Mid-Air Gestures for Proactive Olfactory Interactions in Virtual Reality

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Figure 1: We explored proactive gestural interactions in virtual reality, where users can actively control or interact with scented objects. As shown in the figure, a participant, curious about the scent of a flower, proactively performs a *swipe inward* gesture to (A) release its fragrance. Similarly, she can (B) move the odor from the flower to her virtual clothing with a *pointing* gesture, and (C) obtain the direction of a scent coming from a puppy hiding under a desk by *drawing a circle with her index finger*.

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Abstract

Olfactory experiences are increasingly in demand due to their immersive benefits. However, most interaction implementations are passive and rely on conventions established for other modalities. In this work, we investigated proactive olfactory interactions, where users actively engage with scents, focusing on mid-air gestures as an input modality miming real-world object- and scent-manipulation, e.g., fanning away an odor. Our study had participants develop a user-defined gesture set for interacting with scents in Virtual Reality (VR), covering various object types (solid, liquid, gas) and interaction modes (out-of-reach, not graspable, graspable), participants compared interacting with scents in VR using traditional controllers versus proactive gestures, revealing that proactive gestures enhanced user experience, presence, and task performance. Finally, an exploratory study showed strong participants' preferences for personalization, enhanced interaction capabilities, and multi-sensory integration. Based on these findings, we propose design guidelines and applications for proactive interactions with scents.

CCS Concepts

• **Human-centered computing** → **Virtual reality**; **Gestural input**; **User studies**.

Keywords

Olfactory interactions, Proactive olfactory experiences, Mid-air gestures, User-defined gestures, Virtual reality

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1 Introduction

Olfactory experiences have emerged as a significant element in enhancing immersion and user engagement in Virtual Reality (VR). The incorporation of scent into VR has been shown to elicit heightened emotional responses [2, 66], influence behaviour [18], and enhance spatial perception [9, 57], thereby contributing to a more lifelike and immersive experience. However, the majority of these implementations treat olfaction as a passive sensory experience, where users receive pre-defined scents without having the ability to control or interact with them actively. This passive approach limits the depth of user engagement and diminishes the potential of olfaction as a core element of multisensory interaction in VR, as called "grand challenges" of multisensory design [53].

While some research has explored the potential of proactive olfactory interaction in VR, most existing systems still rely on traditional input methods such as simple grasp-and-sniff interactions [50, 76]. These approaches fall short of allowing users to fully engage with the scent that mirrors how they experience it daily.

To bridge this gap, we explore user preferences of mid-air gestures as an input modality for proactive olfactory interaction in VR. Mid-air gestures present a compelling solution, as they closely mimic how users naturally manipulate objects in the physical world, thus exploiting users' knowledge and experience [64, 81]. By leveraging user-defined gestures, we aim to facilitate more intuitive scent control of objects in VR, adapting seamlessly to the state of the objects and undiscovered interaction context.

This paper presents three user studies to understand the design and application of mid-air gestures for proactive olfactory interaction in VR. The main contributions of this work are as follows: (1) We first conduct a formative study to understand olfactory interactions and scented sources in the real world. We summarize ten olfactory interaction tasks and categorize scented sources based on their physical states (solid, liquid, and gas) and interaction modes (graspable, not graspable, and out of reach). We propose a taxonomy of mid-air gestures from these categories and derive a user-defined gesture set for olfactory interaction. (2) We validate this gesture set through a comparative study with traditional VR controller-based interaction techniques, assessing their usability and performance in proactive olfactory interactions. (3) Through an exploratory study, we investigate user preferences for personalization, extended interaction capabilities, and multisensory integration, offering insights into how users would engage with scented objects in VR. Our findings provide design implications for creating more natural, user-centered multisensory applications with spatial interactions in virtual environments.

2 Related Work

2.1 Smell-Enhanced Experiences & Proactive Olfactory Interactions in VR

Olfactory cues play a vital role in a wide range of applications, from enhancing immersive experiences in gaming [44, 59] and virtual tourism [52, 63] to evoking emotions and training [31, 51] and educational contexts [62]. Within virtual environments, the incorporation of scent significantly impacts multisensory perception, influencing emotional engagement [39], memory recall [19], and decision-making [28]. Most existing olfactory VR systems provide passive experiences, focusing on enhancing the realism of the environment rather than fostering active user engagement. For synchronizing proactive olfactory interactions in virtual environments, Tewell et al. [65] mentioned "Scent synchronization", coordinates the delivery of scents synchronized with the events and actions in the virtual environment. Simon et al. [50] created a scent device that is graspable by the user and affords to grasp and to sniff gestures of objects in virtual space and proposed "enactive smelling," which means a technology that allows for precise, computer-controlled delivery of odor mixtures or measurement of behavioral responses to these mixtures under such active conditions. Besides, prior studies have made efforts to actively interact with odors in virtual environments by manufacturing or using olfactory display devices such as the mouse [47], handheld device [76], and gloves [44].

However, these efforts have only accomplished one or two tasks for odor events and interaction behaviors and have been unable to combine the complexity of odors with more natural interaction behaviours [35]. Therefore, we hope to propose an interactive technology that can achieve "Scent Synchronization" by meeting users' various interactive needs with smells in VR, engaging the user in exploratory, strategic, or playful movements.

2.2 Embodied Interaction & User-Defined Gesture Set

In virtual environments, Fishkin et al. argue that the closer the embodied interaction resembles real-world tasks, the more natural and transparent the user experience becomes [21]. Embodied interaction allows for more natural and intuitive engagement, enabling users to interact directly with objects using their bodies or through indirect gestures [43]. This type of interaction can involve a variety of gesture types, such as those performed with hand-held controllers [49], freehand gestures [60], foot gestures [16], or the use of embodied tools like virtual laser pointers and virtual avatar body [32].

For creating intuitive interactions in scent-based VR experiences, Wobbrock et al. [77] introduced the user-defined methodology to elicit gesture vocabularies and feedback directly from users, providing a promising solution in this regard. Compared to developer-defined [1] and computationally defined [71] approaches, the main advantage of this participatory design method is that the resulting gestures arise directly from user behavior and beliefs about natural mappings to specific actions [80].This methodology has been successfully applied to various gesture interaction scenarios, including deformable displays [67], TV controls [70], and smart glasses [69]. However, most prior studies focus on interactions involving visual or tactile elements, leaving the potential for gesture-based olfactory interactions largely unexplored.To address this gap, we conducted an empirical study to investigate user preferences for mid-air gestures in proactive olfactory interactions within VR.

2.3 Interaction with Various Object Characteristics in VR

The interaction between users and objects in virtual environments has been explored in various characteristics, with a focus on understanding how object properties, such as distance [7], size, shape, and tactile feedback [15, 38], influence user preferences for gesture design [13, 45, 61], and interaction techniques [24, 34, 40]. Studies have shown that object characteristics significantly influence users' hand gestures [54, 61].

In olfactory interactions, where scent is a distinct sensory modality, the relationship between the smell and its source is closely linked to visual and contextual cues [33]. Research suggests that users tend to associate specific gestures with the sensory attributes of the objects emitting the scent [50]. When it comes to olfactory objects, a straightforward proposition is that the source of odorous molecules is the object of olfactory perception [5, 82]. Human perception of scent primarily occurs when odor molecules in the air or gas state reach the olfactory system [23]. However, scent sources often exist in a "stocked form," for example, perfume in a glass bottle—where the scent is contained and only released when triggered, such as when the bottle is opened. While much research has focused on categorizing the odors themselves [33], the classification of scent sources has been largely overlooked. The form of the scent source can significantly influence how users interact with it. For instance, to release a more intense smell, users may shake or swirl a wine glass to get a stronger scent [76].

To investigate how scent sources affect user behavior, we categorized objects in our formative study based on their physical states (solid, liquid, gas) and interaction modes (graspable, not graspable, out-of-reach). We aim to create more intuitive and contextually appropriate gestural interactions for multi-sensory virtual environments by incorporating these object categorizations into our gesture elicitation process.

3 Formative Study

3.1 Study Goal and Procedure

Study Goal. To better inspire users to interact with scents through gestures in virtual environments, it is essential first to clarify the smell carriers they engage with and the purpose of their interactions. Therefore, we conducted a formative study to gather users' olfactory scenarios in daily settings, aiming to understand why and how people interact with scents and what scented media they interact with in the real world.

Participants. We recruited 59 participants (40 females, average age = 22.90, SD = 1.34) from a local campus - 55 undergraduate students, three graduate students, and one research assistant—ensuring a diversity of backgrounds, including product design, fashion design, interaction design, visual communication, computer science, and digital media. None of the participants reported olfactory impairments.

Instructions & Procedure. Participants were required to complete an online questionnaire detailing their real-world olfactory interactions based on three key aspects: (i) *the scented media involved in the interactions*, (ii) *the actions or behaviors performed during the interaction*, and (iii) *the need for scent experiences*. For the third aspect, compared to application-level needs, such as using scents for reminders or meditation assistance, we focused more on users' requirements related to the properties of scent release (e.g., concentration, direction) to ensure better alignment with the scent-release devices' technical parameters. Besides, to guide participants in organizing their responses, we included an example in the questionnaire: **lighting (how → action & behaviors) a lavender-flavored candle (what → scented media) to enjoy the scent (why → scent release from none to presence)**. Participants were asked to provide at least four descriptions of their olfactory interactions. We analyzed 282 olfactory interaction descriptions from the participants using thematic coding based on three core aspects (action, scented media, requirements) to identify critical patterns, categories, and actions related to olfactory interaction [12].

3.2 Key Findings

3.2.1 ***Scented Source Categories***. We collected a total of 82 different scented sources from participants' descriptions, including 15 natural objects (e.g., flowers, fish), 19 food and beverages (e.g., cakes, red wine), 17 personal care products (e.g., perfume, conditioner), 14 household (e.g., refrigerator, range hood), 12 industrial and chemical products (e.g., gasoline, ink), and five ambient environments (e.g., post-rain air, theater air).

To categorize the collected scented sources more comprehensively, we classified them based on their physical states: ***solid (157/282)***, referring to scented sources with fixed volume and shape, such as flowers, scented candles, and food items like oranges; ***liquid (72/282)***, representing fluid sources that could be stored in containers, such as perfumes, falls, and simmering soups; and ***gas***

(53/282), which includes scents dispersed in the air, like cooking aromas and environmental smells such as fresh rain.

3.2.2 ***Interaction Modes.*** From the 282 descriptions, we identified 22 distinct actions and behaviors when interacting with the scented sources. We found that specific interaction actions are heavily influenced by the particular scented media involved, such as pressing a perfume bottle, peeling an orange, cutting an apple, or crushing flowers. Understanding interaction patterns based solely on these behaviors and performances would make the analysis overly case-specific.

Nevertheless, we found that these actions can be shaped based on scented sources' ***manipulability*** and ***mobility***. Manipulability refers to whether the user can physically handle the object. For example, the apple in hand is fully manipulable because the user can directly grasp, rub, and cut to perceive its scent. The apple on the tree is non-manipulable because it is out of reach, requiring the user to rely on indirect methods, such as moving closer to the tree or using gestures to fan the scent toward themselves. Mobility refers to whether the object can be moved (e.g., apple at hand) or is stationary (e.g., stump). We also found this categorization aligns with prior research on spatial classifications in mixed reality [7], where user-object spatial relationships influence interaction possibilities. Based on the scented media's two factors and the spatial relationship between the user and the scented target, we further identified interaction modes into three categories:

Out-of-Reach Sources (53/282) These odor sources are inaccessible or located at a distance, requiring remote interaction through gestures or movements. For instance, the scent from a distant gas leak (gas) or an apple (solid) on the tree may require users to use mid-air gestures to engage with the odor from afar."

Not graspable Sources (82/282) Not graspable odor sources are stationary objects that cannot be picked up and moved, limiting user interaction to proximity or position changes within the scene. An example could be a pot of soup simmering on a stove, emitting scent but remaining immobile. The user can walk closer to or away from the source but cannot directly manipulate it.

Graspable Sources (147/282) This category includes sources users can pick up, giving them direct control over the odor source. For example, a cup of coffee (liquid) or a flower (solid) can be grasped, allowing users to bring the object closer to their nose or move it around, influencing how they experience the scent.

Notably, in these three interaction modes, we focus mainly on the "current" relationship between the user and the scented source. When the user's distance or proximity to the target changes, the interaction mode with the source also shifts. For example, an apple on a tree can be experienced as "*out of reach*" when the user is distant. However, as they move closer and the apple becomes touchable, the relationship transforms into "*graspable*."

3.2.3 ***Interaction Purposes & Task Design.*** Our analysis revealed two primary intentions that resulting olfactory experiences. (1) *Proactive intent for smell experiences*: interactions explicitly aimed at experiencing or manipulating a scent (e.g., sniffing a flower). (2) *Incidental olfactory experience*: actions with non-olfactory intents that result in olfactory experiences (e.g., opening a refrigerator to find food). To more broadly encompass all interaction pursuits, we categorized the olfactory experience outcomes resulting from two types of interaction intents into seven distinct types, which in turn led to the creation of ten olfactory interaction tasks in VR.

Scent Release (120/282) intents that involve initially experiencing or discovering a smell, which can include getting closer to an odor source, sniffing, or actively releasing a scent from an object, for example, peeling an orange, moving closer to a flower to sniff it, deeply inhaling the smell of fresh rain, or opening a sealed spice jar to release its aroma. Olfactory Task Design: Inspired tasks like **Select Scented Source** and **Odor Release**, where users can select a virtual object and initiate odor release, replicating actions like peeling or cutting.

Sustained Scent Release (36/282): Maintaining the continuous emission of a smell over time, often to create a persistent olfactory atmosphere, for example, burning incense, using a diffuser, or lighting a scented candle to sustain a smell in a room. Olfactory Task Design: This task inspired the **Continuous Odor Release** task, allowing users to keep a virtual scent source active continuously.

Smell Enhancement (27/282): making a smell more prominent, often through manipulation of an object, modifying environmental conditions, or enhancing perception ability, for example, rubbing citrus peel to release more oils, shaking a perfume bottle, or lighting multiple scented candles to enhance the olfactory experience. Olfactory Task Design: Inspired the **Odor Increase** task, enabling users to enhance the scent emitted by a virtual object.

Smell Reduction (54/282): aiming at reducing or eliminating an unwanted odor, often by altering environmental conditions, mitigating measures, or modifying perception ability, for example, opening a window to disperse a strong smell, covering one's nose, or sealing a container to prevent a smell from spreading. Olfactory Task Design: Inspired the **Odor Decrease** and **Stop Odor Release** tasks, replicating real-world behaviors to control when and how an odor diminishes or stops.

Mixing and Switching Odors (52/282) Combining multiple smells to create a new olfactory experience or changing from one scent to another. Examples: Mixing different spices while cooking, blending essential oils, or switching an air freshener from one scent to another. Olfactory Task Design: Inspired the **Mix Odor** and **Odor Switch** tasks, allowing users to experiment with combining scents or switching between different scent profiles in VR.

Obtain Odor Direction (5/282) Tracking the direction from which a scent is coming, often to locate the source, for example, following the scent of baking from a neighboring kitchen or sniffing the air to determine the direction of a pleasant aroma. Olfactory Task Design: Inspired the **Obtain Odor Direction** task, helping users identify the direction of an odor in a virtual environment.

Move Odor (2/282) Controlling the distribution or location of a scent, effectively moving it within a space. Examples: Moving a scented candle to a different part of the room or using hand gestures to fan the scent toward oneself. Olfactory Task Design: Inspired the **Move Odor** task, replicating actions that allow users to reposition scent sources in a virtual environment.

Some tasks, such as isolating specific scents or adjusting scent range, were excluded from the framework due to redundancy—odor separation requires prior odor synthesis tasks not covered in this

study, while adjusting scent range overlaps with intensity and direction control.

3.3 Summary

Based on the findings from the formative study and an exhaustive review of existing research [6, 8, 20, 35, 36, 47, 55, 65, 68], as well as an analysis of commercial olfactory-releasing products, we finally categorized olfactory interaction purposes into distinct tasks (Table 1). We contextualized them in realistic VR scenarios using a classification framework (Figure 2) that organizes scented sources by spatial manipulability and physical properties. While the task table focuses on user goals, the framework centers on objects to ensure tasks are placed in plausible contexts. This foundation guided our gesture elicitation study, systematically exploring users' gesture preferences for interacting with various objects and odors in VR.

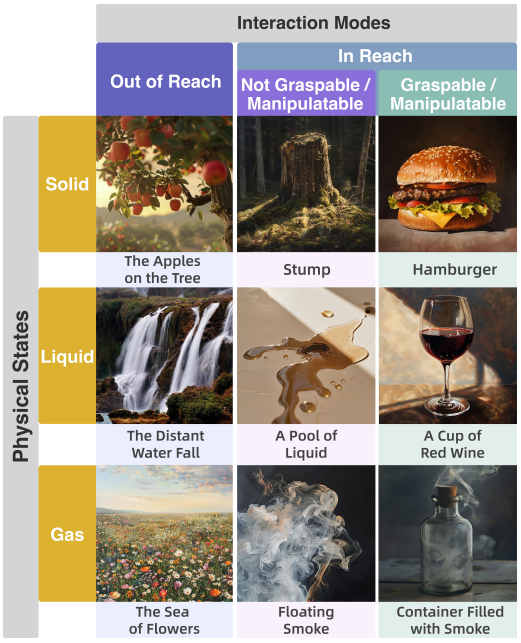


Figure 2: Example objects within our object categories across different interaction modes and physical states.

4 Gesture Elicitation Study

Our primary goal was to elicit diverse mid-air gestures for proactive olfactory interaction tasks in VR. We aim to derive insights into the underlying patterns of how users interact with various physicial states across different interaction modes.

4.1 Experimental Setup

The experiment was conducted in an open office environment with windows open for ventilation. The Oculus Quest 2 was used to provide immersive VR experiences and a Leap Motion [46] for hand tracking. The scent delivery devices were physically connected to a central computer, ensuring stable communication throughout the experiment. The entire setup was recorded using two cameras, capturing the participants' gestures and verbalizations for later data analysis (Figure 4c).

Virtual Scene. The system was developed within the Unreal Engine environment. As Figure 3 shows, the virtual environment used in this study consists of a wide range of objects according to our object categories and interaction modes. The virtual scene was designed to immerse users in a natural environment, positioned at the center of four tables, restricting large-scale movement. This setup encourages localized and present interactions with *graspable* and *not graspable* objects grouped based on physical states and interaction modes. Objects with the same categories are placed on the same table to promote intuitive gestures. The participants were instructed that they were unable to grasp *not graspable* objects in order to maintain a stable relationship between the user and the objects, as movement could alter the dynamics of interaction. Additionally, *not graspable* objects were placed on the table to facilitate predictable interactions. Complex placements, such as large objects on the floor, could complicate the relationship between the user and the objects. Therefore, a simple and consistent placement method was used to enhance the convenience of interaction. In contrast, *out-of-reach* objects are integrated into the surrounding natural landscape (e.g., flower sea over the river), prompting users to interact indirectly. The user's central position within the scene ensures balanced access to all objects, fostering a multisensory experience where visual and spatial cues enhance olfactory interactions.

Additionally, visual feedback plays a crucial role in olfactory perception in VR. Many studies [30, 55, 68] have utilized visual stimuli using particle effects to guide olfactory perception in VR. To represent scent characteristics in scent interaction tasks, we visually render virtual odors with specific colors and intensities with particles, mapping them onto virtual objects.

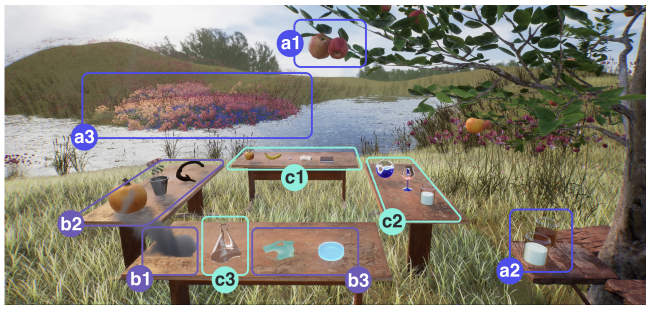


Figure 3: The virtual environment used in this study, including different types of scented sources: (a1) Out of reach, Solid; (a2) Out of reach, Liquid; (a3) Out of reach, Gas; (b1) Not graspable, Gas; (b2) Not graspable, Solid. Participants were informed that the objects were either too heavy to be moved (e.g., pumpkins, tree stumps) or were fixed in place and could not be moved (e.g., flowers in a flowerpot); (b3) Not graspable, Liquid; (c1) Graspable, Solid; (c2) Graspable, Liquid; (c3) Graspable, Gas.

Scent-Releasing Devices. A 3D-printed, neck-worn scent delivery device, created using the Olfackit [75], provided real-time

Olfactory Tasks	Description
Select Scented Source	Select a virtual object for further interactions.
Odor Release	The selected object releases the currently set odor, including odor intensity and type.
Odor Increase	Increases the intensity of the selected object's odor attribute by one level.
Odor Decrease	Decreases the intensity of the selected object's odor attribute by one level.
Odor Switch	Switch the type of scent of the selected object.
Continuous Odor Release	The selected object continuously releases the odor.
Stop Odor Release	The selected object stops releasing the odor.
Move Odor	Move the odor of the selected object to the designated location.
Mix Odor	Mix the odors of two selected objects.
Obtain Odor Direction	Obtain the direction of the existing odor.

Table 1: Ten olfactory interaction tasks used in our gesture elicitation study.

olfactory feedback by releasing four distinct odors: banana, rose, red tea, and sandalwood, each at a concentration of 20% (Figure 4b - right). To better assist users in completing tasks (e.g., when unsure which target the user will choose for the scent-switching task), we assigned four scents to each scented object and randomly selected one as the initial fragrance. The intensity of the odors was controlled by two sets of atomization parameters: a higher intensity setting using 100% voltage at 65v with a 500ms release duration, and a lower intensity setting using 50% voltage with a 100ms release duration. Another scent delivery device, consisting of two separate fogging tablets, was mounted on the top and sides of the VR HMD (Figure 4 b - left). When activated, the fogging tablets dispersed water mist downwards by gravity along both sides of the participant's face. To ensure accurate odor perception, participants were required to turn their heads toward the odor release (left or right). Peppermint was chosen as the odor due to its ability to activate the trigeminal nerve, which enhanced participants' accuracy in identifying the direction of the scent [37]. This design aimed to improve participants' ability to detect the direction of the odor, thereby increasing the experiment's effectiveness.

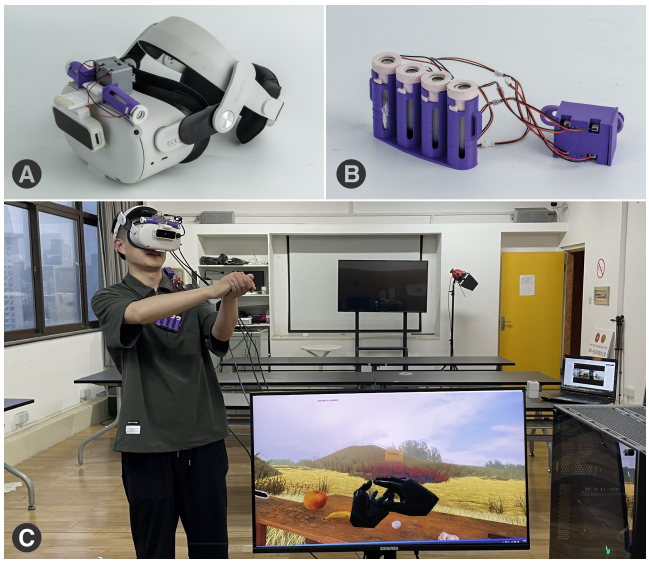


Figure 4: (A&B) The two scent delivery devices used in the study. One was mounted on the headset, and the other was neck-worn by participants. (C) Experimental environment during the study.

4.2 Participants

We recruited 16 participants (9 female) aged between 19 and 29 (M=23.6, SD=2.49) for our study, majoring in visual communication design, arts, finance, or computer science. None of our participants reported any smell impairment.

4.3 Procedure

Participants began by receiving an introduction to the purpose and understanding the interaction method while completing the informed consent procedure. During the experiment, they were asked to select one object from the ***out-of-reach*** categories and two objects from the ***not graspable*** and ***graspable*** categories. Participants designed gestures for eight olfactory tasks for each selected object, excluding *mix odor* and *obtain odor direction*. For *mix odor* task, participants were asked to design two different gestures, considering all object categories, which involves selecting objects from multiple object categories, with its primary focus on the manipulation of the scent itself. Similarly, two distinct gestures were also requested for *obtain odor direction* task, which is not directly related to any specific object category. Specifically, the first eight tasks required selecting one object from each specific object category, resulting in a < 2 *gestures* $> \times < 3$ *Physical states* $> \times < 3$ *interaction modes* $>$ gesture quantity. In contrast, the *mix odor* and *obtain odor direction* tasks did not require object selection, yielding a < 2 *gestures* $>$ gesture quantity. Overall, participants were instructed to design at least two distinct gestures per task for each object category. This strategy can effectively alleviate the legacy bias problem without imposing too much cognitive burden on participants [78].

As Figure 5 shows, participants were first shown the *before* and *after* states of the scented object relevant to the target task. The system provided visual and olfactory feedback through interactive particle effects and scent-delivery devices. Participants designed and performed the most suitable gesture for each task based on these cues. As participants observed the changes in the object's

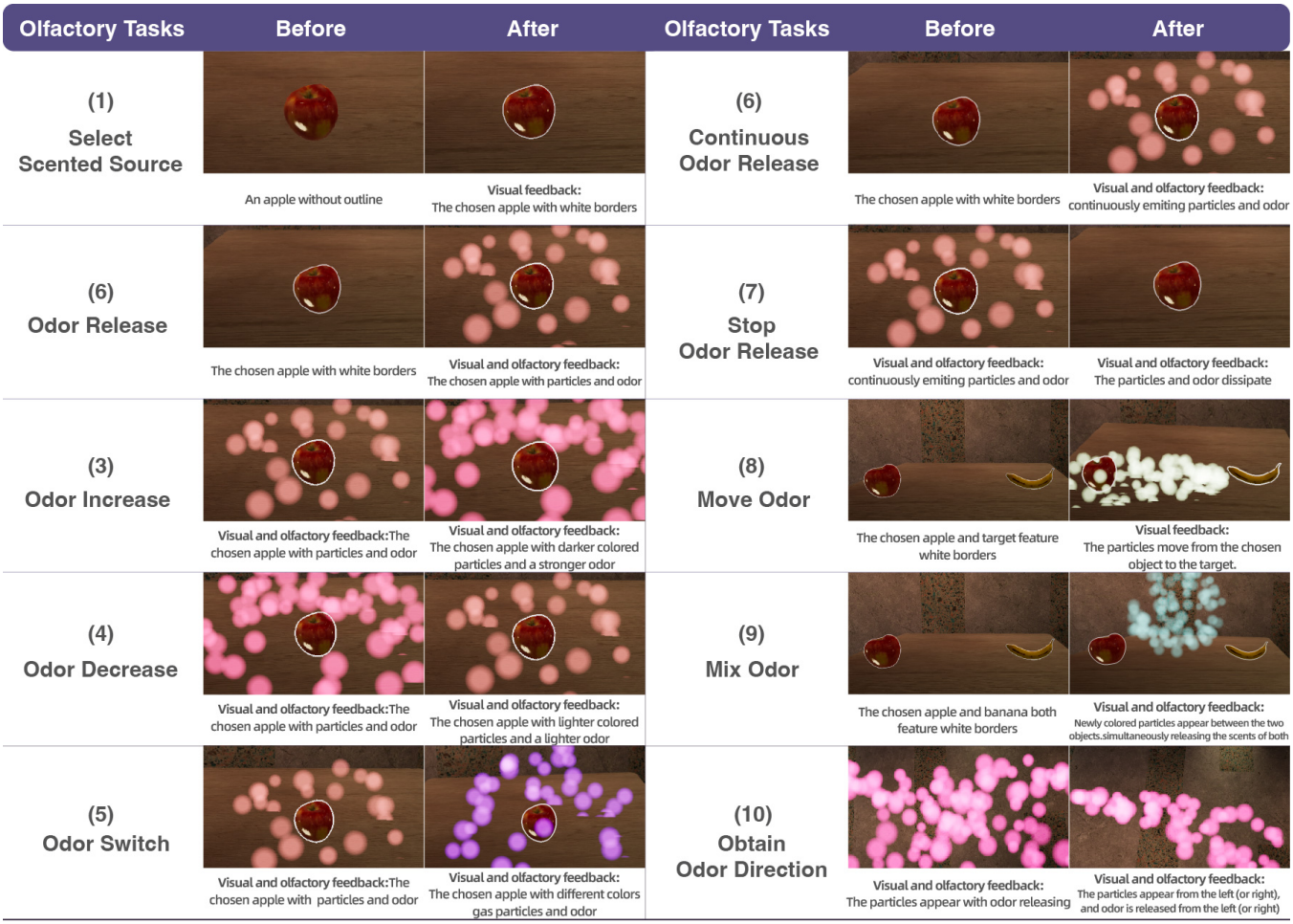


Figure 5: We showed the "before" and "after" states of ten olfactory interaction tasks to the participants as the instructions for generating gestures. We designed the "white border" and "colored particles" as the main visual feedback, indicating the object selection and different released scents. We delivered the scents from the neck-worn device for the first nine tasks while using the one mounted on the headset for the "obtain odor direction" task.

state and odor experience, the researcher offered real-time feedback using the *Wizard-of-Oz* [79], controlling the system's responses behind the scenes. This allowed participants to understand the interaction better and refine their gesture design accordingly.

Participants were encouraged to create as many unique gestures as possible for objects within the same category. After the experiment, they completed a short questionnaire covering demographic information such as age, gender, professional background, and their suggestions for the study. The entire experiment took approximately 90 to 120 minutes.

4.4 Results

The elicitation study collected < 3 *Physical states* $> \times < 3$ *interaction modes* $> \times < 8$ *tasks* $> \times < 16$ *participants* $> \times < 2$ *gestures* $>= 2304$ gestures according to the first 8 olfactory tasks. In addition, as detailed in Section 4.3, we collected < 2 *tasks* $> \times < 16$ *participants* $> \times < 2$ *gestures* $>= 64$ gestures for *Obtain odor direction* and *Mix odor* tasks. In this section, we present the gesture taxonomies according to the categories of physical states and interaction modes. We then analyze the agreement scores between participants. These gestures were analyzed using descriptive labels, segmentation, and phrasing techniques [61].

4.4.1 ***Gesture Taxonomy***. Inspired by the gesture taxonomy work of Wobbrock et al. [77, 79], we classified the user-defined gestures along four dimensions: *nature*, *body parts*, *form*, and *viewpoint*. This taxonomy approach helps us to identify patterns in user behavior, captures the geometric features of mid-air gestures, and allows us to better understand the relationship between gesture attributes. We present the breakdown of gestures in figure 6.

Nature This category can be categorized into four types: physical, symbolic, metaphorical, and abstract gestures. Physical gestures act directly on virtual objects, e.g., opening a virtual book, and their finger scrapes across the object. Symbolic gestures are visual depictions, e.g., drawing a "?" in the air to seek the direction of a

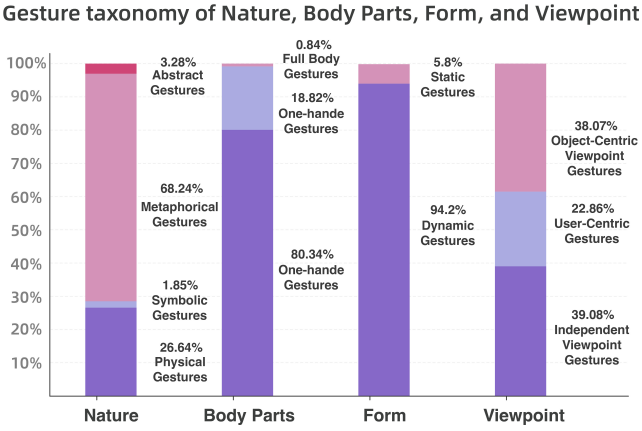


Figure 6: Percentage of gestures in taxonomy of *nature*, *body parts*, *form*, and *viewpoint*.

scent. Metaphorical gestures indicate a metaphor, e.g., fanning to metaphorically represent the release or intensification of a scent. Finally, abstract gestures have an arbitrary mapping with the task, e.g.,flipping the palm from facing up to facing down to signify stopping the release of a scent. Among the distribution, metaphorical gestures were the most widely used type, accounting for 68.24% of the total, followed by physical gestures at 26.64%. Metaphorical gestures were prominently used in tasks such as odor reduction, odor movement, and odor switching.

Body parts The category indicates how body parts are involved in a gesture. It distinguishes between one-handed gestures, two-handed gestures, and body gestures that involve body parts. We found one-handed gestures are the most frequently used, accounting for 80.34% of the total gestures. Two-handed gestures account for 18.82%, for tasks like odor switching and moving odors.

Form This dimension is divided into static and dynamic gestures to describe how the pose and position of hands vary within a gesture. A static gesture refers to the hand pose being held in one location, while a dynamic gesture involves the spatiotemporal movement of the hand pose. We found that dynamic gestures are employed consistently across all tasks accounting for 94.20%.

Viewpoint This category represents which target's position information is required for the gesture. User-centric gestures are performed from the user's point of view, while object-centric gestures act on specific virtual objects. Independent gestures require no information about the context and can occur anywhere. We found that independent viewpoint gestures are the most frequently used (39.08%), particularly in tasks involving odor switching and odor intensity manipulation. Object-centric viewpoint gestures dominate tasks related to object selection and odor movement (38.07%).

Overall, we note that dynamic and one-handed gestures were generally preferred by participants for proactive olfactory tasks. Metaphorical gestures were the most frequently used, reflecting how participants often relied on real-world analogs to interact with virtual scents.

4.4.2 Taxonomy of Action Types. To analyze the actions involved in the proposed gestures and how the selection of these actions varies across different tasks and object categories, we identified the most frequently used action types. Figure 7 illustrates their distribution across tasks and object categories. Our findings indicate that the choice of action is highly task-dependent, with additional underlying patterns related to different object types. Specifically, we identified the following action types:

(i) ***Swipe*** (41.43%) *Swipe* is continuous, directional movement of the hand. Most proposed gestures are swipes, with most participants using this action as a metaphor for directly controlling airflow (or scent). participants intentionally used opposite direction movements, e.g., swipe outward or downward for *odor decrease*, swipe towards or upward for *odor increase*.

(ii) ***Manipulation*** (27.06%) Some participants used actions like scraping solid pieces for tasks like *odor releasing* or *odor increase*, rather than performing a specific gesture. As a result, we defined *Manipulation* as any interaction with an object intended to change its physical shape or physically touch it. This action type was frequently used for interacting with graspable solid or liquid objects.

(iii) ***Draw*** (16.13%): All non-linear swipes were categorized under the action type *Draw*. For example, draw a circle in the air for *Obtain Odor Direction*, resembling a "searching" icon. In this action, a dynamic path is traced by the hand's movement, while the hand pose either remains consistent or changes during the motion.

(iv) ***Stretch*** (14.12%) Some gestures involve in-air finger movement, such as stretching out one or multiple fingers to simulate the diffusion of odors in the air.

(v) ***Others*** (5.51%) Some gestures, like pinching the air and placing it on the body, or rubbing the back of the hand as if shaking off water, were infrequently proposed and involved less commonly used body parts.

These categories highlight the range of intuitive gestures participants proposed for olfactory interactions, with *Swipe* being the most prevalent, followed by object-specific manipulations. For scent-related interactions, participants predominantly used swipe gestures, suggesting a natural mental model of controlling airflow or scent through directional hand movements, particularly for distant or gaseous objects. Contrary to the distribution across tasks, a key insight is that physical states and interaction context did not significantly influence the choice of action type. However, for touchable objects (graspable and not graspable-solid, not graspable-liquid), over 30% of the proposed gestures involved manipulation, where participants focused on altering the object's physical state.

4.4.3 ***Agreement Scores.*** To identify the level of consensus between participants' proposals, we calculated the agreement scores (*AS*) for the ten target tasks following the agreement formula proposed by Vatavu et al. [72].

$$AS(r) = \frac{|P|}{|P|-1} \sum_{P_i \subset P} \left(\frac{|P_i|}{|P|} \right)^2 - \frac{1}{|P|-1} \quad (1)$$

where P is the set of all proposed gestures for task r, and Pi represents subsets of identical gestures from P. The higher the agreement score is, the more likely the same gesture will be selected. Gestures with the same characteristics will be grouped into one gesture, such as the same direction of motion. Gestures with similar features need to be discussed on how to group participants based on their design reasons explained during the experiment to believe they agree. The

TASKS	OBJECTS									Mean	SD
	Out of reach			Not Graspable			Graspable				
	Soild	Liquid	Gas	Soild	Liquid	Gas	Soild	Liquid	Gas		
1 Select	0.658	0.875	0.875	0.675	0.542	0.675	0.475	0.675	0.600	0.672	0.126
2 Odor Release	0.208	0.250	0.267	0.391	0.350	0.250	0.279	0.184	0.250	0.270	0.061
3 Odor Increase	0.167	0.208	0.208	0.258	0.216	0.175	0.224	0.233	0.233	0.214	0.027
4 Odor Decrease	0.258	0.250	0.250	0.258	0.267	0.300	0.175	0.267	0.233	0.256	0.033
5 Odor Switch	0.650	0.550	0.756	0.875	0.650	0.758	0.325	0.467	0.558	0.621	0.158
6 Keep Releasing	0.216	0.258	0.225	0.201	0.275	0.233	0.281	0.216	0.167	0.230	0.034
7 Stop Releasing	0.141	0.133	0.158	0.143	0.108	0.225	0.081	0.108	0.092	0.132	0.041
8 Move Odor	0.425	0.408	0.467	0.408	0.358	0.425	0.290	0.308	0.325	0.379	0.058
Mean	0.340	0.367	0.401	0.401	0.346	0.380	0.266	0.307	0.314		
SD	0.198	0.227	0.258	0.236	0.164	0.207	0.107	0.170	0.167		
9 Mix Odor	0.267										
10 Obtain Odor Direction	0.083										

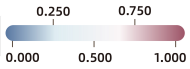


Figure 7: Agreement scores for ten olfactory tasks, shown individually for interaction modes and physical states.

results are shown in Figure 8. Agreement rates ranged from 0.083 (low agreement, $AS \leq 0.1$) to 0.875 (very high agreement, $AS > 0.5$). The mean AS across all objects and tasks was 0.299 ($SD = 0.157$), which can be qualified as medium agreement [73] ($0.1 < AS < 0.3$).

Agreement rate among different tasks. The agreement rate across different tasks varied significantly. Participants tended to show higher agreement for more straightforward tasks, such as *select* and *odor switch*. This can be attributed to participants' mental models, as they often relied on familiar mappings from prior experiences—such as pointing for selection or swiping for switching. In contrast, more abstract tasks, like *stop releasing odor* and *obtain odor direction*, had notably lower agreement rates.

Agreement rate among different object categories. The agreement rate across different object types and interaction contexts showed less variation compared to tasks. However, the agreement rate for graspable solid objects was notably lower than for other object types. This suggests that the specific characteristics of an object significantly influence the gestures proposed by participants. For example, when interacting with graspable solids like a book versus an apple, participants tended to propose distinct gestures tailored to the object's function or behavior. For a book, gestures such as opening or flipping were commonly suggested as part of the odor-release interaction, whereas for an apple, gestures like breaking or cutting were more frequently proposed to simulate scent release. This variability in gesture suggestions indicates that users' mental models of how different solid objects behave in the real world strongly influenced their gesture choices, leading to lower overall agreement for this category.

4.5 User-Defined Gesture Set

We derived the user-defined gesture set based on the agreement scores, shown in Table 2. Due to the variations observed, relying solely on the commonly used frequency ratio method in elicitation studies proved ineffective, as it led to conflicts between tasks and object types. Instead, we adopted a more comprehensive approach that considers both frequency and user mental models, allowing us to account for task- and object-specific nuances. Below, we outline the rationale behind finalizing the proposed gesture set (Figure 9).

(i) For the selection task, participants typically used pointing or tapping gestures for non-graspable objects and grasping gestures for graspable ones, suggesting that an object's shape and physical affordance influence gesture choice. To address this, we standardized the selection gesture as pointing for all objects, with the option to grasp for graspable ones, providing a more intuitive and flexible interaction experience.

(ii) For the scent release task, participants mostly used the fanning gesture, except with graspable solid objects, where manipulation gestures like scraping or tearing were preferred. Due to the complexity of implementing manipulation gestures, we recommend standardizing the fanning gesture for all object types, as it provides a simpler, more intuitive interaction that aligns with user behavior.

(iii) For Odor Increase, participants commonly used an upward swipe, fanning, and object manipulation, with the upward swipe being the most frequent. However, for liquid and gas containers, shaking a bottle or glass was often suggested. We recommend using the upward swipe as the primary gesture, with shaking reserved for containers.

(iv) For Odor Decrease and Stop Odor Releasing tasks, participants commonly proposed a downward swipe or outward push, as both involve reducing scent intensity. To differentiate the gestures,

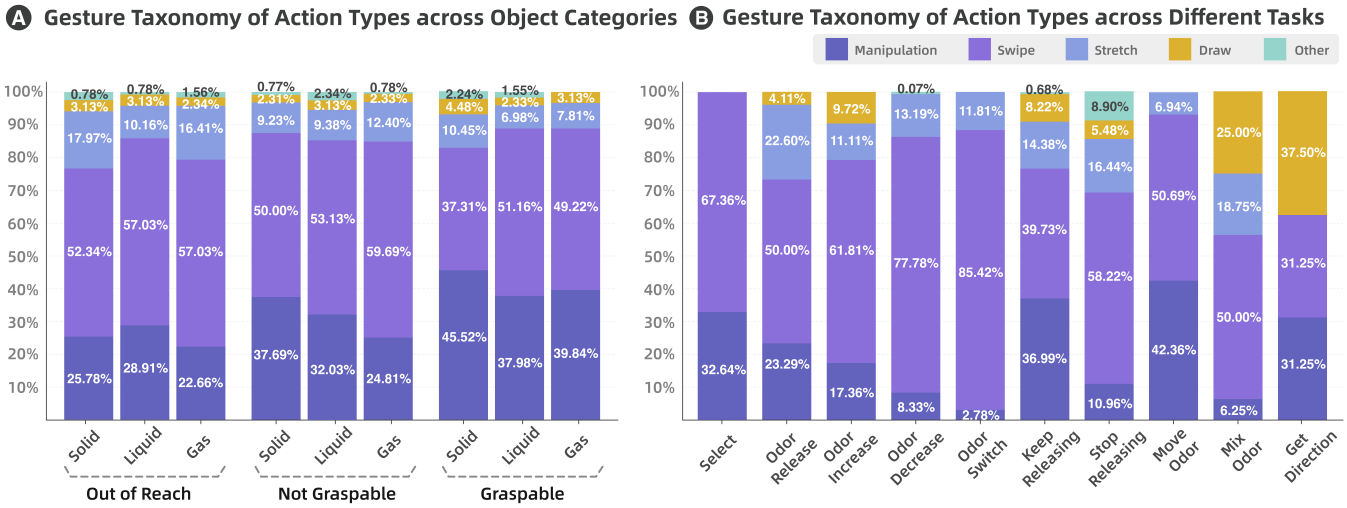


Figure 8: Action distribution for objects (left) and olfactory tasks (right).

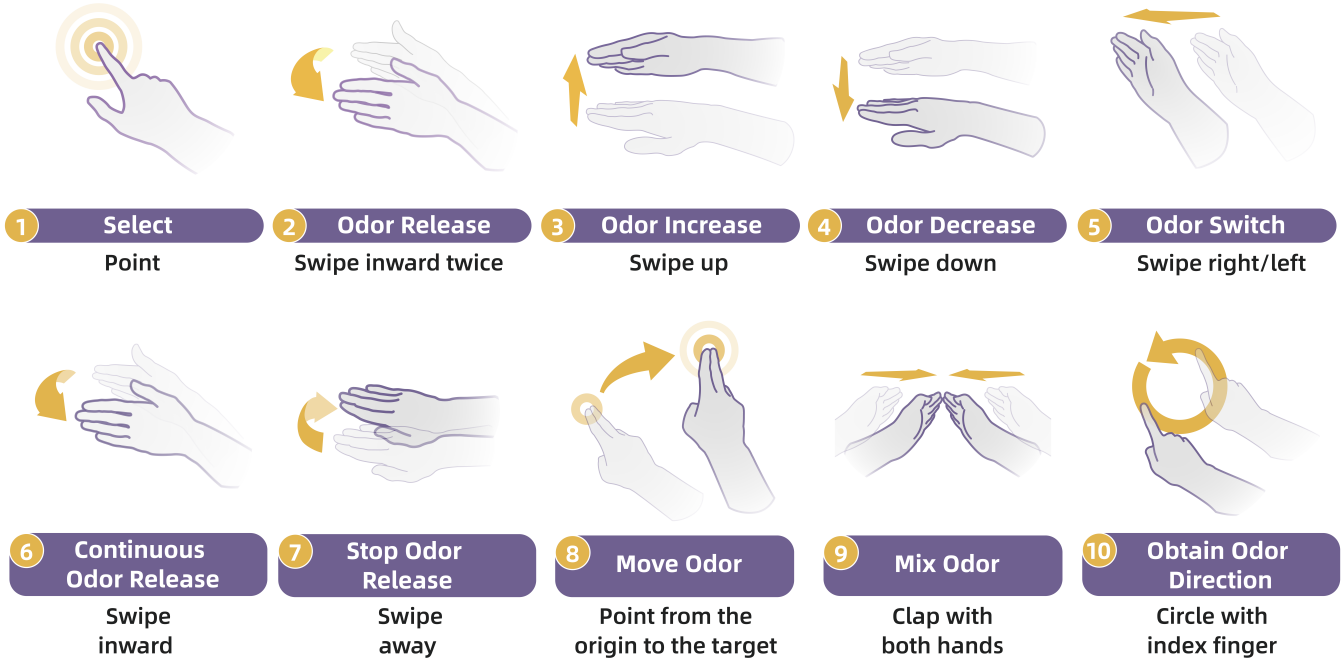


Figure 9: User-defined gesture set for ten olfactory tasks in VR.

similar to volume control, we assigned the downward swipe to the decrease task and the outward push to the stop task, ensuring clear interaction distinction.

(v) For the Continuous Releasing Odor task, most top gestures were waving motions (fan gestures), similar to those used for scent release. To differentiate the two tasks, many participants suggested using multiple waving motions for continuous release. This maintains the intuitive gesture while providing a clear distinction through repetition.

(vi) For the Move Odor task, although fanning towards the target was the top choice, we opted for a directional movement gesture (like pointing or sliding), which was the second most frequent. This avoids redundancy with other fanning gestures and aligns with participants' preference for using directional gestures to control scent movement.

Interaction Modes	Task	Physical States		
		Solid (AS)	**Liquid (AS)**	**Gas (AS)**
Out-of-reach	Select Scented Source	Point (0.658)	Point (0.875)	Point (0.875)
	Odor release	Swipe inward twice (0.208)	Swipe inward twice (0.250)	Swipe inward twice (0.267)
	Odor increase	Swipe up (0.167)	Swipe up (0.208)	Swipe up (0.208)
	Odor decrease	Swipe down (0.258)	Swipe down (0.250)	Swipe down (0.250)
	Odor switch	Swipe right/left (0.650)	Swipe right/left (0.550)	Swipe right/left (0.758)
	Continuous odor release	Swipe inward (0.216)	Swipe inward (0.258)	Swipe inward (0.225)
	Stop odor release	Swipe away (0.141)	Swipe away (0.133)	Swipe down (0.158)
	Move Odor	Fan towards the target (0.425)	Fan towards the target (0.408)	Point from the origin to the target (0.467)
Not graspable	Select Scented Source	Point (0.675)	Point (0.542)	Point (0.675)
	Odor release	Manipulation (0.391)	Swipe inward twice (0.350)	Swipe inward twice (0.250)
	Odor increase	Swipe up (0.258)	Swipe up (0.216)	Swipe up (0.175)
	Odor decrease	Swipe down (0.258)	Swipe away (0.267)	Swipe down (0.300)
	Odor switch	Swipe right/left (0.875)	Swipe right/left (0.650)	Swipe right/left (0.758)
	Continuous odor release	Pat (0.201)	Pat (0.275)	Swipe inward (0.233)
	Stop odor release	Swipe down (0.143)	Swipe away (0.108)	Swipe down (0.225)
	Move Odor	Fan towards the target (0.408)	Fan towards the target (0.358)	Fan towards the target (0.425)
Graspable	Select Scented Source	Grasp (0.475)	Grasp (0.675)	Grasp (0.600)
	Odor release	Manipulation (0.279)	Shake the container (0.233)	Shake the container (0.233)
	Odor increase	Swipe up (0.224)	Swipe up (0.175)	Swipe up (0.175)
	Odor decrease	Swipe down (0.175)	Swipe down (0.267)	Swipe down (0.283)
	Odor switch	Swipe right/left (0.325)	Swipe right/left (0.467)	Swipe right/left (0.558)
	Continuous odor release	Pat (0.081)	Pat (0.175)	Swipe inward (0.167)
	Stop odor release	Swipe down (0.081)	Swipe away (0.108)	Swipe down (0.216)
	Move Odor	Fan towards the target (0.290)	Fan towards the target (0.308)	Fan towards the target (0.325)

Table 2: The table shows our eight tasks and their corresponding top gestures and agreement scores between object categories and interaction modes.

4.6 Discussions

The above results provide key insights into how task and object types influence user-defined gestures for proactive olfactory interactions in VR. While tasks emerged as the most significant factor in shaping gestures, we also uncovered nuanced effects related to the object's physical states and interaction contexts. For instance, participants tended to propose different gestures for manipulating touchable objects, such as graspable and not graspable-solid or not graspable-liquid items. In contrast, out-of-reach objects often elicited more generalized gestures, regardless of their specific states.

The degree to which these factors influenced mid-air gesture suggestions varied, yet we observed a consistent preference for certain gesture types during scent-related interactions from our participants. Rather than adhering strictly to frequency-based approaches commonly seen in gesture elicitation studies, we adopted a more flexible methodology. By considering user preferences alongside task and object contexts, we reconciled conflicts and established a gesture set that is adaptable and intuitive, ensuring better alignment with real-world interactions. Compared with prior user-defined gesture sets, our findings highlight the nuanced relationship between proactive olfactory tasks, object properties, and the physical context of interaction in determining intuitive gestures.

5 Evaluation Study

To gain deeper insights into the usability and adaptability of the gesture set derived from the previous study, we conducted a comparative study to explore participants' perceptions when using user-defined gestures versus conventional controller techniques for proactive olfactory interactions. This study examined the advantages and limitations of gesture-based interaction. Additionally, we carried out an exploratory experiment to further investigate user behavior, preferences, and expectations for multisensory integration in proactive olfactory interactions. Through these two experiments, we aim to provide valuable insights into the potential of proactive gesture-based olfactory experiences, ultimately informing unimagined multisensory VR applications.

5.1 Experimental Setup

The experimental setup comprises a gesture recognition pipeline and scent delivery devices mounted on the headset.

Gesture Recognition Inspired by GesturAR [74], our gesture recognition system recorded hand information for each frame, including joint positions, palm positions, movement speed, and more. This data was used to compute hand postures, movement directions, and palm rotations to determine if they matched the predefined gesture states. We separately processed tracking data for the left and right hands for gestures involving both hands, such as mixing scents. The gesture was detected when the state lists for both hands matched. We tested ten user-defined gestures, achieving an average recognition accuracy of 88.2%.

Experimental Apparatus The hardware setting in this experiment was consistent with the gesture elicitation study (Figure 4). In addition, traditional interaction techniques were implemented



Figure 10: We reused the natural environment from the previous gesture elicitation study for the comparative study, retaining the task-specific scented sources (A). We created a coffee shop scenario for exploration study to encompass various interaction possibilities, including general graspable items (e.g., cups), a shopping area with clothes, artistic paintings on the walls, and a chatting area (B).

using the controllers of Oculus Quest. The whole system was developed within Unreal Engine, utilizing the Leap Motion SDK for hand tracking and OpenXR plugins for interactions.

5.2 Participants

We recruited 13 participants (6 female) aged between 21 and 25 years (M = 23.08, SD = 1.54) for this study. The participants were from diverse academic backgrounds, including product design, electronic science, digital media art, and human-computer interaction. None of the participants reported any olfactory impairments, and none had prior experience with gestural interaction in VR.

5.3 Tasks & Procedures

Participants first completed a tutorial session to familiarize themselves with both interaction methods: gesture-based input and handheld controllers. The tutorial covered fundamental operations for interacting with virtual scents, including object selection, scent release, and intensity adjustment. Once participants were comfortable with the interactions, the study commenced. We divided the study into two phases: a comparative study and an exploration study (Figure 10).

5.3.1 ***Comparative Study.*** In this sub-study, participants completed eight predefined olfactory interaction tasks to assess each interaction method's efficiency and effectiveness in performing various scent-related interactive tasks (Figure 11). Initially, participants were required to identify the four pre-loaded scents in the VR environment, ensuring accurate recognition and differentiation between the odors. The study lasted approximately 30 minutes for one person. Tasks in this phase are listed as follows:

- Adjust the scent of a virtual banana to the correct odor.
- Combine the scents of an apple and a banana to create a mixed odor that is released simultaneously.
- Increase the intensity of the scent emitted by flowers in a potted plant by one level.
- Set the flowers to release their scent over time continuously.
- Move the scent from the flowers to a virtual pet, then begin moving the pet.
- Track dog pet by following its scent trail.
- Stop the continuous emission of the scent from the pet.
- Reduce the intensity of the flowers' scent by one level.

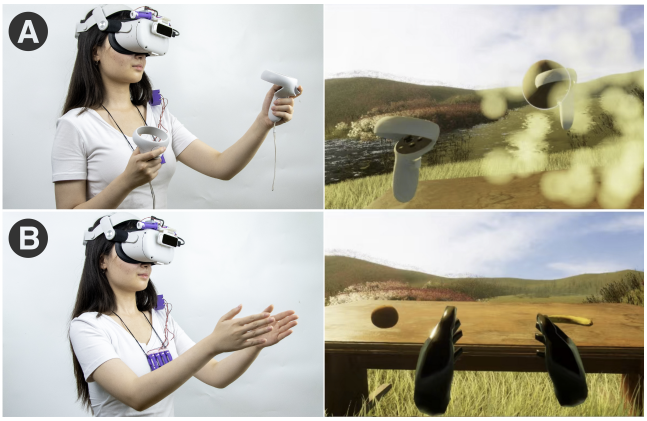


Figure 11: Comparative study setup for olfactory interaction tasks with handle controller interaction(A) and gesture-based interaction(B).

Upon completing the tasks with each interaction method, participants were asked to complete several questionnaires, including the User Experience (UX) Questionnaire [41], the NASA-TLX [25] for workload assessment, and the Igroup Presence Questionnaire (IPQ) [58] to measure their sense of presence in the VR environment. Participants were given a 10-minute rest period. A Latin Square Design was also employed to counterbalance the order in which participants completed the tasks to ensure a balanced comparison between gesture-based and controller-based interactions. Seven participants used gestures first, followed by the controller, while the remaining six used the controller first, followed by gestures.

5.3.2 ***Exploration Study.*** Participants were invited to engage in an exploratory experiment set in a virtual coffee shop environment, as shown in Figure 10 B. Participants were encouraged to freely interact with various scented objects using gestures, focusing on scent-related interactions and their potential social implications. They were also prompted to explore as many objects as possible and reflect on how these interactions could be improved or adapted according to personal preferences. Participants were required to think aloud, sharing their thoughts during interactions to provide real-time insights into their decision-making processes.

After the exploration, the experimenter conducted a semi-structured interview (≈ 30 to 45 minutes) to explore several key areas related to user interaction with olfactory experiences in VR. Specifically, the following questions guided the discussions: *(1) Which objects or social aspects were most commonly referenced or utilized by users during the olfactory interaction? (2) Based on user choices and interactions, were there any emerging extended interaction methods, specific properties of objects, or unique interaction effects that users utilized?*

We conducted audio and video recordings throughout the sessions, focusing on think-aloud protocols and semi-structured interviews. Two experimenters transcribed approximately nine hours of audio recordings verbatim. The transcriptions were then analyzed using thematic coding [11] to identify recurring patterns and

insights. Specifically, the analysis focused on three key themes derived from the two guiding questions mentioned above: Preferred Objects for Olfactory Interaction, Most Commonly Referenced Social Aspects, and Olfactory Complement for Extended Interactions.

The experimenters observed and analyzed participants' interaction gestures and behaviors from the video recordings. They documented how participants used gestures and non-verbal cues to complement their verbal responses. Through an iterative process, the experimenters first familiarized themselves with the data by reviewing the transcripts multiple times. They then applied open coding to identify key phrases, responses, and behaviors related to the primary themes. The coding process revealed patterns in participants' choices of scented objects and corresponding olfactory interactions, the application of olfactory interactions in social contexts, and unique insights into olfactory interactions in VR.

5.4 Results

5.4.1 ***Results on Comparative Study.*** To compare the seven metrics: task completion time, error count, presence (IPG), user experience (UX), task load (NASA-TLX), physical demand, and mental demand—between the two conditions, we conducted paired Wilcoxon signed-rank tests for each metric (Figure 12). The Wilcoxon signed-rank test with Benjamini-Hochberg correction was selected because of its suitability for small sample sizes and non-normal data, which was confirmed before testing.

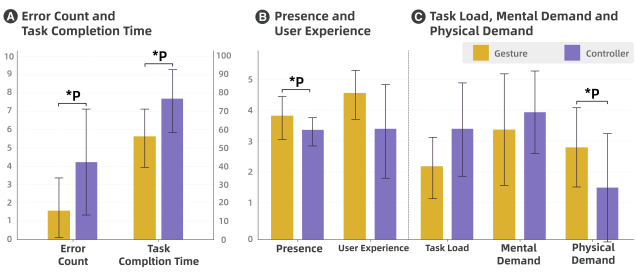


Figure 12: Comparison of gesture and controller input methods in terms of task completion time, error count, presence, user experience, and task load, including mental and physical demand.

Task Completion Time. Participants using gesture-based interactions completed the tasks faster, with an average time of 56.81 seconds (SD = 15.38), compared to those using controllers, who had an average completion time of 77.31 seconds (SD = 16.63). A significant difference was found ($p = 0.004$), which is smaller than the corrected p-value threshold of 0.0071.

Error Count. We recorded the number of attempts required by participants to complete the task using two different interaction methods. The total number of attempts varied significantly between participants, as it was influenced by individual comfort levels and manipulation habits. On average, participants made fewer errors using gesture-based interactions (M = 1.64, SD = 1.43) compared to controller-based interactions (M = 4.18, SD = 2.79). A significant difference was found ($p = 0.012$), which is smaller than the corrected p-value threshold of 0.0143.

NASA-TLX (Task Load Index). The NASA-TLX scores were analyzed to assess the perceived workload associated with each interaction method, with an average error count of 2.28 (SD = 0.90) compared to 2.71 (SD = 1.37) for the controller-based method. Although there was no significant ($p = 0.414$) overall workload difference between the two methods, the physical demand dimension showed a significant difference ($p = 0.019$), which is smaller than the corrected p-value threshold of 0.0214. Participants reported higher physical demand when using gestures, with a score of 2.85 (SD = 1.17) compared to 1.62 (SD = 1.60) for the controller-based interactions. For mental demand, gestures and the virtual handle controller averaged 3.38 (SD = 1.64) and 3.92 (SD = 1.21), no significant difference was found ($p = 0.233$).

IPG (Igroup Presence Questionnaire). The Igroup Presence Questionnaire (IPG) scores indicated a significant difference in the sense of presence between the two interaction methods. Participants reported a higher sense of presence with gesture-based interactions, scoring an average of 3.82 (SD = 0.63), compared to 3.39 (SD = 0.42) for controller-based interactions. A significant difference was found ($p = 0.027$), which is smaller than the corrected p-value threshold of 0.0286.

User Experience (UX) Scores. The UX scores further emphasized the advantages of gesture-based interactions. Participants rated the gesture-based method higher in overall user experience, with an average score of 4.52 (SD = 0.72), compared to 3.40 (SD = 1.38) for the controller. No significant difference was found ($p = 0.047$), which is bigger than the corrected p-value threshold of 0.0357.

In summary, the results of Phase 1 demonstrate that gesture-based interactions offer significant advantages over traditional controller-based methods in task completion time, error count, and presence, in VR olfactory environments. However, the increased physical demand associated with gestures may need to be addressed to optimize their usability further.

5.4.2 ***Results on Exploration Study.*** **Preferred Objects for Olfactory Interaction.** Participants displayed distinct interaction preferences and requirements based on the olfactory properties of objects. For objects with vital scent attributes, such as perfume and food items, participants tended to focus on experiences that could enhance or adjust the actual scents. Many expressed the desire to release or intensify scents they found appealing or to experience multi-layered scents, such as switching sauces for a steak to simulate different flavor profiles. For example, P3 shared, "*I'd like to switch the scent of the sauce to match what I'm eating,*" illustrating the intention to explore more complex, layered scent interactions. Additionally, users often tended to reduce or modify the scent for objects with unpleasant odors, such as trash. P5 mentioned, "*I'd like to decrease the scent of the trash, maybe make it disappear completely,*" reflecting an active approach to managing unpleasant odors through interaction.

In contrast, for objects with weaker olfactory properties (e.g., personal belongings like jewelry), participants tended to transfer scents from stronger olfactory objects to weaker ones. This was especially prevalent in cases where users sought to pair scents with items like clothing or jewelry for personalization or self-expression. P4 commented, "*I'd add my favorite scent to my jewelry so it becomes a part of my style.*" Similarly, participants also envisioned combining

scents with visual or auditory elements, as in art pieces or music, to create multi-sensory experiences. P7 explained, "*I think each artwork should have its own scent; it would add another layer of emotion.*" For some participants, marking or tagging objects with a specific scent was also appealing. This could be applied to objects with weaker olfactory properties to create new sensory associations. P6 suggested, "*I'd mark my belongings with a unique scent so I could recognize them easily.*"

In summary, participants demonstrated a clear distinction in their interaction preferences based on the olfactory strength of the objects. They preferred authentic experiences focused on enhancing, releasing, or modifying scents for strongly scented objects. For objects with weaker scent properties, they creatively incorporated external scents to fulfill personalization, artistic expression, or practical tagging purposes.

Most Commonly Referenced Social Aspects. Participants frequently mentioned olfactory interactions as a tool for enhancing social dynamics in virtual environments. A common theme was using scent to mark *personal territory* in public spaces. P7 stated, "*I would use a unique scent to mark my personal space in a crowded virtual room, making others aware of my presence and boundaries.*" This reflects a desire to use scent as a subtle social signal for maintaining personal space and privacy in shared virtual environments.

Additionally, several participants (6 out of 13) wished to assign a unique scent to their virtual avatars, using it as *an identity form* or "*olfactory business card.*" P4 suggested, "*I'd want my avatar to have a signature scent that others recognize, like a personal calling card that reflects my mood or personality.*" This highlights the potential for olfactory cues to serve as an extension of one's virtual identity, creating a memorable and personalized way to connect with others.

Another prominent use of scent in social contexts was its role in *modulating the atmosphere* during interactions. Participants mentioned adjusting scents to create a specific mood during conversations or group interactions. For example, P3 stated, "*I'd release a calming lavender scent during intense discussions to help everyone relax.*" This demonstrates how users envisioned olfactory cues to influence social environments and enhance emotional communication. In more playful or expressive interactions, participants described the use of scent-based actions such as *"liking" someone's comment* with a pleasant fragrance or sending *virtual scented gifts.* P2 mentioned, "*I'd send a virtual gift with a nice scent, like a rose, as a way to show appreciation.*" Conversely, "bad smells" were proposed as humorous or mischievous tools for lighthearted interactions, with P6 suggesting, "*I could release a bad smell, like rotten eggs, as a joke or prank in a friendly setting.*"

Overall, participants saw olfactory cues as a versatile tool for subtle and expressive social interactions. From marking personal space to enhancing communication and playful exchanges, scent in virtual environments was valued for its ability to add an extra layer of personalization and emotional expression.

Olfactory Complement for Extended Interactions. Participants demonstrated creative approaches to expanding scent-based interactions in VR, often suggesting multisensory experiences and dynamic control over scents. 38% of participants (5 out of 13) proposed that scent could complement tasks where visual or auditory feedback felt insufficient. For instance, P5 envisioned using scent to indicate object characteristics change (e.g., beef's cooking progress): "*I'd love to smell the steak cooking in VR, with the scent changing as it goes from raw to done—it's a more immersive way to know it's ready without just looking.*" Another participant suggested a combination of scent, visuals, and sound: "*Imagine playing the piano and releasing a different scent for each note, like a 'scent symphony' that adds a new layer to the performance*" (P3). Additionally, 31% of participants (4 out of 13) saw the potential for the scent to influence narrative and navigation within virtual environments. One participant described using scent for spatial orientation: "*Scent could act like a compass in large virtual spaces—growing stronger as I get closer to my destination*" (P8). Others saw scent as a feedback mechanism for task progress: "*If I'm solving a puzzle, the scent could change as I get closer to the answer, like how 'warmer' or 'colder' works"* (P6).

6 Discussions

6.1 Implications of Freehand Gesture Design for Olfactory Interactions

Our evaluation study validated the effectiveness of the gesture set derived from task-specific, object-specific, and user-mental models through a comparative experiment. Participants preferred using gestures in olfactory interactions, noting that the engaging and playful nature of the gestures increased their time spent in the system. This demonstrates the value of a flexible, collaborative design approach, which can enhance the usability and the enjoyment of olfactory interactions in VR environments.

Besides, we have derived several insights for designing freehand gesture-based olfactory interactions in virtual reality. While tasks, such as Odor Release or Odor Increase, are consistent across different object types, the gestures proposed by users showed variation depending on whether the object was touchable. For example, users frequently opted for manipulation gestures (e.g., shaking a bottle or cutting an object) when interacting with graspable objects. In contrast, air-based swiping gestures dominated interactions with distant objects. This suggests that gesture design for olfactory interaction should consider the nature of the object and its interaction distance.

While the overlap between user-elicited olfactory gestures and visual-based interactions might appear as a limitation in novelty, it significantly reduces cognitive load and allows for a more intuitive user experience. This can be further envisioned by integrating into cross-domain consensus gesture sets [29]. As shown in the results of the gesture elicitation experiment, the *manipulation* gesture category includes more complex actions that require users to engage with the object in a way that goes beyond simple movements. For example, actions like shaking a wine bottle [50] or peeling an orange involve both gestural precision and physical interaction. This highlights the design challenge of ensuring that the system's response aligns with the nature and properties of the objects involved. This deeper exploration of gesture complexity has important implications for the design of unique olfactory or multisensory systems.

Additionally, to mitigate the higher physical demand of gesture-based interactions, future systems could incorporate minimal and purposeful gestures, as frequent interactions with scents are not ideal due to the time required for scent dissipation and the potential for sensory overload in multi-scent environments. Additionally,

reducing the complexity of gesture inputs and optimizing the scent delivery system can help maintain user comfort and clarity.

Expanding the gesture vocabulary for multisensory VR interactions has excellent potential. With the advancement of olfactory display devices, we anticipate that more complex interactions, such as setting the range and diffusion direction of scents or even splitting scents, will become feasible. The gesture set developed through our research provides a solid foundation for further exploration.

6.2 Personalization through Proactive Olfactory Interaction in VR

Olfactory technology has already been integrated into applications like gaming [83], virtual tourism [22], and artistic expression [17], enhancing immersion through passive scent cues. However, active olfactory interaction introduces a new dimension by allowing users to personalize and control their scent experience, unlocking novel applications and future possibilities.

Proactive olfactory interaction allows users to personalize immersive experiences by adjusting scent characteristics—such as intensity, timing, and type—to match their moods or preferences. For example, in virtual home environments, cinemas, or mindfulness yoga sessions, users can dynamically modify the scent to suit the desired ambiance.

In virtual shopping environments, proactive olfactory interaction also creates opportunities for personalized retail experiences. Users could select or alter scents associated with specific products, such as perfumes and scented candles. Integrating olfactory stimuli with virtual shopping interfaces can allow users to sample food items or even associate certain products with distinct scents, thereby enriching the online shopping experience. The potential for personalization in virtual retail aligns closely with prior research on the influence of olfactory stimuli on consumer behavior [28, 42]. Studies demonstrate that scent-enhanced virtual environments can increase product evaluation accuracy and perceived value [10, 14]. Integrating scent sampling and customization within virtual shopping interfaces could enable users to associate specific products with distinct smells, such as perfumes or scented candles. This approach may significantly enhance consumer decision-making and satisfaction by simulating the tactile and sensory aspects of in-person shopping.

Additionally, prior work has largely explored the use of scent in VR-assisted aromatherapy to improve mental well-being [26]. Proactive olfactory interactions could allow users to choose the most calming or invigorating scents for relaxation [48], stress relief [3, 39], or pain management [27]. For example, integrating scent control into virtual therapy sessions could help users personalize the experience to better align with their emotional and physical needs.

The ability to personalize olfactory interactions aligns with broader trends toward user-centered design, offering vast potential for multi-sensory customization in future virtual environments.

6.3 Social Aspects of Proactive Olfactory Interaction

Our exploratory study revealed several potential uses for olfactory in social contexts, ranging from marking personal territory to playful exchanges like sending scented virtual gifts. These findings open up various possibilities for social interactions in virtual environments. However, while the potential for using scent in these ways is exciting, several important considerations and limitations exist.

For instance, using unpleasant odors for pranks or playful interactions—such as the suggestion of using bad smells for humor—requires careful consideration. Similar to sending offensive emojis or messages, using unpleasant odors could cross personal boundaries and lead to negative experiences if misused. Therefore, permission and consent should be integral to the design of such features. A potential solution would be to implement a permission-based system where users can only send certain smells (especially unpleasant ones) to others if both parties have agreed to this type of interaction. This would ensure these interactions are safe, consensual, and contextually appropriate.

Cultural sensitivities and norms should also be considered when designing olfactory-based social features. Different cultures may have varying associations with specific smells—what is considered pleasant or offensive may differ widely across cultural contexts. Developers should consider including customizable scent settings that allow users to adjust or disable certain smells based on their cultural or personal preferences. This would help avoid potential discomfort or misunderstandings in cross-cultural virtual environments. As virtual environments evolve, unique or branded scents could become commodities similar to digital assets like music, art, or emojis. For example, a user might send a signature branded perfume as a virtual gift, which could introduce copyright and ownership issues.

6.4 Limitations & Future Work

While our study provides promising results, it also has several limitations. First, while the object categorization used in this study can cover most typical interaction scenarios, it does not fully account for the complexity of users' perceptual behaviors when interacting with scents. For example, actions such as deep breathing to better perceive an odor, covering the nose to avoid an overwhelming scent, leaning forward to get closer to the scent source, or even isolating the object (e.g., sealing a container to stop scent dispersion) are not captured by our current classification framework. These actions fall outside the predefined interaction modes. Individual sensory perception, preference, and situational context differences often drive these subtle but essential behaviors. Further research could focus on the user-centered olfactory perception, embracing context-aware sensing technologies (e.g., breathing and behaviors).

Besides, the sample size of 16 participants is relatively small, which may limit the generalizability of our findings to broader populations.To enhance the applicability of our results, future research should aim to include a more diverse participant pool, encompassing a wider range of cultural [4, 56], demographic, and sensory profiles. Moreover, our work primarily relied on a single form of visual feedback during the interaction process. This limited form of feedback may have influenced user perceptions of their gestures, as participants could not experience more diverse or dynamic feedback modes, such as tactile cues, which might enhance or alter their gesture choices. Future work should explore the outcomes of user gesture design and satisfaction with olfactory interaction

experiences across different forms of visual feedback, including those with and without any olfactory cues.

Additionally, we did not incorporate unpleasant or "bad" smells during the gesture elicitation phase. The absence of these types of scents may have affected participants' suggestions for gestures, as dealing with unpleasant odors could evoke different interaction needs and preferences compared to pleasant smells. The specific type and nature of odors likely play a crucial role in shaping the interaction methods proposed by users, and this remains an area for future exploration.

7 Conclusion

In this study, we explored proactive olfactory interaction in VR through user-defined hand gestures, focusing on how object types and interaction modes influence gesture design. Our findings indicate that while task-specific requirements predominantly shape gesture preferences, the object's physical state and interaction distance also play critical roles in determining the types of gestures users naturally adopt. Additionally, our comparative study showed that gesture-based interactions significantly enhance user experience, presence, and engagement compared to traditional VR controllers. Participants appreciated the intuitive and immersive nature of freehand gestures, particularly when combined with multisensory feedback, which created a richer and more dynamic experience. Overall, our research contributes guidelines and insights for designing intuitive gestures for *proactive olfactory interactions* in VR, offering potential benefits for applications such as games and social platforms that seek to incorporate this novel input modality.

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