Abstract
Introducing olfactory display in the virtual reality (VR) system brings the immersive experience to new heights. However, it is intractable to simulate olfactory features (such as the intensity and the direction) with multiple levels. Visual stimuli have been proved to dominate human perception among multiple sensors in virtual environments. If visual stimuli can be used to guide the olfactory sense in VR, the design of the olfactory display can be simpler but still able to provide olfactory experience with more diversity. To understand the visual-olfactory effect on different olfactory characteristics, a portable olfactory display that can control the intensity and direction of odors was developed. An experimental study was conducted to investigate cross-modal human perception, i.e. how the visually virtual odor representation in VR influences human perception of real odor produced by the proposed olfactory display. The results showed that the perception of odor intensity and directionality can be modulated by visually virtual odor representation.

Keywords: virtual reality, olfactory display

Index Terms: Human-centered computing—Virtual reality——

1 Introduction

Researchers have been working hard on building immersive virtual environments (VEs) to deliver better experiences and improve user’s sense of presence. Since humans sense the real world through multiple avenues of perception, the use of multisensory interaction has been commonly discussed in virtual reality (VR) [1–4]. Ranasinghe et al. [2] proposed a multisensory narration VR system called Season Traveller, which provided odors, temperatures, and wind feedback to increase the sense of presence in a "four seasons" narration experience. In their experiments, the presence and game experience of participants based on different combinations of stimuli were investigated. The use of multisensory integration led to a higher sense of presence compared to traditional VR experiences. Gonçalves et al. [4] investigated the influence of including multisensory stimuli, e.g. visual, haptic, and olfactory in VR. The results indicated that the sense of presence was significantly increased when all multisensory stimuli were provided.

Olfaction, a process of using chemoreceptors to create the perception of smell [5], has been proved to have direct connections to emotions and memories [1, 6]. The use of olfactory feedback can not only aid the memory recall of real-world experiences but also improve the sense of presence in VR. However, olfactory stimuli is a less studied factor in VR [7], and the use of olfactory stimuli has only been discussed in the last few years [8]. Compared to other stimuli in VR, it is much more difficult to implement a portable system that can activate realistic odor. For example, we can easily simulate a visual scene or an audio clip of a car driving from left to right by using a game engine (such as Unity) and a head-mounted display, but it would be a challenge to simulate the flower odor coming from a specific direction by using a portable device with limited size and weight. Further investigation is needed to make good use of olfaction, which is one of the most important senses in human perception.

In this work, we aim to design a portable olfactory display that can produce odors with more direct controllable features, i.e. odor intensity and odor directionality. Moreover, utilizing visual cues to modulate the sense of olfaction has been discussed in recent years [9]. We also try to discover whether the visual representation of virtual odor can influence human perception of the real odor produced by the proposed olfactory display. As shown in Figure 1, the visual representation of virtual odor is rendered above the virtual environment. The color of the particles is designed based on the semantic of the object. For example, on top of an citrus slice model, we placed particle simulation to modulate the sensing of olfaction has been discussed in recent years [9]. We also try to discover whether the visual representation of virtual odor can influence human perception of the real odor produced by the proposed olfactory display. As shown in Figure 1, the visual representation of virtual odor is rendered above the virtual environment. The color of the particles is designed based on the semantic of the object. For example, on top of an citrus slice model, we placed particle simulation rendered in orange, that semantically corresponds to the citrus. The intensity and directionality of the virtual odor particles can be controlled according to our demands. We design experiments in which the users see the visual odor representation matches or mismatches the actual odor produced by our olfactory display. The experimental results show that there is cross-modal interactions between visually virtual odor representations and real olfactory stimuli, which means proper design of visual feedback could modulate user’s perception of the olfactory feedback provided by our device. With the help of visual stimuli in VEs, the proposed olfactory display can strike a balance between mobility and diversity of olfactory feedback.
2 RELATED WORK

2.1 Improving Presence in VR by Olfaction

Regarding the sense of presence in VR, the concept of the perception or illusion of being in a virtual world might come to mind [10]. The improvement of presence by increasing the quality of the five senses (sight, sound, touch, smell, and taste) perceived by a human in a VE has been often explored [11]. Moving on to olfactory stimuli, previous studies [7, 12] have already revealed that the integration of olfactory feedback can provide stronger feelings of the presence in immersive VR. Munyan et al. [12] investigated whether the existence of olfactory stimuli can increase the presence and further affect anxiety responses in exposure therapy in VE. Narciso et al. [7] studied the influence of tactile and olfactory stimuli on participants’ sense of presence and cybersickness while watching a 360° video using an HMD. Both results showed that the inclusion of odors significantly increased participants’ self-reported presence during the experience.

2.2 Olfactory Displays

Olfactory displays, which combines both physical and chemical stimuli to deliver odors [13], have been developed to provide olfactory feedback in immersive VR scenarios [2, 16–19]. Patnaik et al. [17] implemented a multi-odor olfactory display called viodor, which allowed the switching of flow temperature, frequency and direction to accompany a data visualization application. Additionally, by controlling the speed and direction of wind stimuli, the olfactory module proposed by Ranasinghe et al. [2] could deliver different perceived levels of intensity/directionality, and types of olfaction. Making use of flexible tubes, Micaroni et al. [18] designed a directional multi-odor olfactory display in which the directionality of the odor was based on the arrangement of the tubes attached to the headset. Overall, these displays might have the ability to change more than one olfactory factor (i.e. odor type, directionality, and temperature/intensity); however, improving the precision of the perceived levels for olfactory factors while maintaining the advantage of device portability is difficult. That is to say, it is challenging to design a portable olfactory display to simulate multiple perceived levels of olfactory intensity, temperature, and directionality.

2.3 Visual-olfactory Interaction

In cognitive neuroscience and chemosensing, many researchers have already provided evidence of the cross-modal effects between visual and olfactory sensors. Different olfactory characteristics have been investigated, including odor type, intensity, and directionality.

2.3.1 Odor Type

Real-worlds objects spread distinct odors that are robustly verified to have different fragrance categories in human perception [20]. Some studies performed odor discrimination or identification tasks to explore whether the semantic congruence of visual cues affects the human perception of olfaction [9,21,22]. Zeller et al. [22] thoroughly reviewed studies that investigated different aspects of influence that color can have on odor, such as odor identification, intensity, and pleasantness. Semantically congruent images were proved to benefit the process of the human olfactory system and enable the rapid detection of the presence of an odor [9]. Similarly, in rapid olfactory discrimination, the congruent color and shape information of visual cues facilitated the task and led to better performance in reaction time and correctness [21]. In a subjective manner, Amsellem et al. [23] found that the congruence between bi-model stimuli can both decrease the response time and increase the pleasantness. Likewise, authentic odors and congruent video content were suggested to provide more pleasantness and emotional arousal in a visual-audio simulation [24].

2.3.2 Intensity

Compared with the interaction between visual cues and odor type, the effects that visual stimuli have on the perception of olfactory intensity are less well explored. Olfactory intensity represents the concentration of an odor in the air. Researchers [25, 26] have found that the presence of color in visual stimuli is an important factor in the enhancement of perceived odor intensity. The odor intensity was rated higher in the colored situation than in the colorless one.

2.3.3 Directionality

The directionality of olfaction can be defined as the source position emitting an odor relative to the sniffer’s position. Directional smelling is defined as the human ability to localize an olfactory source by sensing odor distribution. A study proved that humans have the ability to discriminate odor from left or from the right only when perceiving mixed olfactory and trigeminal stimuli [27]. The implicit ability of directional smelling in humans was clearly demonstrated in an experiment using a visual-olfactory spatial cueing paradigm [28]. The question of whether the sense of vision can dominate the perception of olfaction in an HMD-based environment was proposed by Micaroni et al. [18]; however, this was only a preliminary experimental workflow, and no real experimental data were collected by their prototype in the paper. Although many researchers have explored humans’ directional smelling ability, few previous study have investigated how the position of visual stimuli can influence the localization of the olfactory source. In addition, studies investigating the odor directionality usually directly insert the tubes into nostrils, which might highly influence human’s feelings in VR experience and many users would resist to use this kind of device.

In summary, portable olfactory displays enable the control of multiple olfactory characteristics, such as type, directionality, and intensity, to provide more realistic simulations. However, keeping both the mobility and distinct levels of olfactory perceptions is a knotty problem. Furthermore, except for [18, 24], most visual-olfactory-related studies used a 2D-monitor as the visual stimuli display, which can only provide a low-immersion experience for users. The cross-modal interaction between visual cues and perceptions of the intensity and directionality of olfactory stimuli are still less examined in VEs using HMDs to provide high-immersion visual stimuli. This study investigated how virtual odor representation might influence perception.

3 PROPOSED OLFATORY DISPLAY

Figure 2 shows the proposed olfactory display. The display employed an Arduino KTDuino UNO R3 A1 as a controller to change the different levels of olfactory characteristics. In the proposed device, the olfactory display unit (Figure 2(a)) is composed of an odor generator and an odor deliverer, which can provide the basic functions of an olfactory display [13]. In the odor generator, an absorbent cotton core was put inside a reservoir filled with essential oil to absorb the odor liquid (Figure 2(b)). Using an atomization-based vaporization method, an ultrasonic atomizer (Grove – Water Atomization v1.0) was attached to the cotton core to diffuse the odor into the air (Figure 2(c)). For the odor deliverer, a 5-V fan (Figure 2(d)) with two-pin connector provided the active delivery of airflow. To modulate airflow intensity more accurately, a MOSFET
within-subjects design was used such that each participant experi-
exenced all conditions of the trials in two separate tasks: an intensity 
task (task 1) and a directionality task (task 2).

A pilot study was conducted to investigate the cross-modal inter-
vention. The olfactory stimulus was presented by the proposed portable olfac-
tory display described in Section 3. Both stimulation devices were 
connected to the laptop running Microsoft Windows 10.

In the experiment, we used 100% pure essential without diluted. 
The ingredients of each essential oil are listed as follows. (1) wood: 
Chamaecyparis Obtusa extracted by stream distillation; (2) citrus: 
Citrus Sinensis extracted by cold pressed method; (3) flower: Lavand-
ula Angustifolia extracted by stream distillation.

In the experimental virtual scene, a participant sat in front of 
a virtual table, with a corresponding target virtual object and a 
monitor arranged on it. The participants could see a target object 
and its virtual odor representation with semantically related color 
(diffused in a conical distribution, as shown in Figure 1). Detailed 
description of the virtual odor representation was stated in Section 
4.2. Furthermore, a questionnaire system was implemented inside 
the VR experiment scene. According to a study [29], completing the 
presence questionnaire directly in VR reduced the study’s duration 
and distraction factors and increased the consistency of the variance. 
During the experiment, participants could read the question on 
the virtual monitor and answer it by clicking the checkbox of their 
choice using the Vive controller.

4.2 Virtual Odor Representation

In this study, the virtual odor representation accentuates the visual 
effect representing the odor a user can see in the virtual scene but 
not physically smell. It was rendered by the particle system in the 
Unity game engine. This particle system has the ability to robustly 
simulate particle effects such as moving liquids, smoke, and flames. 
The emission-spawning rate was modulated to simulate different 
intensities of odor effects. The simulation of bi-directional olfactory 
feedback in the virtual scene was implemented by arranging the 
target object and its particle simulation on the left or right side 
related to the user.

4.3 Participants

Thirty participants (14 males and 16 females) were recruited from 
the local university by advertising at the campus. These participants’ 
ages were in the range 18 to 29 (M=22.10, SD=3.58). The partici-
ants’ previous experience with VR were also determined (17 had 
ever used VR, and 13 used before). Participants were randomly 
assigned to an odor type (wood, citrus, flower) in the experiment. 
The number of participants for each odor type was 10.

4.4 Procedure and Measurements

Participants were told about the experimental environment and the 
goal of this study upon arriving at the laboratory. After they had pro-
vided informed consent to participate in the experiment, they were 
shown the proposed olfactory display and VR interaction system. The participants experienced several test trials to familiarize them 
with the experimental operations, such as the method of selecting an 
answer using the Vive controller.

The experimental procedure consisted of three main sessions: the 
trial, a rest period, and an exit-questionnaire. In the trial session, 
two kinds of tasks were conducted to investigate the influence of 
intensity-related and directionality-related factors. In both tasks, 
various levels of intensity and directionality were modulated in 
visual and olfactory perceptions. The virtual odor representation is 
the virtual effect which can be perceived visually in VR. The real 
olfactory is the real odor released by our olfactory display and can
be physically smelled by the user. Detailed description of these tasks are described as follows.

**Task 1. Intensity:** The goal of this task was to investigate whether the intensity of virtual odor representation might influence the perception of real olfactory intensity. In psychology, an early study [30] showed that people can correctly identify three different levels of olfactory intensity. Therefore, the task involved nine kinds of intensity conditions, i.e., three levels of intensity (none, weak, and strong) for virtual odor representation × three levels of intensity (none, weak, and strong) for real olfactory. As shown in Figure 3, various level of intensity ((a) none, (b) weak, and (c) strong) for virtual odor representation were presented.

**Task 2. Directionality:** The goal of this task was to investigate whether the directionality of virtual odor representation might influence the perception of real olfactory directionality. Due to the complexity of providing high-quality directionality in a portable device, this task simply involved four kinds of directionality conditions, i.e., two levels of direction (left and right) for virtual odor representation × two levels of direction (left and right) for real olfactory. As shown in Figure 3, various level of directionality (a) left, and (b) right) for virtual odor representation were presented.

Figure 3: Virtual odor representation of various intensity conditions (a) none, (b) weak, and (c) strong. In each condition, the emission-spawning rate was modulated to simulate various intensity of particles visually.

![Figure 3](image)

Figure 4: Virtual odor representation of various directionality conditions (a) left and (b) right. In each condition, the virtual object was positioned at the left-hand or right-hand side of the user.

In both tasks, different conditions were used in a single trial and repeated for three times which resulted in 27 and 12 trials for task 1 and 2, respectively. The order of different conditions was counterbalanced among participants (the order of 27 trials is different among participants). The target odor was presented until participants had indicated the intensity levels/the directionality they perceived or the trial termination time (9s in both tasks) had been reached. In addition, the system asked participants to rate the confidence of their answer on a 5-point Likert scale. Next, a 30-s rest period was provided to ensure that there were no between-trial effects during the experiment. After all trials finished, an exit-questionnaire session was conducted. Two exit-experiment questions were asked to gain further understanding: (1) which odor type did you smell in the experiment? (2) In your opinion, how consistent was the real odor with the virtual odor representation? Participants took 10-minute breaks between the task types.

To assess the users’ perceptions of different levels of olfactory features, for each trial, the correctness of the perceptual intensity/perceptual direction answer, the completion time of answering, and the self-reported confidence of submitted answers were recorded for each trial. In addition, the exit questionnaires were conducted as a subjective evaluation.

### 5 Results

In this section, the experimental results, including the correctness, completion time, self-reported confidence of the submitted answers, and exit-questionnaires, are reported. The correctness was defined as the ratio of matching between selected olfactory-perceived intensity and direction by the participant with the olfactory stimuli. The completion time was counted from the start of a trial until the participant gave their answer or the trial termination time (9 s).

Following the recommendation in [31], the mechanism of bootstrapping was used to derive the estimated distribution of data for the correctness and completion time; bootstrapping uses resampling with replacement to get a asymptotically more accurate estimation for further analysis. In this study, bootstrapped confidence interval was illustrated to show a more general results on various data across odors. Figure 5 shows the bootstrapped mean (N = 1000 iterations) with 95% confidence intervals of the correctness and completion time in each task. The bootstrapped mean (95% confidence limits) correctness of all trials in tasks 1 and 2 was 42.32% (34.44%, and 47.78%) and 40.41% (35.00%, and 45.83%). The bootstrapped mean (95% confidence limits) completion time in tasks 1 and 2 was 5.83s (5.54, and 6.10) and 5.93s (5.60, and 6.26). The bootstrapped mean (95% confidence limits) self-reported confidence in tasks 1 and 2 was 4.04 (3.87, and 4.21) and 3.89 (3.69, and 4.08).

Figure 6 shows the results in congruent and incongruent conditions for the different trial types. A paired-samples t-test was conducted to compare the correctness and completion time between congruent/incongruent conditions for both type of trials. There were significant differences in the correctness between the two conditions in both tasks 1 (t(29) = 14.070, p < .001) and 2 (t(29) = 14.284, p < .001). There were no significant effect on the completion time and the self-reported confidence between congruent/incongruent conditions.

The answer matrix is used to analyze the data in different conditions, which can separately illustrate each participant’s performance in each real-virtual congruent and incongruent condition. For example, as shown in Figure 7(a), the correctness in the trials that did not present both virtual odor representation and real olfactory stimuli is 40.00%. That is, 36 answers were correct out of all 30 (number of participants) × 3 (number of repetition for each condition) = 90 trials. Figure 7 shows the answer matrices of (a) the correctness, (b) the completion time, and (c) the self-reported confidence for tasks 1 and 2.

To further investigate the influence of different odor types, a one-way between subjects ANOVA was conducted to compare the effect of odor type on the correctness, completion time, and confidence in wood, citrus, and flower odors. It was concluded that there was no significant difference in mean correctness (F(2, 27) = 0.403, p = 0.673), completion time (F(2, 27) = 0.106, p = 0.855), and confidence (F(2, 27) = 0.368, p = 0.696) due to odor type.

The reported results of the exit-questionnaire were as follows. For the first question (Q1), the accuracy of odor discrimination for different odors were 45% for wood, 100% for citrus, and 85% for flower. Figure 8 shows the results of the second question (Q2) for each trial type. The mean of the self-reported consistency between the virtual odor representation and the real olfactory stimuli (Q2) was 3.93 and 3.97, respectively.

### 5.1 Discussion

Overall, participants’ ability to identify different levels of odor intensity and directionality under visually interfered situations was
weak. As shown in Figure 5, most participants were usually confident about their answers but the correctness was only around 40% in both trial types. In the results of the consistency question (Q2), even though 61.54% of trials were visual-olfactory incongruent conditions, the mean self-reported consistency were almost rated as 4.0. We speculate that this might be due to participants’ unawareness of incongruent conditions. In the exit-questionnaire, except for the wood odor, participants could discriminate the odor type after each experiment. The results show that different type of odors does not seem to impact the perception.

The results in congruent/incongruent conditions (Figure 6) demonstrated that the virtual odor representation affected users’ perceptions of different characteristics of real olfactory stimuli. Regardless of task type, participants were more likely to answer the correct real olfactory intensity/directionality in the congruent condition. Even there were effects on the correctness, participants took similar response times to answer and reported similar confidence levels in different conditions. These findings also support the notion that human’s perception is unconsciously influenced by visual cues.

The following paragraph gives further details about the particular conditions. Firstly, as shown in Figure 7(a), when diffusing a strong intensity odor, the correctness increased as the intensity of the virtual odor presentation increased. Participants performed best (62.22%) in strong visual-olfactory congruent conditions and were less likely to choose “Weak” when the real state was “Strong”. Secondly, when diffusing weak-intensity odor, people had difficulty distinguishing between weak and strong odors even in the weak visual-olfactory congruent condition. Lastly, when there was no odor diffused into the air, people still marked the intensity as “Weak” and “Strong”. The reason might be that the odors coming from the odor liquid bottle in the olfactory display unit is not well blocked by our hardware design. Thus, even when the ultrasonic atomizer was turned off, there was probably a trace amount of odor surrounding the device. The other potential reason is that the combined effect of trace amounts and incongruent visual cues influence users’ judgement. A similar pattern of results was obtained in [30] that weak intensity stimuli are less likely to explicitly judge correctly compared with the strong one in the congruent condition. Also, the results in the perception of odor intensity is related with what has been found in [32]. As stated in [32], the odor intensity was underperformed by other sensory features for all data type in their information olfaction study. The perception of odor intensity is subjective and needs extended training to build up shared perception rank. It might be the reason for the confusion between “Weak” and “Strong” even in the congruent condition.

Regarding the directionality, the results in Figure 7(d) show clear support for the influence that virtual odor representation had on the perception of olfactory directionality. With the interference of visual cues, participants can rarely distinguished the directionality in the incongruent condition. Clearly, the perception of olfactory directionality was highly influenced by the congruence between visual and olfactory feedback. The results in [28] showed that people do not have the ability of explicit directional smelling. These results lead to a similar conclusion where an portable olfactory display using VR can only provide a minimal level of directionality (i.e. only one direction). The modulation of different olfactory sources can be mainly controlled by visual stimuli (the position of virtual object in the scene).

There are two shortcomings of the presented study. First, the possibility of a trace amounts of odor surrounding the device exists. We already conducted pilot study to validate the presented olfactory stimulus was consistent with the desired odor state. However, the design of the proposed device was based author’s perception of olfactory stimuli, which is subjective. A more robust architecture should be designed to ensure there is no any odor when the ultrasonic atomizer is turned off. Second, participants’ ability of identifying...
odors and determining directionality without visuals were not tested in this study. In the future work, we will conduct experiments on multiple tests (maybe even on different days) with different odors and various olfactory characteristics without visual hints.

In summary, the results showed that user's smelling might be influenced by the visual effects in VR, especially in incongruent condition of various odor directionality. With the help of this visual-olfactory effect, we do not need to implement different olfactory characteristics (i.e., intensity and directionality) with a lot of levels when designing an olfactory display in VR. Instead, few levels of odor simulation combined with proper visual effects can result in different olfactory perception, which makes the olfactory display easier to be portable. For example, the olfactory display can only provide odor from one direction and modulate user's perception of odor directionality by placing visual odor representations in various position in the VE.

6 Conclusion

In this paper, a prototype of a portable olfactory display with the ability to modulate different levels of odor intensity and bi-directional odor source was developed. To explore the interaction effect between visual (virtual odor representation) and olfactory stimuli in VR, an experiment was conducted to investigate different levels of odor intensity and directionality. Collectively, this paper is the first one that investigates comprehensive visual-olfactory interaction of different olfactory intensity and directionality in immersive virtual environment. Final results shows that the perception of the both features (intensity and directionality) of olfactory stimuli are highly modulated by visual cues in VR. Designers can use proper virtual odor representation to guide the perception of olfactory feedback. A minimal level of these odor features are sufficient for an olfactory display to simulate in an VR experience. The future development of portable olfactory displays in VR can focus on improving other olfactory characteristics to provide better experience.

References


