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Simulating Olfactory Cocktail Party Effect in VR: A Multi-odor Display Approach Based on Attention

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Abstract

Odor display has been a popular approach in virtual reality (VR) to enhance users' multi-sensory experience. The existing multi-odor presentation methods in VR are mostly based on spatiality of scent sources to produce mixed scents, which will possibly compromise users' olfactory experience because humans normally have poor ability to analyze distinct odorant components from a mixture. To tackle this problem, we present a VR multi-odor display approach that dynamically changes the intensity combinations of different scent sources in the virtual environment according to the user's attention, hence simulating a virtual cocktail party effect of smell. We acquire the user's gaze information as attention from the eye-tracking sensors embedded in the head mounted display (HMD), and increase the display intensity of the scent that the user is focusing on to simulate the cocktail party effect of smell, enabling the user to distinguish their desired scent source. We conducted a user study to validate the perception and experience of 2 ways of intensity settings in response to the user's attention shift, which were a strong level of focused scent mixed with weak levels of non-focused scents and strong focused scent only. The results showed that both of the two intensity settings were able to improve olfactory experience in VR compared to the non-dynamic odor display method. Meanwhile, only the method of presenting strengthened focused scent while maintaining the weaker mixture of background scents showed significant improvement on simulating the olfactory cocktail party effect by giving the users an enhanced sense of their own olfactory sensitivity.

Keywords: virtual reality, odor presentation, attention

Index Terms: Human-centered computing—Human computer interaction (HCI)—Human-centered computing—Interaction paradigmsVirtual reality

1 Introduction

The technique of virtual reality (VR) and augmented reality (AR) has been popular presentation tools in various situations such as entertainment [29], training and education [21, 23], medical therapy [18], especially in the time of COVID-19 when on-site events are more difficult to realize than before. in addition to visual presentation with the head-mounted display (HMD), multi-modal displays, such as audio, smell, or haptic, have been developed to provide a more immersive VR experience [8]. Among those senses, the olfactory display is relatively challenging to optimize because the diffusion of scents in the air cannot be controlled precisely, and it requires special and complex devices to convey odors to the user's nose. To tackle this problem, different types of odor display devices and methods have been developed to present odors in VR. With many computer-controllable features, virtual scent display devices have shed light on possibilities of presenting scents in ways that are quite different from reality or even an augmented version of realistic olfactory sensation. In this work, we intend to create an augmented olfactory experience for VR users.

In the aspect of odor presentation in VR, it is common to present one scent corresponding to the entire virtual environment, for instance, to produce the scent of wood when the user is in a virtual environment (VE) of a forest [24]. However, there are also demands to present multiple scented sources in one scene to increase the variety of odor presentation. To simulate the natural perception of multiple scents, it is intuitive to display a mixture of odors, of which the intensities vary according to their distances to the user [4]. This means that if the user is in the same distance to multiple scent sources in VE, they will receive an odorant mixture of almost equal intensities. However, there is a problem that humans have a rather poor ability to detect and distinguish mixtures of odors, compared to audio or visual ability. Studies have found that humans are poor at analyzing the components of odorant mixtures, suggesting that the sense of smell is a synthetic sense in which mixtures are perceived as a whole [32]. As a result, although the distance-based method reflects the olfactory spatiality, users' sense of presence in VR could be compromised when they receive mixed odor presentations they cannot recognize, inconsistent with their visual perception in VE. To tackle this problem, we lay our attention on the cocktail party effect of human sensations.

The cocktail party effect refers to one's sensational ability to distinguish particular stimuli of their attention among others and filter out other non-concerned stimuli such as noise [7]. This phenomenon was first demonstrated in auditory stimuli [9] and was very common among humans [2]. Because of humans' extraordinary ability to distinguish different audio components from overlaying sound signals and high-level perceptual and language processing ability [2], the cocktail party effect of sounds can be very obvious. Considering olfaction, although there is not yet direct proof showing humans also have an olfactory version of cocktail party ability, some studies indicated that some animals could be trained to detect target odorants embedded in unpredictable and variable mixtures [32]. Moreover, multiple studies have proved that human's sense of smell is influenced and modulated by their attention [13, 37].

In real life, the olfactory cocktail party effect is trivial because the human senses tend to perceive odors holistically. But on the other hand, by utilizing some features of virtual odor display devices such as precise duration control and instant scent switch, it is possible to create an odor presentation system with dynamic intensity based on the user's real-time attention. This work proposes a novel odor presentation approach to simulate the olfactory cocktail party effect in VR, which dynamically adjusts the intensity composition of multi-odor mixture presentation according to the user's attention. By this approach, we aim to create an augmented sense of olfactory segregation in VR to compensate for humans' natural lack of odorant mixture analyzing ability. This presentation method is not expected

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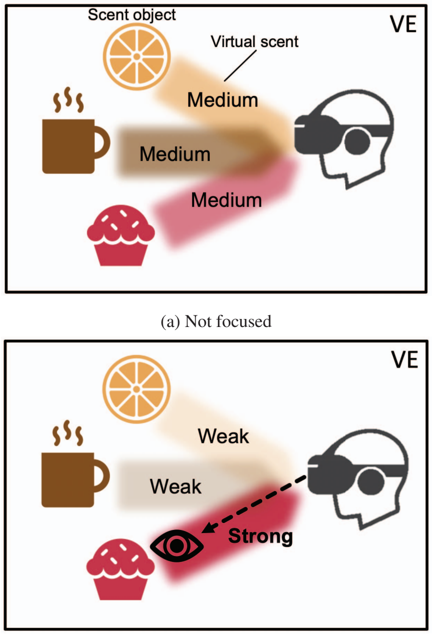


(a) Not focused

(b) Attention detected

Figure 1: The proposed attention-odor intensity composition in VE.

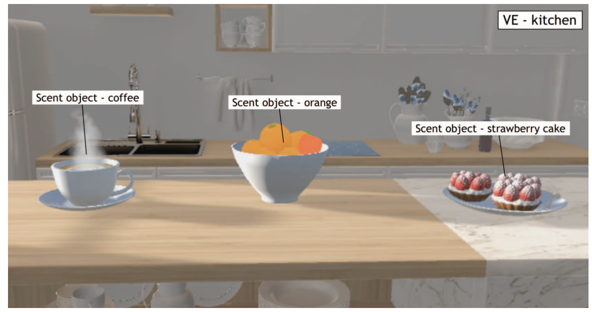


Figure 2: 3 scented objects in the kitchen VE.

to entirely recreate olfactory perception in reality but to optimize virtual odor display to fit the user's visual cognition and attention in VE. We anticipate this method can hence improve the user's sense of presence in the multi-odor VE and provide them with an intuitive virtual olfactory experience. To evaluate our method to that extent, we implemented the proposed system and conducted experiments to investigate users' subjective perceptions and experiences.

2 Related Work

2.1 Odor Presentation in VR

Virtual odor display has been researched to provide a multi-model experience in VR. First, various odor display devices were developed to provide odor presentation. Yamada et al. [38] developed a wearable olfactory display to present the spatiality of odor in an outdoor environment, also able to adjust the odor intensity according to the user's position in the VE. Yanagida et al. [39] used wind and vortex rings to design an odor display system to produce precise spatial and temporal in AR. Studies also demonstrated that odor presentation in VR can improve immersive user experience and can be applied for various purposes. For example, Amores et al. [1] designed a VR system using olfactory interfaces to promote relaxation. VR olfactory presentation has also been applied for better education and learning experience [21].

Recent studies have looked into users' perception of odor presentation in VR and AR. Fujino et al.'s work showed that the sensation of odors could be modulated by temperature manipulation, in their case, presenting warm/cool air [14]. Persky et al. [31] investigated olfactory perception and presence in a VR food environment and discovered that correct perception and identification of the olfactory stimulus was associated with the heightened presence and was likely to sway the user's action choice in VE.

Overall, odor presentation in VR is still a relatively unrevealed territory in VR studies compared to virtual visual and audio stimuli. In most previous studies, only one scent was presented in one scene or certain space. Few have demonstrated multiple odors presented in one scene, as well as how they may affect the user's experience. Recently, Bahremand et al. [4] developed an olfactory presentation system to deliver dynamically mixed odors representative of the spatially propagated odors in the VE. But still, it lacks user study on olfactory perception and experience.

2.2 The Cocktail Party Effect

The cocktail party effect was first addressed by Cherry [9] in 1953. Originally, it referred to one's ability to selectively focus their auditory attention on a target voice in the presence of competing voices, i.e., the phenomenon that people can focus on one conversation and distinguish the speech signals clearly in a noisy cocktail party environment. Afterward, many researchers have been studying human's attention modulation on sensations. There is still no clear evidence showing that humans possess a strong olfactory ability of cocktail party effect. On the contrary, previous studies showed that humans are very poor at analyzing mixtures or detecting target odorants within mixtures [19, 22]. However, some recent studies indicate that humans' olfactory sensing ability is affected and modulated by attention and other sensory stimuli. Forster et al. [13] proved that human's olfactory awareness is dependent on attention. Especially, visual distraction may cause prolonged loss of olfactory awareness. Similarly, in VR, Tsai et al. [37] conducted experiments to investigate cross-modal perception in VR and how the visually virtual odor representation in VR influences human perception of actual odors. Their results showed that the perception of odor intensity and directionality could be modulated by visually virtual odor representation. Bolia et al. conducted an experiment to determine the extent to which hemispheric specialization is manifested in the design of spatial audio displays [5]. Still, not enough work has emphasized how odor display design can be optimized based on attention-odor modulation.

3 Methods

We aim to develop a visual and olfactory VR system that simulates the user's augmented feeling of the olfactory cocktail party effect in a scene containing multiple scent sources. To begin with, we set up a scene in VE where the user is supposed to receive multiple kinds of scents from their corresponding scented objects simultaneously, making it necessary to present mixed scents to the user. We propose to realize the desired system by dynamically adjusting the displayed intensities of the scent mixture according to which scent source the user is focusing on. The process of simulating the olfactory cocktail party effect in VR can be divided into two steps: i) acquiring the user's attention, and ii) changing the proportion of intensities of each scent in the mixture to provide a sense of the focused scent. Specifically, when the user does not focus on any of the scent source objects, we present all of the scents with the intensities setting following a distance-based principal, as is illustrated in Fig. 1a. In this paper, we assumed that objects within reachable ranges were approximately at equal distance to the user in VE to simplify the system. When detecting the user is focusing on a particular scent source object, we increase the presented intensity of the corresponding focused scent to a stronger level, and at the same time, lower those of the non-focused scents, as is illustrated in Fig. 1b. By this dynamic approach, we expected to modify the user's olfactory intensity perception according to their attention, hence giving them a sense of being able to recognize their desired scent.

Compared with existing directional and spatial odor display in VR, the novelty of our approach is to augment the user's olfactory sensation in VR. The spatial techniques in the literature often render a single scent at one time [28, 38], and the switch of scents depends on the user's physical position and direction in the VE, which requires them to spontaneously control their avatars and interact with the VE. In comparison, attention information is acquired directly from the user's eye movement, and both conscious and unconscious attention shifts can be detected. Therefore, we expect our interactive attention-based approach to be more intuitive regarding users' olfactory perception and sense of presence in VR, therefore to realize a sensational expansion effect of olfaction in VR.

3.1 Implementation

3.1.1 Odor Display

To thoroughly implement our proposed dynamic attention-odor approach, we need an odor display device with the following functions. First is displaying the mixture of multiple odors with respective intensity control because we want to create an environment of multiple odors for the olfactory cocktail party effect. Second is instant intensity and scent switching controllable by the computer in order to synchronize the odor display with the user's attention in realtime.

For the above reasons, we used a commercially available odor display device: Aroma Shooter® (developed by Aromajoin). Aroma Shooter® is an ink-jet typed scent display device that ejects very fast scented micro airflow directly to the user's nose. It can present a mixture of at most 6 scents with independent intensity control, and the ejection can be set in the range of 1-100% linear concentration phases for the desired amount of time by the computer. The ink-jet odor display has the merit of instantly displaying intensity changes because the device only produces a micro-airflow containing a very small dose of odorants to reach the user's nose. Therefore, once the emission stops, the odorants distribute into the air to an undetectable level very quickly so that the user is able to sense the change of presentation almost instantly. Also, this device is light and easy to wear, which will not significantly reduce the user's sense of presence in VR.

In this work, we adopted the ink-jet typed device for implementation and experiments. Meanwhile, considering future applications, we believe other odor display devices that provide the demanded functions are also suitable for our proposed attention-odor system.

3.1.2 Attention-odor System

To acquire the information of the user's attention information, we adopted the technique of eye-tracking. Studies have demonstrated that the gazing position can reflect the user's visual attention both in the real world and VR [25, 36]. The dynamic attention-odor display system was designed as follows. Basically, we set 3 levels of the scent intensity—weak, medium, and strong. During the VR display, we acquired the user's eye-tracking data and detected if the user is gazing at a scented object or not. When the user was not focusing on any of the scented objects, we mixed all scents at their medium intensity levels based on the equal distance between scent sources and the user in the VE as a default setting. Once the computer detected continuous attention on a scented object for more than 500 ms, we instantly changed the intensity of the focused scent to the strong level. This 500 ms time threshold was to avoid unnecessary odor display responses when the user accidentally glances at the objects. After pre-testing, we found that 500 ms was suitable to reduce false responses while keeping the delay at an unnoticeable level. Likewise, when the system detected the user's attention has shifted to another scented object, it would adjust the display intensity accordingly to increase the currently focused scent; or when the user changed their focus to the surroundings or non-scented objects, odors of the default setting would be presented.

3.1.3 Pre-selection of Odor Concentration

Before implementing the system, we considered it necessary to pre-select display concentrations of every presenting odors because the concentrations corresponding to certain perceived intensity scales depend on the kind of odors, and it is a common approach to pre-select average presenting concentrations across some users for each odor to unify the perceptual levels [3]. We adopted the labeled magnitude scale (LMS) to measure users' individual sensitivities to the presenting odors. LMS is a semantic scale of perceptual intensity characterized by a quasi-logarithmic spacing of its verbal labels [16]. The scale consists of a vertical line, which is marked with verbal anchors describing different intensities (e.g., "weak", "strong"). LMS is a useful tool to study the perceptual differences between participants, including intensity sensations of smell, taste, and temperature.

For each presented odors in our VE, we needed to select 3 perceptual intensity levels of weak, medium, and strong. The selection procedure is described as follows.

i) Present 3 baseline concentrations and acquire participants' perceptual scales on LMS.

ii) Perform linear regression on the logarithmic values of presenting concentrations and participants' semantic intensity scales to approximate their linear correlation.

iii) Reversely calculate the corresponding average concentrations of the desired perceptual intensity levels of weak, medium, and strong.

The particular choices of odor and concentration selection results will be described in the next session.

4 Experiments

In this experiment, we aimed to evaluate the user's olfactory perception and experience to two methods of focused scent display—strong level of focused scent only and strong focused scent mixed with weak levels of other non-focused scents, and also compare the results with the control condition of non-dynamic odor display of equally mixed odors based on spatiality. It was necessary to evaluate those two methods because we considered inducing weak non-focused scents would increase the realism of the odor cocktail party simulation, but meanwhile, it was still unclear whether mixing weak scents would affect the user's perceptual accuracy of distinguishing the focused scent. For clearance, we will refer to the three focused odor conditions described in Sect. 4 as "strong-weak", "strong-none", and "all medium". In Table 1, we list the intensity combinations of different attention states in all presentation conditions.

4.1 Participants

12 participants in their 20s ($M = 24.5$, $SD = 2.25$) participated in the experiment. All participants were confirmed to be in healthy states with no olfactory disorder and able to distinguish the 3 presented odors in this experiment. The participants had no knowledge of the odor presentation conditions during experiments. The University Ethics Committee approved the data acquisition in this paper and written informed consent was obtained from all participants.

Table 1: The intensity combinations in different presentation conditions. The combinations of orange-focused state are listed, and those of other focused objects are omitted.

Condition		Attention status		
		Not focused	Focus on orange	…
Condition	Strong-weak	M M M	W S W	…
Condition	Strong-none	M M M	N S N	…
Condition	All medium	M M M	M M M	…

Odor: Coffee Orange Strawberry
S: strong, M: medium, N: no odor

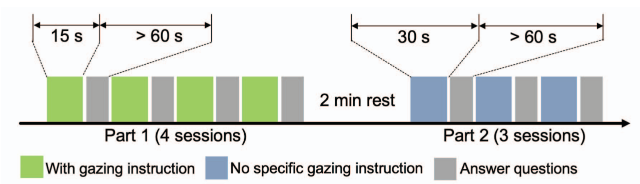


Figure 3: The procedure of each experiment trial. The different gazing instruction was given in each session in part 1 and the order was randomized.

4.2 VE Setting

We created a VE of a kitchen in Unity 3D because it was a suitable scene to contain multiple scent sources, as shown in Fig. 2. For the scent source objects, we selected three objects: strawberry cake, oranges, and coffee, because first, they were suitable for the virtual kitchen scene. Second, the corresponding odors of them were normally easy to distinguish. Those three objects were placed in a row on the table with equal distances between them. In the VE, the user's camera was positioned in front of a table, and the distance between scented objects and the user camera was approximately 60 cm virtually. No user avatar was displayed in VE. In our system, we used a type of HMD that is embedded with eye-tracking sensors (Tobii HTC VIVE), the usage of which is entirely the same as a regular HMD.

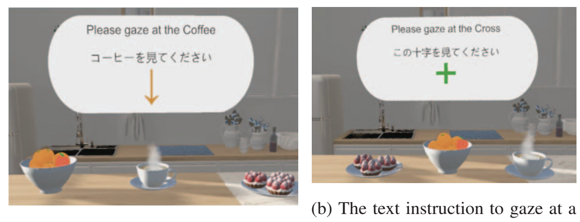
4.3 Selection of Odor and Displaying Concentration

In this work, we selected the odors of strawberry cake, orange, and coffee as the three presented odors in VE. We followed the procedures in Sect. 3.1.3 and gathered data of 6 of the participants. Table 2 shows the final intensity settings for each presenting scent.

Table 2: The presenting concentration of Aroma Shooter®. The target LMS percentages refer to empirical perceptual scales of semantic intensity labels.

Target perceptual levels (LMS)	Virtual scents		
	Coffee	Orange	Strawberry cake
Weak (10%)	15%	10%	9%
Medium (17%)	36%	26%	23%
Strong (32%)	99%	82%	71%

Figure 4: The experiment scene.



(a) The text instruction to gaze at coffee.

(b) The text instruction to gaze at a piont (cross) in the VE.

Figure 5: The text instruction of gazing.

4.4 Experiment Procedure

As is illustrated in Fig. 3, one trial for each odor display condition consisted of two parts: 1) odor segregation and intensity evaluation and 2) subjective experience evaluation. The first part was to measure the participant's olfactory perception of 4 different presenting intensity combinations—the focused pattern of three scented objects and the non-focused pattern with the medium mixture. In each of the 4 sessions, the participant was instructed by text in VE to gaze at a certain scented object (Fig. 5a) or a point in the surroundings (Fig. 5b) for 15 seconds while receiving odor display, and then evaluate their perception levels for each scent. In each session, if the participant was instructed to gaze at an object on the table, the target object was automatically placed in the center while other objects were randomly placed to the two sides to avoid the influence of object placement. Afterward, the participant was asked to evaluate their perceptual intensity scales of all three odors from weak to strong, respectively. We also provided an option of unrecognized odor different from all other selected odors for situations where the participant could not segregate the mixture.

In each session of the second part, the participant received odor display in VE for 30 s without specific gazing instructions. They were only vaguely asked to gaze at each of the three objects on the table for a few seconds for at least one time. Besides that, they were free to look around the VE or to look back at the objects. This was to make sure that first, the participant could look around in VE and shift attention freely so that we could assess the intuitiveness of the odor presentation system. Second, all focused scents were activated at least once to present the entire cocktail party effect simulation. After the VR presentation, the participant was asked to answer a questionnaire about their subjective experience in VE. The questionnaire included questions from Igroup Presence Questionnaire

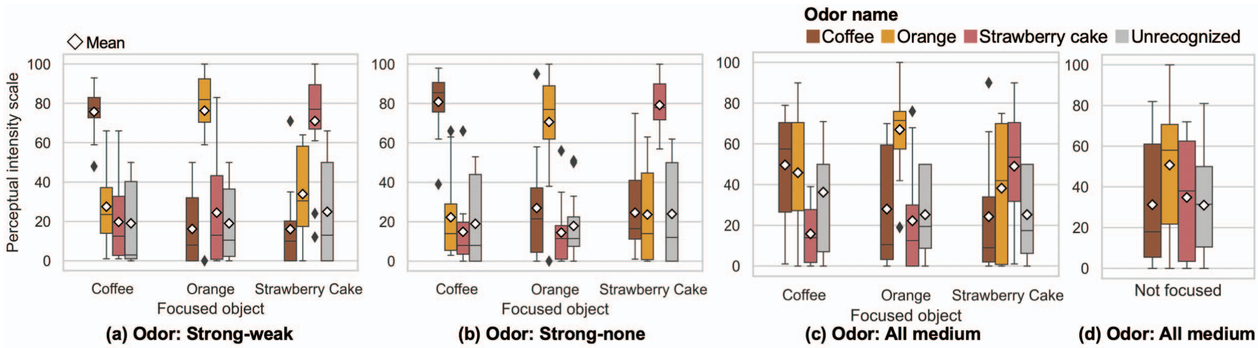


Figure 6: The perceptual intensity scales. In (a) and (b), the intensity of the presented scent differs depending on the object to be focused on. For example, in (a), when the participant focused on coffee, strong coffee aroma, weak orange, and strawberry cake aroma were presented, while in (b), when the focus was on orange, only the strong orange aroma was presented. In (c) and (d), the three scents were equally mixed regardless of whether the object was focused on or not.

(IPQ) [33] and 4 original questions. IPQ is a set of reliable and widely used questionnaires to evaluate participants' sense of presence in VR. In this experiment, we intended to use IPQ to investigate how the proposed odor presentation approach would affect the user's experience of presence. The 4 original questions were asked to assess participants' valence to odors, the experience of enjoyment and intuitiveness of the VR system, and the participant's self-reported olfactory agility. The specific questions and their scale labels are listed as follows.

- The overall pleasantness of the presented odors (Unpleasant - very pleasant).
- The VR experience was enjoyable (Not enjoyable at all - very enjoyable).
- The olfactory VR system was intuitive (Not intuitive at all - completely intuitive).
- Please score your own olfactory sensitivity during the VR experience (Very poor - very accurate).

The above session was repeated 3 times to mitigate the influence from the participant's random gazing actions. Similarly to part 1, the placement of the three scented objects was randomized in each session to avoid order effect.

All evaluation questions in part 1 and 2 were presented in visual analogue scale (VAS) with 0–100 response resolution. The default value of each question was set to 50. Participants answered the questions using an HTC VIVE controller. As noted in Fig. 3, the time to answer the questionnaires was set to no less than 60 seconds for the participants to recover from olfactory fatigue [30]. For each participant, 1 trial in Fig. 3 in each condition (totally 3) was conducted in one day with about 1 hour rest in between to avoid olfactory adaptation and recover from olfactory fatigue. The order of conditions for each participant was randomized to avoid the order effect. The eye-tracking system was calibrated for each participant before each trial.

In each session, odors were produced by continuous ejections to ensure that the participants could receive the odor presentation regardless of their respiration timing. To reduce the possible influence of olfactory habituation, we set the presentation period of each session as short as possible (15 and 30 s) to avoid severe habituation and set the intervals between sessions to at least 60 s for the participants to recover from possible habituation. Previous studies have demonstrated that although depending on specific odors, habituation of continuous olfactory stimuli often appears after 30-40 s [35]; for short-term exposure under a minute, withholding stimulus provides almost simultaneous partial recovery [30]. For future applications, common approaches reducing olfactory habituation, such as pulse ejections synchronized with respiration [20], can be applied to provide longer and more sustained attention-odor presentation.

During VR display in experiments, the Aroma Shooter® was installed on a portable stand that the user wore on their neck, as shown in Fig. 4. Following the user manual of Aroma Shooter®, we kept the distance between the odor diffuse portal and the participant's nose to 15 cm since the manufacturer suggests that the user can receive odors properly within the range of 15-20 cm. Regarding the range of the participant's possible head movement range, after testing, we confirmed that the user could receive steady odor presentation within about 60° range. We conducted the experiment in a spacious and well-ventilated room to reduce the odorant residues. We asked participants to sit still and refrain from turning their heads drastically. Participants were asked to wear a pair of noise canceling headphones (SONY WH-1000XM2) that played white noise, as shown in Fig. 4. This was to prevent the ejection noise of the Aroma Shooter® from distracting the participants as well as to unify the audio environment for all participants. After each trial, we also gathered the participant's free comments.

5 Results

In this section, we report the results of participants' olfactory perceptual scales from part 1 and subjective experience evaluation from part 2 in each trial of the three odor presentation conditions. Fig. 6 shows the results of participants' self-rated perceptual intensity scaling in each focused odor presentation condition. The box plots were drawn to show the results when participants received different gazing instructions to guide their attention—the three scented objects and VE surroundings as non-focused states. These plots show the quartiles, medians, and means. Because the odor presentation was the same for non-focusing instruction in all three conditions, we present those results additionally in Fig. 6d.

The results of participants' subjective experience are demonstrated in Fig. 7. We applied the D'Agostino & Pearson omnibus normality test to the four experiential evaluation items, and confirmed the normality of the distribution for all items. Therefore, we performed the one-way ANOVA to compare the experiential improvement of the proposed dynamic attention-odor methods ("strong-weak" and "strong-none" conditions) with the non-dynamic method ("all-medium" condition). The ANOVA test revealed that there were significant differences between the odor conditions in participants' olfactory valence ($F(2,33) = 7.41$,

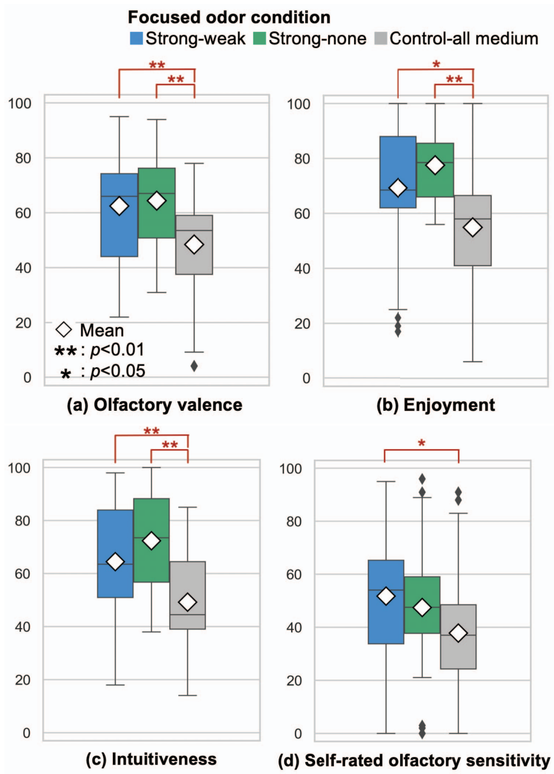


Figure 7: The subjective experience evaluation.

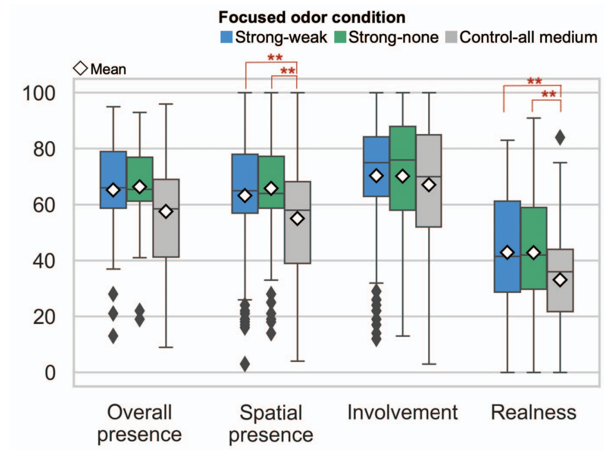


Figure 8: The box plot of participants' overall presence and its subscales in IPQ in each condition.

Table 3: The effect size d to the all-medium condition.

	Condition	
	Strong-weak	Strong-none
Olfactory valence	0.70	0.85
Enjoyment	0.61	1.16
Intuitiveness	0.70	1.22
Self-rated olfactory sensitivity	0.59	0.42

$p = 9.76 \times 10^{-4}$), enjoyment ($F(2,33) = 11.17$, $p = 3.98 \times 10^{-5}$), intuitiveness ($F(2,33) = 11.85$, $p = 2.28 \times 10^{-5}$), and self-rated olfactory sensitivity ($F(2,33) = 3.38$, $p = 0.0379$). Then, we performed the Tukey's multiple comparison test and the independent t-test for means separately between every two conditions. The results showed that there were significant differences ($p < 0.05$) between the dynamic and non-dynamic odor presentation conditions in participants' olfactory valence, enjoyment, and intuitiveness (Fig. 7a, b, and c). Meanwhile, regarding self-rated olfactory sensitivity, only the strong-weak condition showed a significant difference to the non-dynamic method, with the highest mean value among the 3 conditions. To further demonstrate that the results are reliable despite a small sample size, we calculated the Cohen's d values to examine the standardized differences to the all-medium condition (Table 3). These results showed that where there was a significant difference to the all-medium condition, the relative difference was above medium ($d > 0.5$) [11].

Fig. 8 lists the results of participants' presence evaluation by IPQ including it subscales. Because the D'Agostino & Pearson omnibus normality test showed that most of the presence results did not conform to the normal distribution, we conducted Friedman test between each conditions, and this test revealed significant differences in spatial presence ($F(2,177) = 36.56$, $p = 1.15 \times 10^{-8}$), realness ($F(2,111) = 10.51$, $p = 5.21 \times 10^{-3}$), and overall presence ($F(2,33) = 9.75$, $p = 8.33 \times 10^{-3}$) among the scent conditions. There was no significant difference in involvement ($F(2,141) = 2.53$, $p = 0.28$). Then, we conducted the Wilcoxon signed-rank tests with Bonferroni correction between each condition to examine their differences. Within the dynamic attention-odor conditions, we did not discover significant differences.But compared to the all-medium condition, both of the two dynamic conditions showed significant improvements in participants' spatial presence and sense of realness. The significant differences were noted in the figure.

6 Discussion

From participants' olfactory perception level of the strong-weak condition in Fig. 6a and all-medium in Fig. 6d, we can conclude that participants could sense the increased intensity of the focused odor and non-focused mixture correctly. However, Fig. 6b showed that participants also sensed weak levels of non-focused scent, even when only strong focused scent was displayed when they were asked to gaze at one object. This result did not match the actual odor presentation. One most likely reason is the cross-modal integration between visual and olfactory senses. Previous studies found that olfaction can be enhanced when seeing associated colors and shapes [12, 17]. One can also have an illusion of olfactory perception when seeing pictures in a semantically congruent condition [15]. In our experiment, all three scented objects were placed closely so that the other two non-focused objects were also within participants' vision. And thus, the visual perception of the other non-focused virtual objects in VE may give participants a cross-modal effect of smells. These results align with previous findings that there is a strong cross-modal association between odor and vision, and it is important to present integrated visual and olfactory stimuli to enhance users' presence in VR [6]. Similarly in Fig. 6c, the visual-olfactory cross-modal effect appeared in all-medium condition. When participants were focusing on an object, they sensed stronger levels of the corresponding odor of the main visual cue, although there were always three odors presented at the same time in equal intensity.

Regarding participants' subjective experience in Fig. 7 and Fig. 8, the results supported our hypothesis that the dynamic attention-odor presentation would improve users' pleasant experience and presence in VE compared to the all-medium condition. First, both the strong-weak and strong-none conditions of the dynamic method significantly improved olfactory valence (Fig. 7a) as well as the enjoyment experience of whole VE (Fig. 7b). From participants' free comments after each trial, 2 of them specifically reported having unpleasant feelings in the non-dynamic condition when they could not recognize the odorant mixture, and their visual and olfactory perception was inconsistent. On the other hand, 2 participants said they had a fun experience when they noticed that virtual odors were dynamically changing according to their attention. Therefore, we believe that the proposed dynamic method successfully reduced the unpleasantness caused by unrecognizable odorant mixtures and improved valence in olfactory perception, and thus led to a more pleasant overall experience in VR.

Secondly, the sense of intuitiveness was also higher for the strong-weak and strong-none conditions, as shown in Fig. 7c, suggesting that the interaction between participants' attention and odor presentation fit their olfactory instinct. Although the olfactory cocktail party effect is a rare experience in real life, its enhanced simulation in VR remained to be an intuitive olfactory presentation approach. Furthermore, intuitive interaction design is also crucial to enhance users' presence in VR according to existing knowledge [10].

The third, also a very crucial point, is that Fig. 7d demonstrated only the strong-weak condition showed significant improvement to the all-medium condition regarding participants' self-reported olfactory sensitivity, also the highest among all conditions. We infer that the key factor was whether to keep weak background odors while displaying the strengthened focused odor because it was the major difference between the strong-weak and strong-none conditions. Keeping the background odors might be essential in the attention-odor presentation to provide augmented olfactory experience, giving the participants an illusion of the improvement in their own olfactory sensitivity.

Finally, we discovered from participants' comments that the overall realness evaluation was relatively lower compared to other subscales of IPQ was because the entire VE was generated by virtual models without any real photographic materials. Regarding differences between conditions, results of participants' sense of presence in VE by IPQ (Fig. 8) showed that the dynamic attention-odor method was better at providing the senses of spatial presence and realness than the non-dynamic method. By inference, the improvement in spatial presence is probably a result of interaction between visual spatiality and corresponding odor presentation, because we have known from a previous study that users' perception of odor directionality can be modulated by visual presentation in VE [37]. As for realness, an interesting point is that the simulation of the olfactory cocktail effect was originally considered to reduce the realness of VE because it was very different from real-world experience. But conversely, the sense of realness was also higher for the dynamic method. The improvement in the realness of VE was probably because the strengthened focused odors also had a cross-modal effect of enhancing visual perception [34], thus increasing the realism of virtual models.

In summary, by this experiment, we proved that the proposed dynamic attention-odor method was able to improve pleasant & intuitive experiences and the sense of presence compared to the non-dynamic method. Furthermore, we also found that inducing weak background odors would provide higher self-sensed olfaction. The results also indicated that in the proposed attention-olfactory, the two-way visual-olfactory cross-modal effect was obvious, which was one of the possible causes for experiential improvement.

7 Limitations and Future Work

One major concern is the small sample size of 12 participants in the experiment. To compensate for the shortage of participants, in the second part of the experiment (presence and experience validation), we repeated the session 3 times to increase the total sample size. After examining the results of statistical significance tests, we believe that the conclusions are mostly reliable. Still, in the future, we need to test the proposed method on a larger sample size to provide more profound results.

During the experiments, the scent ejecting device was installed on a stand attached to the user's neck, which restrained the user's range of head movement. It was not a crucial factor in the experiment because all the scented objects were placed in one direction, and the participant did not need to move their head to another direction. To optimize the system in the future, the odor display should be attached to the HMD [28] so that the user can move and turn freely in VE while receiving a stable odor presentation.

There are still space to improve the evaluation method in the experiment. The strong-weak presentation performed better than the strong-none regarding enhancing participants' self-rated olfactory sensitivity. However, as in the current results in Fig. 6a and b, the perceptual levels of odor mixtures were very similar of the two conditions, we cannot yet determine what specific factor of odor perceptions caused the difference in participants' judgments of their olfactory sensitivity. Our perception evaluation method might be insufficient because we found in previous studies that humans are more likely to sense the change in odor intensity rather than the absolute concentration level [27]. From this perspective, both strong-weak and strong-none conditions represented a similar over-arching condition: increase of the focused odor and decrease of peripheral odors. It is likely that regarding the olfactory sensational augmentation effect, the presentation of concentration change played a more important role than the absolute figures, which was not assessed in this experiment. To further investigate the causes in the future, we need to separately evaluate how easily distinguishable going from the medium level to strong, weak, and none levels for each odor in future experiments. Furthermore, in addition to subjective perception evaluation, other objective physiological metrics may be helpful to reveal the inner causes. For example, electroencephalogram (EEG) signals can be a useful tool to investigate brain activities associated with olfactory perception [26].

We determined the user's attention on objects by the gazing time, hence inducing a delay of odor intensity change after focusing on an object. Although we adjusted the gazing time threshold to 500 ms empirically so that the user did not feel an obvious gap between the visual and olfactory stimulus, the temporal congruence of the cross-modal effect is an important factor in the future attention-odor system design. Especially in our approach where the user decides his/her focusing point by gazing, the cross-modal effect between vision and olfaction has a great influence on the user's perception. Further validation is necessary to investigate the timings of attention shiftings and odor presentation responses so as to provide intuitive and realistic olfactory experiences in VR.

In this work, we restrained the participant's location in VE for clear comparisons between different odor presentation conditions. But in actual implementation, the spatiality-based presentation is also dynamic based on the user's location in VE. For future work, this work provides the foundation to a more comprehensive odor presentation system involving two dynamic factors—spatiality and attention in VR. This system will be more complex, so more validation procedures are needed to investigate the effects on subjective experience and presence when spatiality and attention-based odor presentations are combined.

Currently, the usage of the proposed attention-odor presentation technique is still limited in VR, and it is difficult to transfer the intended effects to a real environment. Because humans do not naturally experience the olfactory cocktail party effect in real life, there is a lack of real-world reference to accurately evaluate the proposed method of the sensation augmenting effect. On the other hand, in the VE, it is easier to reproduce the experience for different users with different devices and create a more controlled scenario for experiments. Therefore, the results we discovered in this paper still remain confined only to VR applications.

8 CONCLUSION

This work proposed and implemented a novel dynamic multi-odor presentation approach based on the user's attention. The inspiration of the system was to simulate the olfactory cocktail party effect to augment the user's olfactory experience and improve their sense of presence in such olfactory VEs. To our knowledge, this work is the first to combine virtual odor presentation with attention acquired from eye tracking to enhance the olfactory experience in situations where there are multiple sources of scent in one scene. We conducted an experiment to validate the efficacy of the proposed method and to investigate the effect of keeping background odors while presenting strengthened odor of the currently focused scented object on participants' experience. The final results showed that compared to mere spatiality-based multi-odor presentation, the proposed method performed better in providing pleasant and intuitive experiences and senses of presence. Furthermore, we discovered that it was necessary to preserve a weak level of background odors to give the user an augmented self-sensed olfactory sensitivity.

REFERENCES

[1] J. Amores, R. Richer, N. Zhao, P. Maes, and B. M. Eskofier. Promoting relaxation using virtual reality, olfactory interfaces and wearable eeg. In *2018 IEEE 15th international conference on wearable and implantable body sensor networks (BSN)*, pp. 98–101. IEEE, 2018.

[2] B. Arons. A review of the cocktail party effect. *Journal of the American Voice I/O Society*, 12(7):35–50, 1992.

[3] A. Baccarani, G. Brand, C. Dacremont, D. Valentin, and R. Brochard. The influence of stimulus concentration and odor intensity on relaxing and stimulating perceived properties of odors. *Food Quality and Preference*, 87:104030, 2021.

[4] A. BAHREMAND, C. SPACKMAN, R. C. GERKIN, and R. LIKAMWA. Virtually composing and dynamically mixing complex odors. 2021.

[5] R. S. Bolia, W. T. Nelson, and R. M. Morley. Asymmetric performance in the cocktail party effect: Implications for the design of spatial audio displays. *Human factors*, 43(2):208–216, 2001.

[6] B. R. Brkic, A. Chalmers, K. Boulanger, S. Pattanaik, and J. Covington. Cross-modal affects of smell on the real-time rendering of grass. In *Proceedings of the 25th Spring Conference on Computer Graphics*, pp. 161–166, 2009.

[7] A. W. Bronkhorst. The cocktail party phenomenon: A review of research on speech intelligibility in multiple-talker conditions. *Acta Acustica united with Acustica*, 86(1):117–128, 2000.

[8] Y.-S. Chen, P.-H. Han, K.-C. Lee, C.-E. Hsieh, J.-C. Hsiao, C.-J. Hsu, K.-W. Chen, C.-H. Chou, and Y.-P. Hung. Lotus: Enhancing the immersive experience in virtual environment with mist-based olfactory display. In *SIGGRAPH Asia 2018 Virtual & Augmented Reality*, pp. 1–2. 2018.

[9] E. C. Cherry. Some experiments on the recognition of speech, with one and with two ears. *The Journal of the acoustical society of America*, 25(5):975–979, 1953.

[10] S. Cmentowski, A. Krekhov, and J. Krüger. Outstanding: A multi-perspective travel approach for virtual reality games. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, pp. 287–299, 2019.

[11] J. Cohen. *Statistical power analysis for the behavioral sciences*. Academic press, 2013.

[12] M. L. Dematte, D. Sanabria, C. Spence, et al. Cross-modal associations between odors and colors. *CHEMICAL SENSES-LONDON-*, 31(6):531, 2006.

[13] S. Forster and C. Spence. "what smell?" temporarily loading visual attention induces a prolonged loss of olfactory awareness. *Psychological science*, 29(10):1642–1652, 2018.

[14] Y. Fujino, H. Matsukura, D. Iwai, and K. Sato. Odor modulation by warming/cooling nose based on cross-modal effect. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 929–930. IEEE, 2019.

[15] J. A. Gottfried and R. J. Dolan. The nose smells what the eye sees: crossmodal visual facilitation of human olfactory perception. *Neuron*, 39(2):375–386, 2003.

[16] B. G. Green, P. Dalton, B. Cowart, G. Shaffer, K. Rankin, and J. Higgins. Evaluating the 'labeled magnitude scale'for measuring sensations of taste and smell. *Chemical senses*, 21(3):323–334, 1996.

[17] G. Hanson-Vaux, A.-S. Crisinel, and C. Spence. Smelling shapes: Crossmodal correspondences between odors and shapes. *Chemical senses*, 38(2):161–166, 2013.

[18] S. R. Harris, R. L. Kemmerling, and M. M. North. Brief virtual reality therapy for public speaking anxiety. *Cyberpsychology & behavior*, 5(6):543–550, 2002.

[19] A. Jinks and D. G. Laing. A limit in the processing of components in odour mixtures. *Perception*, 28(3):395–404, 1999.

[20] A. Kadowaki, J. Sato, Y. Bannai, and K.-i. Okada. Presentation technique of scent to avoid olfactory adaptation. In *17th International Conference on Artificial Reality and Telexistence (ICAT 2007)*, pp. 97–104. IEEE, 2007.

[21] A. Klašnja-Milićević, Z. Marošan, M. Ivanović, N. Savić, and B. Vesin. The future of learning multisensory experiences: Visual, audio, smell and taste senses. In *International Conference in Methodologies and intelligent Systems for Techhnology Enhanced Learning*, pp. 213–221. Springer, 2018.

[22] D. G. Laing and G. Francis. The capacity of humans to identify odors in mixtures. *Physiology & behavior*, 46(5):809–814, 1989.

[23] R. Lohre, A. J. Bois, G. S. Athwal, D. P. Goel, et al. Improved complex skill acquisition by immersive virtual reality training: a randomized controlled trial. *JBJS*, 102(6):e26, 2020.

[24] E. Luo and K. Vega. Scentery: a calming multisensory environment by mixing virtual reality, sound, and scent. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, pp. 158–165, 2018.

[25] O. H.-M. Lutz, C. Burmeister, L. F. dos Santos, N. Morkisch, C. Dohle, and J. Krüger. Application of head-mounted devices with eye-tracking in virtual reality therapy. *Current Directions in Biomedical Engineering*, 3(1):53–56, 2017.

[26] G. N. Martin. Human electroencephalographic (eeg) response to olfactory stimulation: Two experiments using the aroma of food. *International Journal of Psychophysiology*, 30(3):287–302, 1998.

[27] S. Menzel, T. Hummel, L. Schäfer, C. Hummel, and I. Croy. Olfactory change detection. *Biological psychology*, 140:75–80, 2019.

[28] T. Nakamoto, T. Hirasawa, and Y. Hanyu. Virtual environment with smell using wearable olfactory display and computational fluid dynamics simulation. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 713–720. IEEE, 2020.

[29] S. Niedenthal, P. Lundén, M. Ehrndal, and J. K. Olofsson. A handheld olfactory display for smell-enabled vr games. In *2019 IEEE International Symposium on Olfaction and Electronic Nose (ISOEN)*, pp. 1–4. IEEE, 2019.

[30] R. Pellegrino, C. Sinding, R. De Wijk, and T. Hummel. Habituation and adaptation to odors in humans. *Physiology & behavior*, 177:13–19, 2017.

[31] S. Persky and A. P. Dolwick. Olfactory perception and presence in a virtual reality food environment. *Frontiers in Virtual Reality*, p. 15, 2020.

[32] D. Rokni, V. Hemmelder, V. Kapoor, and V. N. Murthy. An olfactory cocktail party: figure-ground segregation of odorants in rodents. *Nature neuroscience*, 17(9):1225–1232, 2014.

[33] T. Schubert, F. Friedmann, and H. Regenbrecht. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments*, 10(3):266–281, 2001.

[34] A. Seigneuric, K. Durand, T. Jiang, J.-Y. Baudouin, and B. Schaal. The nose tells it to the eyes: crossmodal associations between olfaction and vision. *Perception*, 39(11):1541–1554, 2010.

[35] N. Sobel, V. Prabhakaran, Z. Zhao, J. E. Desmond, G. H. Glover, E. V. Sullivan, and J. D. Gabrieli. Time course of odorant-induced activation in the human primary olfactory cortex. *Journal of Neurophysiology*, 83(1):537–551, 2000.

[36] M.-J. Tsai, H.-T. Hou, M.-L. Lai, W.-Y. Liu, and F.-Y. Yang. Visual attention for solving multiple-choice science problem: An eye-tracking

analysis. *Computers & Education*, 58(1):375–385, 2012.

[37] S.-E. Tsai, W.-L. Tsai, T.-Y. Pan, C.-M. Kuo, and M.-C. Hu. Does virtual odor representation influence the perception of olfactory intensity and directionality in vr? In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 279–285. IEEE, 2021.

[38] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose. Wearable olfactory display: Using odor in outdoor environment. In *IEEE Virtual Reality Conference (VR 2006)*, pp. 199–206. IEEE, 2006.

[39] Y. Yanagida, T. Nakano, and K. Watanabe. Towards precise spatio-temporal control of scents and air for olfactory augmented reality. In *2019 IEEE International Symposium on Olfaction and Electronic Nose (ISOEN)*, pp. 1–4. IEEE, 2019.