory experiences. Despite achieving millisecond-level response time, there might still be perceptible delays in odor manipulation, affecting synchronization with other sensory cues and reducing immersion [Liu *et al*. 2023]. Individual sensitivity to smells varies, and some users may find certain scents overwhelming, with potential health concerns arising from prolonged exposure to artificial scents. Maintenance and refilling of OGs pose cumbersome upkeep and associated costs that could hinder widespread adoption. Environmental factors like airflow and ambient odors may impact scent dispersion and perception, affecting the interface's effectiveness based on the user's surroundings. Integrating olfactory feedback into VR adds complexity to both hardware and software, with high development costs potentially limiting accessibility. Users also need time to adapt to this new sensory input, and interpreting olfactory cues within a virtual environment may require a learning curve [Liu *et al*. 2024].

2.4 RQ4: Which AI techniques are used to model and simulate olfactory experiences in immersive technologies?

Developing predictive artificial intelligence models based on quantitative structure-odor relationships (QSOR) in the olfactory sensory scope is highly complex due to the intricate biological response involved. Odors, composed of multiple odorants, can produce a wide range of olfactory responses, leading to diverse perceptions. Additionally, many olfactory receptors lack known ligands responsible for the odorant response [Gupta *et al*. 2021, Saini and Ramanathan 2022]. The non-linear relationship between the chemical structure and odor perception adds further complexity to creating accurate predictive models. Despite the difficulties involved, some studies have endeavored to establish links between odorant chemicals and the perceptions they evoke in the olfactory system [Sharma *et al*. 2022]. To address the challenge of predicting whether a molecule has a perceived odor and what olfactory perception it will produce, the crowdsourced DREAM Olfaction Prediction Challenge was organized [Keller *et al*. 2017]. They used a large olfactory physiological data set to develop machine learning models that accurately predicted sensory attributes such as odor intensity, pleasantness, and eight specific semantic descriptors, achieving high predictive accuracy and enabling the reverse-engineering of a molecule's smell [Keller *et al*. 2017].

Achebouche and colleagues [Achebouche *et al*. 2022] employed Convolutional Neural Network (CNN) and Graphical Convolutional Network (GCN) models to analyze the relationship between odorant molecules – odor perception and odorant molecules-olfactory receptors. Kowalewsky and Ray developed machine learning models to predict ligands for 34 human Olfactory receptors (OR) and used these models to assess how OR activity could predict perceptual descriptors. The researchers focused on chemicals previously evaluated by human volunteers and identified ORs that best predicted perceptual descriptors from a subset of training chemicals [Kowalewski and Ray 2020]. Lee and coworkers [Lee *et al*. 2023] employed graph neural networks (GNNs) to develop a Principal Odor Map (POM) that preserves perceptual relationships and predicts the odor quality of new odorants. The model's accuracy in describing odor quality was comparable to that of human evaluators: for a validation set of 400 novel odorants, the model-generated odor profiles were more closely aligned with the average ratings of a trained panel (n=15) than those of the median panelist [Lee *et al*. 2023]. Snitz and colleagues Snitz *et al*. [2013] developed a model that predicts the perceptual similarity of odorant mixtures based on their molecular structure.

By representing mixtures as single structural vectors, the model accurately forecasts how similar two novel odorant mixtures will smell, suggesting a synthetic processing approach in the brain [Snitz *et al*. 2013]. Ravia el at. collected [Ravia *et al*. 2020] perceptual similarity estimates of 49,788 odorant pairs from 199 participants who smelled 242 different multicomponent odorants. Using this data, they refined a predictive model combining 21 physicochemical features into a single number, expressed in radians, to accurately predict perceptual similarity and create olfactory metamers—odorants with different molecular compositions that produce identical smells [Ravia *et al*. 2020].

Digital scent technology uses electrochemical sensors and machine learning for scent recognition (Internet-of-Smell), and employs chemical or electrical stimulation for scent synthesis. Digital noses, electronic devices that detect odors, are used in quality control and environmental monitoring. In the food and perfume industries, they ensure product quality by detecting off-flavors and evaluating aroma intensity and longevity [Sehad *et al*. 2024]. Olfactory interfaces enhance emotional and cognitive functions, productivity, and relaxation in virtual environments, influencing 75% of our daily emotions. In VR, this technology enhances realism in training, culinary experiences, tourism simulations, and therapeutic applications through controlled emission and dispersion of scents using odor-releasing devices, cartridges, or embedded scent generators within VR headsets, triggered by visual or audio cues [Sehad *et al*. 2024, Panagiotakopoulos *et al*. 2022].

Digital noses ensure food product quality and assess perfume aroma. Olfactory interfaces enhance emotional and cognitive functions, productivity, and relaxation, particularly in VR, where they increase realism, enrich culinary experiences, create authentic atmospheres, and support therapeutic applications. This technology involves controlled scent emission through devices like odor-releasing gadgets or embedded generators in VR headsets, triggered by visual or audio cues to enhance sensory experiences [Panagiotakopoulos *et al*. 2022].

Developed by L'Oréal's technology incubator in collaboration with Yves Saint Laurent and the neurotechnology company Emotiv, a new retail consultation experience links neuro-responses to fragrance preferences using a multi-sensor electroencephalogram -based (EEG) headset [Johnston 2022]. This headset uses machine learning algorithms to interpret EEG data, measuring consumer reactions to proprietary scents. This technology allows for the sensing and monitoring of behavioral states, stress, preferences, and attention in various environments and contexts [Johnston 2022].

Furthermore, AI-driven scent technology holds substantial promise for the food industry, particularly in the strategic marketing of products. AI systems can deliver tailored nutrition advice and develop food designs with unique attributes, such as customized scents, to more effectively sway consumers' dietary decisions or address specific preferences [Honaman 2024]. A range of industries can leverage AI-enhanced digital olfaction to create unforgettable product experiences, enriching marketing efforts by integrating scents that evoke particular emotions, enhance brand recognition, or stimulate memory recall. This frequently subconscious technique paves the way for the concept of interactive, immersive scent experiences [the guardian 2022].

Herris and colleagues explores the potential of VR to influence eating behaviors through immersive food stimuli. The first part assessed whether VR could elicit food cravings, finding that VR environments significantly increased salivation, food craving states, and the urge to eat, comparable to real food stimuli. The second part investigated the impact of adding olfactory and interaction cues in VR, revealing that these enhancements further heightened food cravings. These findings suggest that VR can effectively simulate eating experiences and trigger real cravings, highlighting the need for further research into VR's applications in food-related therapy and behavior modification [Harris *et al*. 2023].

Olfaction feedback systems have the potential to influence human emotion, boost alertness, provide clinical therapy, and create immersive virtual environments. However, current technologies face significant challenges, such as noticeable delays in odor manipulation, large device sizes, and limited odor options.To address these issues, a wearable, high-performance olfactory interface is utilized, incorporating miniaturized odor generators (OGs) and advanced AI algorithms [Liu *et al*. 2023]. These OGs offer significant advancements in response time, power efficiency, and compact size. Powered by robust AI, this olfactory interface promises latency-free mixed reality experiences and rapid scent enhancement, with applications in entertainment, education, medical treatment, and human-machine interfaces [Liu *et al*. 2023].

2.5 RQ5: In what ways can the integration of olfactory perception into virtual reality enhance immersive experiences and therapeutic interventions?

OVR is an emerging area of research that aims to integrate the sense of smell into virtual reality (VR) environments, significantly expanding users' sensory experience [de Paiva Guimarães *et al*. 2022]. Several studies have explored the potential of OVR in various applications, from treating mental health conditions to enhancing immersion in virtual environments. One of the highlighted studies is by Herz, which discusses how OVR can be used in the treatment and prevention of PTSD [S Herz 2021].Herz suggests innovative ways to implement OVR in PTSD therapy, aiming to trigger effective therapeutic responses and prevent the development of the disorder [S Herz 2021].

Furthermore, studies demonstrate the effectiveness of OVR in relieving anxiety, pain, and stress, providing evidence that stimulating the olfactory system in virtual environments can enhance the therapeutic benefits of interventions [Tomasi 2020]. Other research investigates the integration of vision and olfaction in innovative virtual reality systems, exploring the functionality of the sense of smell and its interaction with other sensory stimuli (**Figure 3**). These studies underscore the potential of OVR in various applications, from treating mental health conditions to creating more engaging immersive experiences in virtual environments. Integrating smell into virtual reality environments can provide a more

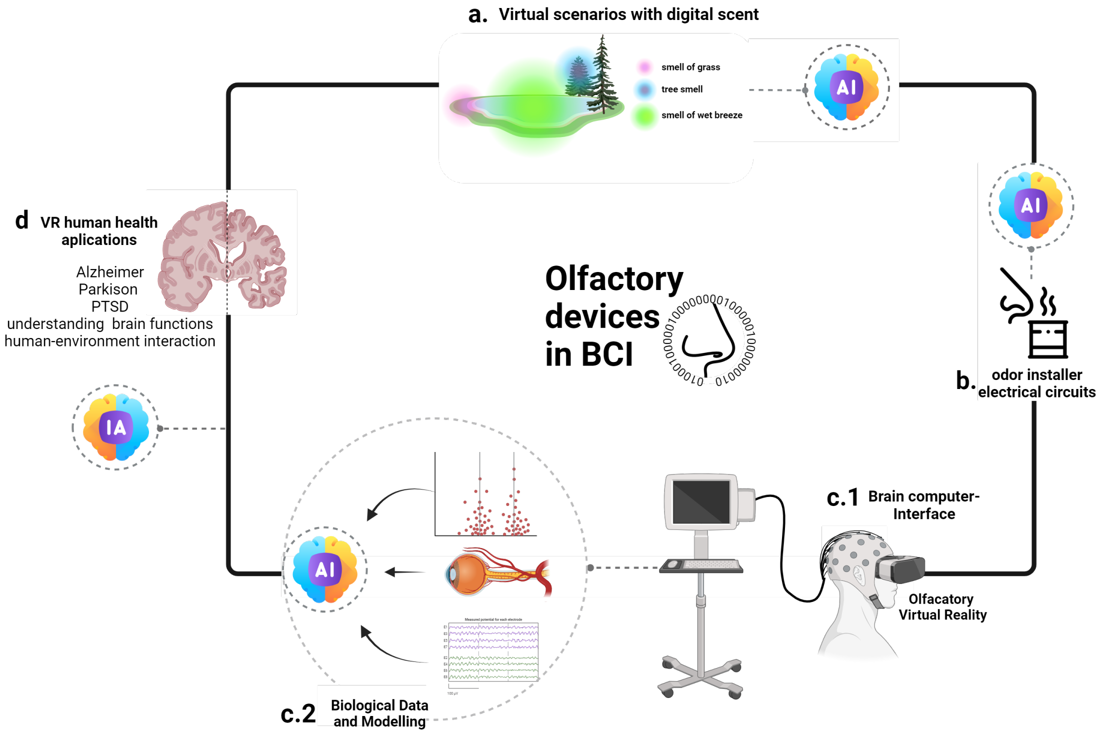

Figure 3. Workflow for the description of devices using OVR in medical studies for dementia, anxiety, and PTSD.

complete and impactful sensory experience, opening up new possibilities for research and development in this promising field [Tomasi 2020].

The integration of braincomputer interfaces (BCI) and VR technologies has emerged as a promising frontier in the field of neurological rehabilitation. This interdisciplinary approach leverages the strengths of both technologies, providing a platform for patients with severe motor dysfunctions to interact with the world and promoting brain function recovery through immersive environments [Bockbrader *et al.* 2018, Barry 2018]. This synergy has the potential to amplify cognitive participation and neuroplasticity, ultimately accelerating the recovery of motor and cognitive skills in neurological patients [Wen *et al.* 2021]. Although in its early stages, BCI-VR integration holds promise for personalized treatment and broader applicability, necessitating further research to refine algorithms, optimize VR technology, and expand the treatable neurological conditions [Wen *et al.* 2021]. Despite the potential, there are significant challenges that need to be addressed, including real-time capability, performance variability, and user experience. Furthermore, the application of BCI-VR systems in various neurological conditions such as stroke, spinal cord injury, Attention deficit hyperactivity disorder (ADHD), Alzheimer's, and Parkinson's disease has shown promising results, but further research is needed to fully understand the implications and optimize the systems [Barry 2018, Wen *et al.* 2021]. The future of BCI-VR in clinical treatment is promising, and its significance in neurological rehabilitation cannot be overstated [Wen *et al.* 2021, Bockbrader *et al.* 2018].

Improving contextual understanding involves ensuring that odor delivery in virtual environments aligns with the narrative progression of films, enhancing synchronization with visual cues. Current multi-modal systems suffer from delays and computational inefficiencies, requiring refinement to integrate images, text, and smells seamlessly [Zhang *et al.* 2024]. Speech recognition technologies can enhance comprehension of dialogue-based plot developments, boosting accuracy in context recognition. However, current odor delivery strategies, while aiming for visual alignment, may lead to user fatigue, necessitating more nuanced rules. Exploring diverse odor delivery technologies can inform the development of more effective and user-friendly devices for immersive experiences [Zhang *et al.* 2024].

A recent paper by Liu and colleagues introduces an "olfactory generator" (OG) that measures approximately 1.5 centimeters across and produces a single scent by boiling a scented liquid with a small heating element [Liu *et al.* 2023]. The compact size of each OG distinguishes this method from previous attempts at smellovision, which struggled with piping scents from large external devices into VR headsets. This is a significant challenge for VR experiences that allow users to move freely. The study presents mask designs with two or nine OGs, each operating wirelessly. However, a drawback is that low-volatile odor compounds could release scents continuously for only 91 minutes, necessitating frequent replacements. Despite this, eliminating cumbersome wires and tubes represents a notable advancement, bringing us closer to experiencing scents in virtual environments. One of the major challenges remaining is the miniaturization of these devices [Liu *et al.* 2024].

The exclusive reliance on chemical data for olfactory stimulation is not invariably the singular recourse. There are shared patterns, particularly evident in the context of direct trigeminal nerve stimulation, known as trigeminal scents [Hariri *et al*. 2016]. Furthermore, the direct electrical stimulation of receptors has significantly contributed to advancements in auditory and visual studies, with potential implications for enhanced sensory prostheses. These stimuli elicit a spectrum of responses across diverse cultural milieus, encompassing both adverse and favorable perceptions. While some individuals may perceive such scents as disagreeable and discomforting, others construe them as invigorating or rejuvenating [Licon *et al*. 2018, Fournel *et al*. 2016].

Karunanayaka and colleagues have developed a computer-controlled smell reproduction technology that uses weak electric pulses to stimulate human olfactory receptors. Their prototype generates rectangular-shaped electrical pulses with varying frequencies, duty cycles, and currents, and was tested on 31 healthy participants[Karunanayaka *et al*. 2023]. Notably, eight participants reported chemical and fragrant smells at 1 mA with 70 Hz, and sweet smells at 1 mA with 10 Hz. This research marks the first development of a digital device for olfactory stimulation, recording the intensities of 22 sensations, and exploring user perceptions of its utility [Karunanayaka *et al*. 2023]. Hariri and colleagues propose a digital interface for actuating smell sensations by stimulating olfactory receptors with weak electrical pulses. This method addresses the complexity, expense, and lower controllability of traditional chemical-based smell activation. Their study aims to evaluate the sensitivity and effectiveness of electrical stimulation on human smell receptors using various current and frequency parameters with real users, advancing the field of multisensory communication technology [Hariri *et al*. 2016].

Immersive all-sense communication aims to integrate all human senses, including touch, taste, scent, and BCI, along with sight and sound, to create an experience indistinguishable from reality. This concept, known as the Internet of Senses (IoS), facilitates telepresence-style communication by digitally streaming sensory information. The IoS encompasses various domains: Internet of Touch, Taste, Smell, Sound, Sight, and BCI. Generative AI and large language models (LLMs) play a crucial role in synchronizing and generating multiple media for semantic communication. Haptic interfaces enhance touch sensation through devices like gloves and exoskeletons, while gustatory interfaces aim to replicate taste, though this is still in early stages [Panagiotakopoulos *et al*. 2022]. Digital scent technology involves recognizing and generating scents using electrochemical sensors and machine learning, enhancing virtual experiences in industries like food, perfume, and VR training. XR devices create immersive visual experiences, and spatial audio simulates sound perception in a three-dimensional space. BCIs enable direct communication between the brain and machines, essential for executing actions based on multisensory perception [Sehad *et al*. 2024].

In the Internet of Touch, haptic interfaces replicate physical sensations, crucial for applications like surgical training in VR, requiring low-latency synchronization with other media. Gustatory interfaces focus on controlled taste stimulation, although replicating taste is complex due to its dependency on other senses. Digital scent technology, using digital noses and olfactory interfaces, enhances sensory engagement and realism in various applications, including quality control, therapy, and virtual tourism [Floyd Mueller *et al*. 2021, Ranasinghe *et al*. 2012]. Internet-of-Sight uses XR devices for immersive video experiences, while spatial audio enhances auditory immersion by positioning sounds in a three-dimensional space [Floyd Mueller *et al*. 2021, Ranasinghe *et al*. 2012]. BCIs translate neural activity into machine-readable signals, facilitating direct control and communication in the IoS framework, either through human brains or multimodal AI. These advancements aim to create a comprehensive, immersive sensory experience, bridging the gap between physical and virtual realities [Sehad *et al*. 2024].

3 Future Directions and Perspectives

The future of virtual and multisensory olfactory realism promises to profoundly transform how we interact with virtual and augmented environments. Recent research indicates that integrating olfactory signals into immersive experiences can significantly enhance users' sense of presence and engagement. With continuous advancements in olfactory sensors and deep learning algorithms, it will be possible to capture and reproduce a wide range of odors with high precision [Panagiotakopoulos *et al*. 2022, Holloman and Crawford 2022]. Moreover, recent studies highlight the potential of devices such as electronic noses to accurately identify chemical compounds, even at very low concentrations, paving the way for more sophisticated and realistic applications in virtual reality [de Paiva Guimarães *et al*. 2022, Zhang *et al*. 2024]. With ongoing advancements in olfactory sensor technology and AI algorithms, the ability to capture, reproduce, and integrate scents into VR/AR experiences will become increasingly sophisticated, opening up new possibilities for enhancing user engagement and creating more immersive, realistic virtual experiences [de Paiva Guimarães *et al*. 2022].

AI algorithms play a critical role in processing and interpreting the complex data generated by olfactory sensors. These algorithms can learn to recognize patterns in the chemical composition of different scents, enabling the accurate identification and reproduction of odors. As machine learning and deep learning techniques continue to evolve, they will further enhance the capability of olfactory systems to provide realistic and nuanced scent experiences [Zhang *et al*. 2024].

The prospects for integrated multisensory technologies are promising. Combining olfactory signals with visual, auditory, and tactile stimuli can create experiences virtually indistinguishable from reality. Personalizing these experiences based on individual preferences and responses will be a crucial differentiator, potentially driven by adaptive AI that adjusts sensory profiles in real-time [Lyu *et al*. 2023a]. Moreover, collaboration between researchers and hardware developers is leading to the development of more compact and efficient odor emission devices, which can be easily integrated into virtual and augmented reality systems [Technology 2020, Liu *et al*. 2023].

However, as these technologies advance, challenges such as scalability, robustness, miniaturization, and individual performance remain critical areas for development. Research initiatives focused on understanding individual complexity and developing devices that can adapt to each user's nuances have progressed with the use of AI tools [Liu *et al*. 2024]. Despite these advancements, a key challenge remains in developing technology that enables precise, computer-controlled delivery and measurement of odors in an interactive manner, known as "enactive smelling" [Niedenthal *et al*. 2019]. With growing collaboration among scientists, engineers, and regulators, the future of immersive olfactory technologies appears not only promising but also responsible, safe, and personalized [de Paiva Guimarães *et al*. 2022].

We have identified several unresolved challenges within the analyzed works:

- **Latency in Scent Delivery:** The delay in synchronizing olfactory stimuli with visual and auditory cues can disrupt the immersive experience. Addressing latency issues is crucial for enhancing the realism of VR environments.
- **Technical Complexity and Cost:** Integrating olfactory feedback into VR systems increases both hardware and software complexity, leading to higher development costs. Finding ways to reduce complexity and cost is vital for broader adoption.
- **Limited Range of Scents:** Current technologies often struggle with a limited variety of odors that can be accurately reproduced. Expanding the range of scents is essential for creating more diverse and engaging virtual experiences.
- **Miniaturized and Flexible Substrate Integration:** One of the primary challenges is that the entire system should be constructed on a soft substrate, in a wearable or even skin-integrated format, featuring a miniaturized size and lightweight design.
- **Integration and Usability:** Olfactory feedback systems are challenging to integrate into wearable or skin-integrated devices in a practical and usable manner. Despite advancements like bionic fibrous membranes, these systems still face issues with response time and usability, limiting their application in VR.

In conclusion, the future of immersive olfactory technologies holds great promise, significantly enhancing our engagement with virtual and augmented environments. Overcoming the challenges outlined in this review is essential to unlocking this potential. As AI tools evolve, the creation of personalized and adaptive olfactory systems will become increasingly attainable, providing users with more immersive and tailored experiences. By prioritizing safety, responsibility, and innovation, the incorporation of olfactory realism into digital environments promises to transform our perception and interaction within the virtual field.

Declarations

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Authors' Contributions

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Competing interests

The authors declare that they have none competing interests.

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