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ScentClue: Enhancing Story Engagement in Virtual Reality Through Hedonically Varied Olfactory Hints

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ABSTRACT

To enhance the engagement and significance of olfaction as a novel medium in multimedia systems, we aim to integrate different hedonic odorous cues into narratives to augment immersion in virtual experiences. We introduce the ScentClue system, comprising (1) an original and murder-themed experimental film incorporating four distinct hedonic odor cues synchronized with audio-visual elements, (2) a neck-worn scent delivery device capable of dispensing four different odors, and (3) an Unreal Engine-based virtual cinema environment enabling rapid control of video playback and odor dissemination. Experimenting with 18 participants divided into control groups with and without odor stimuli, we validated the system's usability and effectiveness of odor cue settings. Furthermore, we found that the use of odors with different hedonic qualities could enhance odor recognition, amplify thematic story ambiance, and aid in the rapid differentiation of complex relationships. Finally, we discussed expanded scenarios and interaction modalities for ScentClue, proposing future narrative-driven olfaction-enhanced multimedia designs with considerations for odor cue settings, odor material selection, and scent-releasing setup, particularly unpleasant odors.

KEYWORDS

Smell-enhanced Multimedia; olfactory cues; virtual viewing experiences; narrative; atomizaiton-based scent release; pleasant and unpleasant odors; odor hedonics

1. Introduction

As a powerful and highly potential medium, the human sense of smell has unique value and significance compared to human vision and hearing in creating realistic virtual experiences (Baus & Bouchard, 2017; Khan & Nilsson, 2023) and conveying rich information (Kaye, 2004). However, due to the unique properties of olfactory media (e.g., inability to program without a base odor or diffusivity), further understanding, research, and exploration of smell still need to be explored. Currently, in the field of Human-Computer Interaction (HCI), mainstream research focuses on accurate odor identification and synthesis techniques (Lee et al., 2023; Reardon, 2023), efficient and durable odor delivery technologies (Dobbelstein et al., 2017; Seah et al., 2014; Wang et al., 2020; Yamada et al., 2006), and precise odor interaction techniques (Niedenthal et al., 2023; Sugimoto et al., 2010). However, the relevance of odor release to the entire narrative and story is always overlooked, leading to relatively isolated smell experiences, such as releasing odors based solely on scenes (e.g., grass (Brkic et al., 2009)) and scented objects (e.g., virtual roses (Cowan et al., 2023)) in the visuals, weakening the involvement and importance of odor, thereby affecting deeper immersion. Besides, constructing a compelling storyline that attracts users and allows them to resonate with characters or plots is also crucial for enhancing immersion (Gorini et al., 2011). In this work, we aim to utilize the informational properties of odors, integrate scent release and experience into the narrative, allow odors to carry important information in the story, and serve as a critical factor driving the development of the entire story and experience.

Additionally, previous research has shown that unpleasant odors can evoke a stronger sense of immersion (Baus et al., 2022; Baus & Bouchard, 2017), and users tend to react more efficiently to them (Bensafi, Rouby, Farget, Vigouroux, & Holley, 2002). Although some HCI researchers have mentioned the potential of using unpleasant odors (Lu et al., 2020; Wang et al., 2023), exploratory studies are still rare in specific design cases. This work aims to extend the use of unpleasant odors and explore their potentials and boundaries in immersive experiences.

Therefore, based on the challenges above, we propose the *ScentClue* system, aiming to incorporate scent as critical clues into narratives. *ScentClue* allows users to learn, understand, and judge olfactory clues with different hedonics, thereby driving the story's development to deliver a richer, more immersive multisensory experience for multimedia systems. We aim to enhance olfaction's necessity, engagement, and importance as an emerging medium in immersive adventures.

Firstly, as a starting point, (1) we created an original and smell-driven experimental short film centered around a" murder" theme. Viewers are guided to understand and make judgments based on pre-set, distinct olfactory clues to uncover the perpetrator. We provided a detailed overview of

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the script's design and production process, including the storyline, scene, character settings, and filming and editing techniques. Secondly, (2) we defined four types of critical olfactory clues and their associations with the story and characters. Based on these olfactory clues, we customized four categories (six types) of scent materials, encompassing both pleasant and unpleasant odors. We elaborated on the types of scents, smell descriptions, material selection and preparation, modulation processes, and the timeline settings for scent release. (3) Thirdly, leveraging existing rapid prototyping tools for odor-emitting devices, we designed a neck-worn device that utilizes atomization to release four scents. It communicates with the Unreal Engine-based software platform via a USB connection to control video playback and odor release. (4) Subsequently, we conducted a user-involved evaluation and validation process comprising a previewing scent learning and a smell-enhanced virtual viewing experience. Through experimentation, we validated the system's usability and user satisfaction. We demonstrated that using different hedonic odors can assist users in memorizing, understanding, and categorizing information (with the highest odor recognition accuracy of approximately 86.61%). Furthermore, without prior knowledge of scent-associated information, participants could still comprehend scene details, character statuses, and relationships by following our pre-set olfactory clues. Additionally, they could gain expanded information based on scent hedonics, including immersive thematic atmosphere and insights into character images (e.g., positive and negative traits) and emotions (e.g., darkness, innocence, fragility). Finally, we explored *ScentClue*'s potential future expansions, including thematic types, usage scenarios, and interactive methods for narrative-based scent-enhanced immersive experiences. We also discussed considerations for selecting scent types, the granularity of scent release parameters, precautions (especially when using unpleasant smells), and limitations and future iterations of *ScentClue*.

Our main contributions are summarized as follows:

- **Implementation**. We designed and implemented an open-ended story and VR-based scent-enhancement system centered around the theme of" murder," incorporating four scent clues. *ScentClue* system included script development, filming and editing, a neck-worn scent delivery device, and UE-based scent parameter configuration and release control.
- **Definition**. We meticulously defined four primary scent clues: the odor type, description, relationship with the suspects, corresponding audio-visual elements, odor source selection, and scent release setup.
- **Evaluation**. We validated the usability of *ScentClue* system and the immersive viewing experience through two user tests. We discovered the expansion of information transmission through scents with varied pleasantness.
- **Discussion**. Based on *ScentClue*, we discussed and highlighted the narrative-based olfaction-enhanced multimedia system in terms of potential applications, interaction methods, design guidelines, and considerations for smell learning and scent clue setting, as well as limitations and future iterations.

2. Related works

2.1. Smell-Enhanced multimedia

Currently, smell-enhanced multimedia systems have extended into various fields, including entertainment (e.g., games (Nakamoto et al., 2008; Ranasinghe et al., 2018, 2019), film (Lin et al., 2019), advertising (Lwin & Morrin, 2012; Pornpanomchai et al., 2009), education and training (Kwok et al., 2009; Lu et al., 2023), healthcare (Amores et al., 2018; Arzi et al., 2010), tourism (Flavián et al., 2021), driving (Dmitrenko et al., 2017; 2018; 2020), retrieval (Alkasasbeh & Ghinea, 2023), and tool design (Brooks & Lopes, 2023; Fei et al., 2024). Video imagery has been extensively explored as one of the most widely used and accepted forms. For example, Lin et al. focused on providing a multisensory, low-cost movie-watching platform that integrates smell, touch, and audiovisual sensations to create a household 4D movie environment (Lin et al., 2019); Comsa et al. proposed enhancing the quality of experience in 360-degree video content by adding olfactory and other multisensory cues (Comsa et al., 2019); Simiscuka et al. focused on providing a solution for omnidirectional enhanced olfactory VR 360-degree video transmission (Simiscuka et al., 2023). Researchers have also explored the relationship between different types of odors and video content, such as odor pleasantness and odor-video content consistency (Alper, 2017; Seo & Hummel, 2011). Existing work primarily attempts to enhance interaction experiences through detailed olfactory interaction techniques (Jain, 2004).

Additionally, compared to immersive interactive technologies (Dias et al., 2018; Mayor et al., 2021), narrative is more conducive to enhancing emotional responses and inner presence in experiencers (Gorini et al., 2011); Pillai et al. also emphasized the importance of narrative in enhancing immersion in VR filmmaking (Pillai & Verma, 2019). The 1960 film" Scent of Mystery," directed by Michael Todd Jr., combined an engaging suspense story with scents, regarded as the precursor of scent-enhanced immersive movies[1]; Ranasinghe et al. integrated scents into gaming experiences through narrative approaches (Ranasinghe et al., 2019). In this work, we aim to enhance the correlation between hedonically varied olfactory hints, scent-releasing, storytelling, and audiovisual elements to improve the immersion experience further. We set the story's theme as mystery-solving and created an original script, shooting it into a 3-minute 2D video, allowing users to decode the mystery through scent clues.

2.2. Odor-Induced information

Due to the different chemical compositions emitted by substances, odors can provide information about the substance's type, composition, and characteristics. The human olfactory system can recognize and distinguish hundreds to thousands of odors, making odors helpful in conveying specific

information (Streeter & White, 2011). Moreover, olfaction can directly influences human memory (Jellinek, 2004; Wilson & Stevenson, 2003), emotions (Herz & Cupchik, 1995; Willander & Larsson, 2007) and cognition (Bensafi, Rouby, Farget, Bertrand, et al., 2002).

Many HCI researchers use odors' informational properties for multimodal design. For example, Dobbelstein et al. designed a necklace-style scent release device that uses customized scents to convey information about different contacts and daily tasks (Dobbelstein et al., 2017); Yamada et al. used odors of different concentrations to present positional information of wearers in virtual space to locate targets (Yamada et al., 2006); Dmitrenko et al. used different types of odors to convey driving-related information to assist visual information while driving (Dmitrenko et al., 2018); Ranasinghe et al. applied the story of bananas and ghosts from local legends to game design to convey a sense of horror (Ranasinghe et al., 2019); Lu et al. preset different odors as feedback information in online teaching (Lu et al., 2023). Alkasasbeh et al. developed an application combining textual passwords and scents for registration and login, demonstrating that scents can shorten login time, increase success rates, enhance password recall, and provide a fun, enjoyable, and highly adaptive user experience Alkasasbeh et al. (2021).

In this work, we aim to use odors as essential clues and information to assist users in understanding narratives and advancing the story, enhancing the participation and importance of smell as a promising medium. We propose and define four odor clues related to critical suspects based on the original experimental video.

2.3. Pleasant and unpleasant odors

To ensure the effectiveness and satisfaction of user experience, current research in HCI primarily focuses on using pleasant or functional aromas in smell-enhanced applications, such as lavender (Amores et al., 2018), lemon (Dmitrenko et al., 2018), or mango (Ranasinghe et al., 2019). Depending on different scent delivery methods, the selection of scent materials mainly includes essential oils (Amores et al., 2018; Amores & Maes, 2017), perfumes (Yamada et al., 2006), hydrosols (Wang et al., 2020), wax-based balms (Choi et al., 2011; Fei et al., 2024), gels (Dobbelstein et al., 2017), and scent stickers (Brooks & Lopes, 2023). Some HCI researchers and designers also discussed the potential of using unpleasant odors. For example, Wang et al. proposed exploring unpleasant odors through scent classification and sharing (Wang et al., 2023); Lu et al. mentioned using" bad breath" in storytelling to enhance vividness and interest (Lu et al., 2020); Murray et al. investigated the quality of different types of odors (pleasant and unpleasant) in 360-degree audio-visual video experiences and find that unpleasant odors can be accepted and recognized by users in special situations (Murray et al., 2016).

Besides, previous research on scent as information transmission has also pointed out that using similar odors (e.g., floral and fruity) can lead to errors in scent discrimination (Ranasinghe et al., 2019), highlighting the importance of using more easily identifiable scents (Lu et al., 2023). Therefore, in this work, we attempt to include unpleasant odors to create novel human-smell interactions, exploring their informational potential in immersive virtual experiences, addressing more detailed usage issues, and increasing scent discrimination.

2.4. Scent-Dispensing apparatus

Currently, the mainstream methods of scent release in the field of human-computer interaction mainly include four types: cannon ring (Hu et al., 2021; Seah et al., 2014), air pump and valve (Lu et al., 2023; Yamada et al., 2006), heating and airflow (Dobbelstein et al., 2017; Fei et al., 2024; Liu et al., 2023), and ultrasonic piezoelectric atomization (Amores et al., 2018; Amores & Maes, 2017; Wang et al., 2020, 2023). The first two methods have limitations regarding device miniaturization and noise generation caused by pump vibration. Although heating and airflow can promote the rapid movement of scent molecules, this method is susceptible to external factors and prototype fabrication methods (e.g., rapid and real-time feedback). Ultrasonic piezoelectric atomization involves atomizing scented liquid through ultrasonic vibration to generate mist, which is then delivered to the user's olfactory organs (Jung et al., 2017). This method has advantages such as affordability, fine-grained programming, noiselessness, and high availability. Amores et al. designed a necklace for daily wear (Amores & Maes, 2017); Ranasinghe et al. designed a desktop device capable of releasing four different scents, allowing users to experience corresponding scents while playing games (Ranasinghe et al., 2019). Meanwhile, open-source and rapid design tools based on atomization-based olfactory display have emerged in recent years. For example, Lei et al. designed an open-source tool based on multiple scent release methods and cardboard (Lei et al., 2022), while Wang et al. proposed a rapid design and fabrication method for piezoelectric atomization-based scent release devices (Wang et al., 2023). For fast testing in Virtual Reality, Fei et al. proposed three UE-based olfactory interaction blueprints (e.g., scentmovie) combined with virtual scenes (Fei et al., 2024).

In this work, we focus on selecting a quiet, noiseless, precise, and real-time method of scent release. Considering the control of scent release and video playback in virtual experiences, we ultimately chose Olfackit to implement a wearable scent release device based on ultrasonic atomization, using the video blueprint provided by OdorCarousel to control playback and scent release.

3. Design rational

3.1. Open-ended story and smell-enhanced Hints

We aim to allow users to immerse themselves deeply in actively discovering, understanding, and learning scent clues and draw corresponding conclusions while watching. Therefore, we chose the genre of mystery puzzles. Additionally, to naturally integrate different levels of pleasantness into the storyline, we attempted to select a story type that may bring about unpleasant experiences. Inspired by

'Scent of Mystery,' we finally created an original storyline centered around murder. We created an original narrative centered around campus bullying. Additionally, current research mainly utilizes pre-defined scent-user associations (Dobbelstein et al., 2017) or (Lu et al., 2023; Ranasinghe et al., 2019) to ensure the effectiveness and accuracy of scent applications. Due to the unique nature of this work (specific scent information may affect the murder conclusion), we choose to set scent clues as relatively direct information. For example, the scent of lavender in the story represents all possibilities related to lavender (e.g., lavender perfume, shower gel, etc.). We aim to explore how viewers establish connections between these scents, character attributes, and storyline developments. Therefore, we set scent clues for different core characters and explore and uncover the potential of expandable scent information by setting open-ended story outcomes.

3.2. Variety and safety of odors

We aim to expand the selection range of pleasant scent materials while ensuring that all materials are safe, non-toxic, and pose no potential danger to human health. Firstly, the selection of pleasant scents is straightforward: gather existing synthetic perfume materials available on the market, including alcohol-based perfumes (e.g., perfume), oil-based perfumes (e.g., perfumed oil and essential oils), and water-based fragrances (e.g., hydrosols, and edible perfumes).

For unpleasant odors, we referred to a series of psychological studies on unpleasant odors (Cornelio et al., 2020; Nakamoto et al., 2008) and fragrance knowledge.[2] We attempted to explore specialized single-fragrance materials used in perfumery. For example, civetone can emit a leather scent at low concentrations but releases a foul animal feces odor at higher concentrations. Although some chemical agents also possess" unpleasant" properties, such as H2S (Bensafi, Rouby, Farget, Bertrand, et al., 2002), jasmine (Cook et al., 2015), and pyridine (Millot & Brand, 2001), we decided not to use them in this study due to issues related to accessibility, user acceptance, and material safety. We also explored materials commonly encountered daily that may evoke unpleasant odor perceptions, such as shrimp oil (a common attractant used in fishing with a fishy odor), seafood-soaked water, and fermented plant odors used for pranks. Considering the high disgust associated with the latter two sources, we chose to use shrimp oil.

3.3. Video making and viewing

To better align and strengthen the correlation between scent clues, storyline development, and audiovisual elements, rather than using existing works, we attempt to create an original script and conduct on-location filming. We produced the story as a 2D video image as an initial step for lower production costs, design efficiency, and potential issues such as dizziness in panoramic videos and the increased variability in attention focus, which could affect users' perception and understanding of scent clues, story development, and scent experiences. Additionally, to minimize external distractions such as unnecessary noise and dynamic visual information, we aimed to have participants wear VR headsets for the experience to increase the immersion. We created a virtual environment resembling a" movie theater" within the VR environment.

4. *ScentClue* implementation

In this chapter, we will provide a detailed explanation of the *ScentClue* system (Figure 1), including (1) narrative design

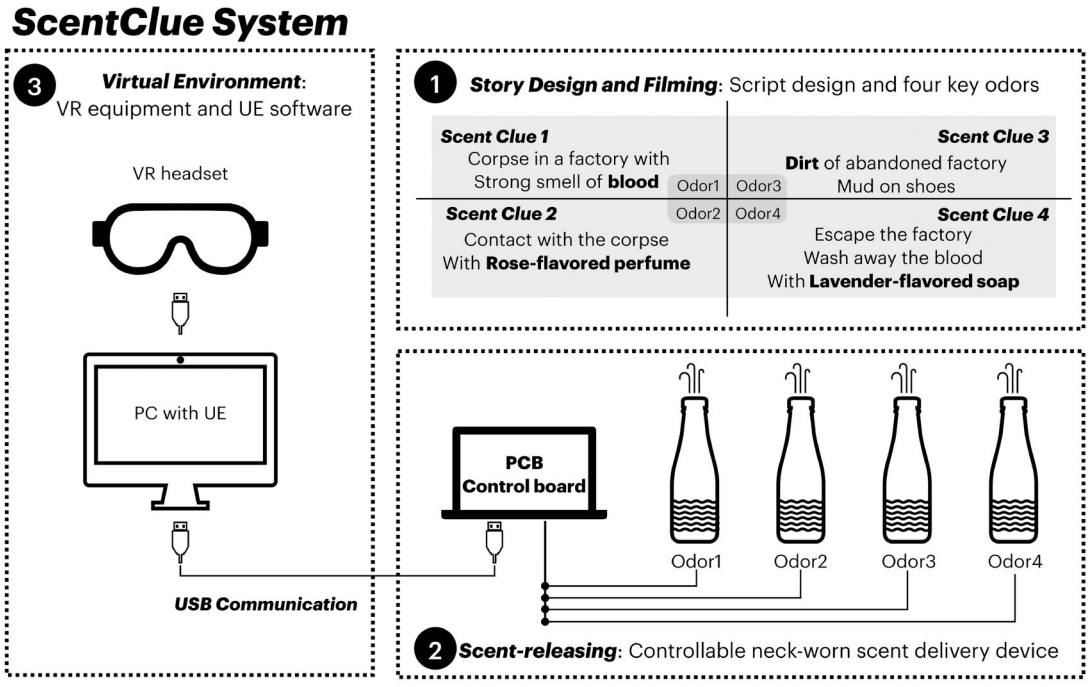

Figure 1. *ScentClue* System construction.

and experimental short film production driven by scent; (2) definition of four scent clues, scent release settings, and selection and production of scent materials; (3) a neck-worn scent release device capable of releasing four different scents; (4) and a video playback and scent release control platform based on Unreal Engine 5.

4.1. Story design and filming

- **Story Setting**: The story revolves around the testimonies of three suspects and scent clues to determine the ultimate culprit behind the murder. It begins with a bullying incident on campus, which ignites a murder case that unfolds in an abandoned factory. The narrative commences with Suspect A making a distress call near the deceased's body at the factory, leading to the involvement of the other two suspects, Suspects B and C. The police conduct separate interrogations with each suspect, but inconsistencies arise in their testimonies and alibis. Scent clues contradicting the suspects' statements are assigned to each of them.
- **Scene Setting**: (1) Incident Location: We have chosen an abandoned factory as the setting for the murder incident because, first, the desolate atmosphere adds complexity to the emotional and odor resonance, setting the tone and ambiance for the murder mystery. Second, juxtaposing the abandoned factory with the bullying incident on campus creates a contrasting and memorable backdrop, enhancing the narrative conflict. (2) Interrogation Room: This setting is where the three suspects provide their statements to the police officer. It is a crucial scene where valuable clues are revealed. (3) Campus: This scene primarily showcases the characters' identities and explores the origins of their motives for the murder. It provides context to the characters' backgrounds and motivations.
- **Main Character Setting**: We have defined five characters, including four key individuals (one victim, Suspect A, B, and C) and one interrogating police officer (Figure 2). The participants primarily experience communication with three suspects as a police officer, immersing themselves visually, auditorily, and olfactorily. Each essential character is imbued with distinctive personality traits. The victim was known for bullying others during their lifetime and had a habit of using perfume. Suspect A and B are individuals whom the victim previously bullied; Suspect A exhibits a dark and secretive personality, while Suspect B is comparatively introverted and sensitive. Suspect C was once the victim's companion but possesses a calm and decisive demeanor.
- **Filming and Editing**: We conducted on-site shooting on the campus based on the predetermined script, storyboards, and dialogues. The video footage was edited and integrated using Premiere Pro. We organized the story into three timelines based on the key locations: (1) the bright timeline representing the interrogation room (cold tone visual style), (2) the dark timeline representing the abandoned factory (black and white), and (3) the flashback timeline representing the campus (warn tone). The timelines were structured to depict the events' causes, progression, climax, and the alternating appearances of the three suspects. The final experimental short film lasts 3 minutes and 34 seconds, with a resolution of 1080P and in MP4 format. The original footage has been provided in the supporting documents.

4.2. Key moments for scent release and odor selection

4.2.1. Define the key moments for scent release

We have defined the following four key scent clues and summarized them in Figure 2 and Table 1:

- **Scent Clue 1 - Blood (Unpleasant)**: We designated clue one as the odor of blood when Suspect A came into contact with the victim, implying that Suspect A likely had contact with the victim before her death. Clue 1 represents the interpersonal relationship between Suspect A and the victim while also hinting at the crime scene through the presence of blood. We aimed to select scents that evoke bloodiness, a metallic tang, and an unpleasant odor, complementing the appearance of visual scenes featuring bloodstains.
- **Scent Clue 2 - Lavender-flavored soap (Pleasant)**: We designated clue two as the scent of lavender body wash on Suspect B after taking a shower, suggesting that Suspect B

Figure 2. Four main characters and scent clues correspond to the suspects and their primary visual cues.

Table 1. Four key scent clues with their hidden information.

Odor type	Odor description	Odor hedonics	Criminal suspect	Hidden information	Type of information
Scent Clue 1: Blood	*Bloody Metallic Fishy*	Unpleasant	A	close contact with the deceased suggesting crime scene	Character Relationship and Scene information
Scent Clue 2: Lavender-flavored soap	*Soap scent Hand Wash lavender*	Pleasant	B	B took a shower and the traces	Character status
Scent Clue 3: Dirt	*Wilderness Moisture Soil*	Neutral	B and C	B and C went to the factory	Scene information
Scent Clue 4: Rose-flavored perfume	*Fragrant Sweet Rosey*	Pleasant	C	C had close contact with the deceased	Character Relationship

had been to the crime scene but managed to clean up important clues related to the case. Clue 2 primarily represents Suspect B's physical state. We aimed to select lavender-flavored and soap-like fragrances, accompanied by focused scenes of Suspect B turning around with the wind blowing through their hair and scenes of washing hands. We classified this scent as a pleasant aroma.

- **Scent Clue 3 - Dirt (neutral)**: We set clue three as the fragrance of soil at the abandoned factory, indicating that Suspects B and C lied about not being at the crime scene. Clue 3 also represents the location and the status information of Suspects B and C fabricating their alibis. Our objective was to select scents evocative of the outdoors, soil, and dampness, which align with scenes of Suspect B running in their recollection and focused shots of mud on Suspect C's shoes.
- **Scent Clue 4 - Rose-flavored perfume (Pleasant)**: We selected clue four as the residual perfume on Suspect C, suggesting that Suspect C may have been at the crime scene and indicating information about the relationship with the victim. We aimed to select the pleasant and floral rose perfume, complemented by flashback scenes of Suspect C's interaction with the victim. Understanding clue 4 requires knowledge of the victim's habit of using perfume, so we strategically released the scent multiple times in the video to plant the idea.

4.2.2. Odor selection and materials

Scent Clue 1 - Blood. We selected specific fragrance ingredients to represent the target odors, including the fragrance oils with metallic and fishy attributes (Gaicolin Spice Essential Oil Shop) and shrimp oil (Tianyue). Due to the subjective nature of perceiving blood, we aimed to present blood odor differently. Five testers conducted the tests, screening, and blending of the odor materials based on three categorizations: (1) The ***physical*** sensation of blood, characterized by the metallic and fishy smell of blood itself, for which we selected aldehydes such as formaldehyde, beaver musk with an animal odor, and Borneol and dihydromyrcenol commonly used to create metallic scents in perfumery. (2) ***Psychologically*** oriented nausea, for which we chose shrimp oil as the main ingredient. (3) A ***combination*** of psychological and physical blood sensations, incorporating the characteristics of the first two types. Testers blended each type of blood material differently (3 samples for each) according to these classifications, resulting in nine different odor samples. We recruited ten volunteers from the campus (5 Males) to identify the most representative blood odors for each orientation. Volunteers needed to subjectively accept the test theme (i.e., willing to smell unpleasant odors), not be allergic to odors, not have cold symptoms, and not have lost their sense of smell. Volunteers were required to sign an informed consent form before the test. The average odor sensitivity of the volunteers was 5.89 ($SD = 1.12$). During the experiment, volunteers sequentially smelled and rated nine different odors based on different classifications using a 5-point Likert Scale (1 = Strongly Disagree; 5 = Strongly Agree). Finally, we have one recipe for each type of blood.

Scent Clue 2, 3 and 4. The odors for Scent Clues 2, 3, and 4 are commonly found in the market. We directly selected the appropriate fragrances for the desired scents. We listed the final odors with the recipe in the supplement materials.

4.3. Neck-Worn odor-emitting device

We chose to separate the odor delivery device from the HMD to avoid increasing the weight load on the head while wearing VR. Simultaneously, considering that users may move or adjust their bodies during the viewing, we opted to have users wear the odor delivery device to ensure precise odor transmission direction and distance. Therefore, we designed a wearable odor-delivery device that can be worn around the neck.

For implementation, we utilized the rapid design tool provided by OlfacKit (Wang et al., 2023) and its corresponding hardware materials, including piezoelectric atomizing sheets, control circuit boards, PTFE tubing, and connecting wires (Figure 3(A)). For the design details, we chose a vertical structure capable of releasing four types of odors, employing four 16 mm diameter piezoelectric atomizers for odor release (Figure 3(B)). To ensure prolonged use, we set the height of the odor container to 45 mm (about 3 milliliters). We prepared separate odor containers for the six target odor samples for easy replacement. Opting for a split-body design, we separated the odor container from the control circuit to distribute the device's weight. The odor containers were linked with ring connectors, while the PCB case utilized a clip-sliding groove structure. The device was placed on the chest (Figure 3(C)), with each odor release duration defined as a concentration and parameters set at 100 ms/s. The device's net weight is 86.3 g, and with four 3 ml vials filled with scent materials, the total weight is 93.5 g.

4.4. Scent release performance

Considering that users need to experience multiple scent releases during viewing, we conducted a small-scale

Figure 3. The neck-won scent-releasing device devised by using OlfacKit.

experiment to understand scent release performance better. This experiment included the perception time after scent release, the duration the scent lingers, and the residual scent in the space after multiple releases. Due to potential delays and errors from traditional gas sensors, we included human testers.

4.4.1. Experiment configuration

We recruited 6 participants (female = 4) from the campus, with an average age of 22.4 years (SD = 1.2). The average odor sensitivity of the participants was 6.0 (SD = 0.63, not sensitive = 1; very sensitive = 7). The participants' majors ranged from visual communication, product design, and interaction design to computer science. We selected two different scents (coffee and mango for neutral and sweet tones) to be alternately released at 8-second intervals and conducted six sets of 12 scent releases. Participants evaluated the perception time and lingering time for each scent and the residual scent in the space after the test (using a Likert 7-point scale, where 1 = no odor and 7 = strong intensity).

The number of scent releases (12 times) was based on the frequency of releasing four scent cues three times each. We set the piezo operation time to 100 ms/s. The experimenter wiped the piezo and device with alcohol before each user test to minimize scent residuals errors. The experiment was conducted in an open office space with good ventilation, and the room temperature was maintained at approximately 23 °C.

4.4.2. Experiment procedure

First, participants needed to pre-smell the two scents. The experimenter then assisted the participants in wearing the device and adjusting it to the appropriate height to ensure they could not smell any potential residual scents from the piezo. The distance from the participant's nose to the device was recorded. During the formal test, the participant and the experimenter used timers to record the times. The experimenter started the timer when releasing the scent, and the participant pressed the timer upon detecting the scent (perception time) and when the scent disappeared (lingering time). The experimenter then organized and calculated the data. After the six sets of 12 scent releases, participants needed to leave the test location and quickly return to evaluate the scent concentration. They also evaluated the scent concentration in the environment at the original test site after 2 minutes and 5 minutes.

4.4.3. Results

We found that when users wore the scent release device at an average distance of approximately 16.1 cm (SD = 2.35), their average perception time was 1.83 seconds (SD = 0.47). Considering the differences in scent sensitivity, breathing time, and frequency among users, we recommend setting the scent release timing 1-2 seconds before the visual cue to ensure users can recognize the scent within a complete breathing cycle.

We also found that the average lingering time for the two scents was 3.89 seconds (SD = 1.15). Similarly, we recommend setting the minimum scent transition time in the short film to no less than 4 seconds. Most users reported being able to recognize the release of the two scents (M = 6.4, SD = 0.8) and hardly noticed any residual scent (M = 2.6, SD = 0.49), with no impact on distinguishing between the scents (M = 6, SD = 0.89). Additionally, after all releases were completed, users felt that the scent in the environment was relatively weak (M = 3, SD = 1.26). After two minutes, there was almost no scent (M = 1.4, SD = 0.49), and after five minutes, there were no residuals (M = 1, SD = 0).

Therefore, users can achieve a high-quality scent experience under the above scent settings. However, due to scents' unique properties, it is impossible to eliminate scent residue. Therefore, throughout the experience, we still need to consider factors such as the cleanliness of the scent-release device, controlling the total amount of scent released, the distance between users (especially in multi-user settings like cinemas), and maintaining good ventilation.

4.5. Virtual environments in Unreal Engine

To efficiently set up and control the release of odors at specific points and create a cinematic viewing experience in virtual environments, we connected the control circuit of the odor release device (esp32) to Unreal Engine 5 (UE5) via a data cable. UE5's operating system environment is Windows 10. We chose Meta Quest 2 as the virtual experience device (Figure 4(A)). In this work, we utilized the *ScentMovie* blueprint created in OdorCarousel (Fei et al., 2024) to set and modify the odors associated with clues and scent release timing in the video (Figure 4(B)). We only need to input the PIN corresponding to the desired odor in the" Odor Type" section of the blueprint interface, and there is no limit to the number of times odors can be released during

Figure 4. The left image depicts the users wearing VR devices to watch the short film. Image B displays the parameter settings interface of ScentMovie in UE5. Image C shows the virtual cinema environment.

Table 2. Scent clues and release timeline in the video.

Release order	Time points	Scent clue	Visual content	Audio content
1	00:34	Blood	Suspect A Introduction	–
2	00:56	Blood	Hand slipped off the clothes	–
3	01:07	Lavender soap	Suspect B Introduction	–
4	01:18	Blood	Corpse in a messy scene	*"Abandoned Factory"*
5	01:27	Dirt	Running in the factory with mud	–
6	01:39	Rose perfume	Suspect C Introduction	–
7	01:55	Dirt	Mud on shoes	*"Stay at her home all day"*
8	02:38	Rose perfume	Memories of the bullying	*"I do hate her."*
9	02:53	Lavender soap	Turn around with wind blows the hair	–

video playback. The specific timing and odor types can be referenced in the Table 2.

Considering the distance between the neck-worn scent release device and the nose (approximately 15-20cm) and individual differences in odor sensitivity, users may be delayed in perceiving the odors. To ensure precise synchronization between odor release and video cues, we pre-tested the delay time between odor release and odor perception (≈ 1.4 seconds). Therefore, we set the timing of odor release points to be approximately 1.5s ahead of the actual visual frames. Furthermore, we built a scene named" ScentClue-Scene" in UE5 and configured it in 2D viewing mode. We created a virtual cinema scene in UE5 to simulate the immersive experience of a real cinema, including the position, screen angle, and cinema seats (See Figure 4(C)).

5. Pilot study

We conducted a preliminary user test to ensure that users have a comfortable and easily understandable smell-enhanced storytelling experience, which includes the scent release concentration, frequency, and compatibility of visual-olfactory content.

5.1. Experiment configuration

We recruited nine participants (female = 4) from the campus, with an average age of 22.57 years (SD = 1.62). The participants included undergraduates, postgraduates, and a research assistant majoring in digital media, visual communication, product design, Human-computer Interaction, and fashion design. All participants were non-smokers with an ordinary sense of smell and were advised to avoid using perfumes on the day of the experiment. The study occurred in a standard open office (≈ 25 degrees Celsius). The hardware used for the experiment included the odor-releasing device, a Windows computer, and a Quest 2 VR headset for viewing videos. Throughout the testing process, we ensured that the windows remained open.

We have chosen three visual scenes most relevant to each key scent clue (each one released thrice), totaling 12 scent releases. Scent Clue 1-Blood is released in sync with the following scenes: the bloodstain on suspect A's chest, the corpse, and the bloody wooden stick. Scent Clue 2-Lavender soap aligns with the first appearance of suspect B, the emotional outburst, and the wind blowing through the hair. Scent Clue 3-Dirt is synchronized with the scenes of both suspects fleeing from the factory, a close-up of the muddy ground in the factory, and the mud on suspect C's shoes. The first appearance of Suspect C triggers Scent Clue 4-Rose perfume, the victim bullying Suspect B, and Suspect C's interrogation. The minimum interval between scent releases is 5 seconds with a 100 ms/s piezo working time. The video lasts 3 minutes and 20 seconds.

5.2. Experiment procedure

First, we provided the participants with a brief explanation of our experimental objectives, process, and the theme and motivation of the short video. The participants were required to sign an informed consent form. Next, we randomized three unpleasant odors for the participants, who were required to pre-smell and memorize all odors. The experimenters then facilitated the participants' wearing the VR headsets to ensure comfort, and then the participants experienced the smell-enhanced short movie. After the test, participants completed a post-study questionnaire (questions rated on a 7-point Likert scale), followed by an informal interview. The study lasted approximately 30 minutes for one person.

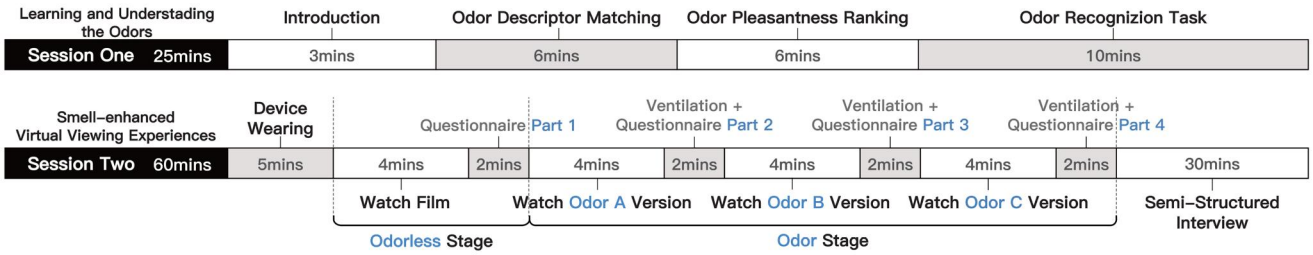

Figure 5. User study structure of smell-enhanced virtual viewing experience.

5.3. Results and design iterations

Generally, we found that participants could easily identify the four types of scents (M = 5.71, SD = 0.95) and considered the timing of scent release to be reasonable (M = 5.29, SD = 1.11). Participants also believed that integrating scent cues with the story was smooth and without delays (M = 5.57, SD = 0.98).

5.3.1. Scent-release concentration

Three users found that unpleasant odors were perceived more intensely than pleasant ones. To avoid affecting the overall viewing experience, we reduced the operating time of the piezo for unpleasant odor (scent clue 1-blood) from 100 ms/s to 60 ms/s.

5.3.2. Scent-release frequency and timeline

Five users reported that the odor release frequency was relatively high and affected the ability to consume audiovisual content. Hence, we optimized the number of odor insertions (also to prevent potential excessive odor residuals). We reset the shortest interval between two clues to 9 seconds. Besides, viewers should be allotted sufficient time to learn and understand the relationship between characters and odors. Therefore, we provided at least two instances of scent release corresponding to each suspect. Each suspect's first show includes their first scent release, and a second scent release is played during their testimonies. The scent clue 3-Dirt also represents suspects B and C in their respective recollections. Due to the uniqueness of scent clue 1-Blood, which not only serves as a clue for suspects but also aligns with the murder theme of the story, we specially included three instances of blood release. Ultimately, we included nine releases, comprising five of unpleasant and four of pleasant scents. Detailed information regarding the scent clues, release timings, and corresponding audiovisual content can be found in Table 2.

5.3.3. Understanding the odors

We also found that while a quick learning session before viewing can help distinguish different scents, it can lead to broad associations, causing misinterpretations that affect understanding of the story. For example, P5 focused on the manufacturing process of Rose perfume (noting a pungent smell) rather than the scent itself. As P2 and P9 suggested, we supplemented the experiment with semantic descriptors to assist in scent recognition and memory to reduce such perceptual biases.

Additionally, to help users understand scents from different perspectives, we introduced a task to rank the pleasantness of scent cues. After the experiment, we consulted the participants again, and six users believed this method would be more effective.

5.3.4. Video editing optimization

Three participants mentioned that fast-paced transitions in the film made it difficult to remember characters and plots, which hindered their understanding and reflection on the storyline. Consequently, we extended the duration of each essential character's first appearance and the scenes corresponding to scent release points. The short film's length increased to 3 minutes and 34 seconds.

6. Evaluation

6.1. Experiment goal and structure

In this experiment, we conducted two tests (see Figure 5), which included:

- **Session One: Learning and Understanding the Odors.** The objective of this phase was to familiarize users with different odors and observe their subjective judgments of odor pleasantness and memorization before watching the short video. Session one primarily consisted of odor descriptor matching, odor pleasantness ranking, and odor recognition tests.
- **Session Two: Smell-enhanced Virtual Viewing Experiences.** This phase involved the odorless stage and an odor-enhanced stage for comparison, and the latter stage was also divided into three blood versions for assessing the acceptability and their design methods. The goal was to validate the usability of the *ScentClue* system, compare the informativeness and immersion provided by different types of scent clues, and assess users' willingness to use and accept odors of different hedonics. We also aimed to explore the information-expanding capabilities of odors with different hedonics and identify considerations for future use.

Considering the subjective differences in scent perception and information acquisition among users, we chose a within-subjects method. This approach aims to minimize individual and between-subject differences (Steenbergen

et al., 2009). We then compared the differences in user immersion and scent cue acquisition under conditions with and without scent (odorless vs. odor version) and across different scent conditions (three different blood versions).

We consistently placed the no-odor phase first because we had two experimental goals corresponding to two conditions: viewing with or without scent and viewing with three unpleasant scents. The first goal was to explore whether users could obtain more complex information through scent cues, which involve irreversible cognitive changes and are affected by sequence effects.

6.2. Participant selection

6.2.1. Initial selection based on topic preference

We aim to select participants interested in suspense and mystery genres to explore and acquire expanded olfactory information. Firstly, we conducted an online survey on the local campus platform to understand users' interest in smell-enhanced suspense-themed short films. The questionnaire included participants' basic information, preferences for suspense genres (7-Point Likert Scale, 1 = Strongly not like; 7 = Strongly like), preferred types of suspense genres, odor sensitivity (1 = Strongly not sensitive; 7 = Strongly sensitive), and whether they had experience with olfactory design. Sixty-seven participants took part. We pre-selected those with a preference of equal to or greater than 5. We also excluded participants who expressed aversion to unpleasant odors, had odor allergies, diminished sense of smell, smoked regularly, or were currently experiencing a cold. Ultimately, we identified 18 participants for the experiment.

6.2.2. Biography of final participants

The 18 participants (male = 8) had an average age of 21.50 years ($SD = 1.62$), including 14 undergraduates and four postgraduates. Their majors or research fields encompassed information management, digital media design, electronic information, product design, human-computer interaction, visual communication design, and fashion engineering design. The average odor sensitivity of the participants was 4.8 ($SD = 1.17$), and none of them had prior experience with odor interaction design. However, they expressed a keen interest in this type of design ($M = 6.06$, $SD = 1.08$). Each participant spent approximately 85 minutes participating in the experiment, and every user who took part in the test received a gift prepared by us. Before participating in the user experiment, we advised participants not to wear perfume on the day of the experiment to ensure sensitivity to olfactory sensations.

6.3. Environment and apparatus

The experiment was conducted in a spacious indoor area with an approximate area of 63 square meters ($10.5\,m \times 6\,m$). The indoor temperature during the experiment was around 20 degrees Celsius. Throughout the testing, the room's windows were kept partially open to facilitate ventilation and the dissipation of odors. We communicated the scent-releasing device with a Windows computer via a data cable and a Quest 2 VR headset for viewing video content.

We arranged Session One and Two on opposite sides of the open office, and users completed each session sequentially according to the order. The spatial setup is illustrated in Figure 6. Before the formal start of the experiment, users

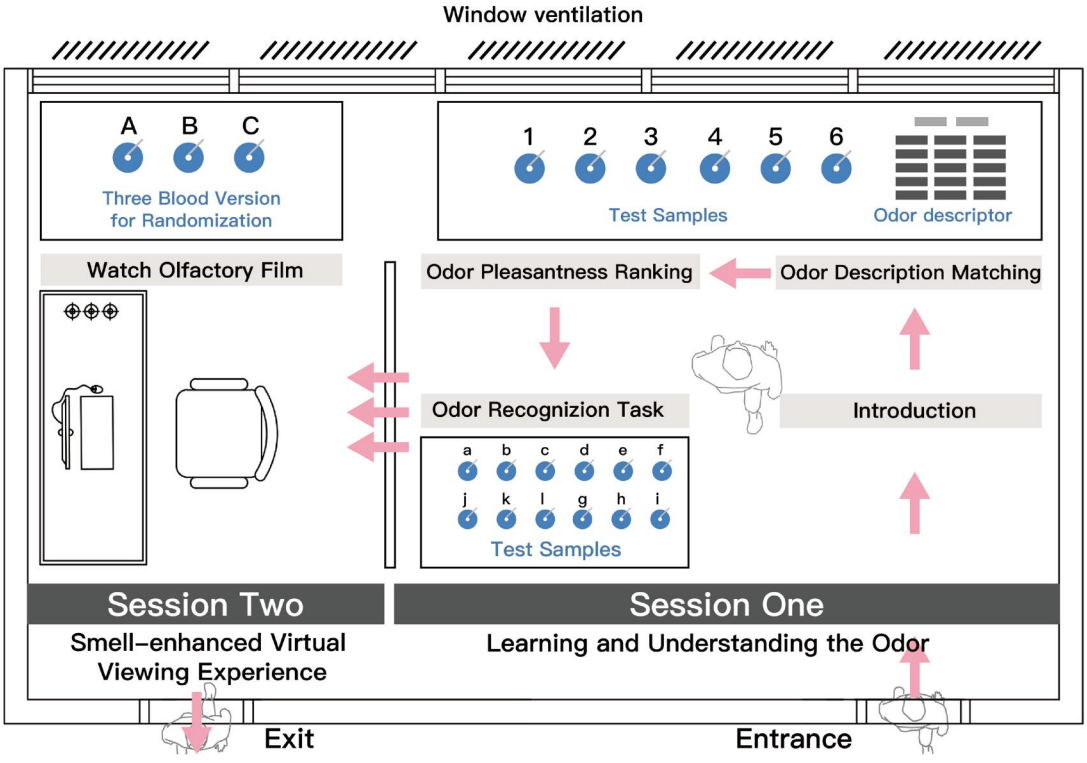

Figure 6. Test procedure and environment setting.

were given a brief explanation of the experiment objectives and the overall process (≈ 5 *min*), and they were required to sign the consent form according to the experiment's requirements.

6.4. Session one: Learning and understanding the odor

In this session, we designed three small tasks to help users quickly recognize, understand, and memorize the odors present in the video material before formal viewing. Users could smell the prepared odor strips multiple times at any time. Three tasks lasted approximately 25 minutes.

- **Task 1: Odor Descriptor Matching.** Firstly, the experimenter created and prepared two types of labels based on the six odor types. One type consisted of mandatory labels indicating the level of pleasantness, including" *pleasant*" and" *unpleasant*." The other type comprised multiple-choice labels describing odor perceptions, such as" *pungent*,""*outdoorsy*," and" *sweet*," among 14 other descriptive terms. Users were allowed to freely match any semantic labels to each odor, assisting them in better understanding and identifying the odors. Experimenters took photographs of the results after users completed the label matching.
- **Task 2: Odor Pleasantness Ranking.** Users were required to rank the pleasantness level of each odor type and rate it based on 7-point Likert Scales (1 = Extremely unpleasant, 7 = Extremely pleasant).
- **Task 3: Odor Recognition.**We employed random sampling for testing to observe users' learning, memory, and recognition of different odors. They were required to match 7 test samples provided by the experimenter with six target odors. The experimenter recorded the choices made by the participant and calculated the accuracy rate.

6.5. Session two: Smell-enhanced virtual viewing experience

In this session, the participants were required to watch four versions of a suspense video, including one odorless stage and three odor stages (Blood1 - Physical, Blood2 - Psychological, Blood3 - Combination). This stage aimed to assess the acceptability and their design methods. We employed a within-subjects design with randomized order to mitigate these differences and enhance data reliability. Specifically, we used a Latin square design, which systematically varies the order of conditions so that each condition appears an equal number of times in each position, effectively controlling for sequence effects and balancing position effects. We encompassed three types of blood smells to observe users' feedback and acceptance and how the scents affected their understanding and experience of the story. The entire session lasted approximately 60 minutes. The specific procedure is outlined below:

- **Preparation (≈ 5 *min*)**: The experimenter briefly introduced the assembly and usage of the odor-releasing device, assisting the participants in wearing the equipment. The experimenter also assisted the participants in wearing the VR headsets, ensuring comfort.
- **Virtual Viewing (≈ 25 *min*)**: We employed random sampling to test the three odor versions. Participants watched the odorless version and filled out the Part 1 questionnaire. Then, they filled out the respective Part 2, 3, and 4 questionnaires based on the three random experimental groups. After each viewing, the experimenter ventilated the room to minimize residual odors in the environment. The interval between each viewing was approximately 2 minutes.
- **Semi-structure Interview (≈ 30 *min*)**: After the viewing, participants were required to complete a comprehensive questionnaire. Subsequently, the experimenter conducted semi-structured interviews with the participants. The experimenter categorized and analyzed the questionnaire results, oral reports, and the experimental process.

7. Results and findings

7.1. Learning and recognizing the odors

7.1.1. Descriptors facilitate the learning process

The participants completed the task relatively quickly (less than 5 *min*). On average, the participants selected 2-4 descriptors for each odor. For Dirt, descriptors mainly included" *damp, outdoors, industrial*"; for Lavender-flavored soap, descriptors were mostly" *refreshing, floral, soapy*"; and for rose perfume, descriptors leaned towards" *sweet, refreshing.*" The three blood scents shared similar descriptors, such as" *complex, greasy, pungent.*" Furthermore, we observed tendencies in descriptor preferences among the three blood odors: Blood 2 - Psychological leaned towards" *food-like,*" Blood 1 - Physical was more akin to" *metallic,*" and Blood 3 - Combination tended to be more" *pungent.*" Additionally, some users added new labels to the scents, such as" *bitter*" and" *smelling like cooked rice*" for blood, and describing dirt as" *dirty*" and" *attic-like.*" Most users found this session helpful in quickly" *in categorizing and understanding the scent types.*"

7.1.2. Pre-watching odor pleasantness ranking

We observed significant differences in the hedonics among the six scents before viewing but no apparent differences between genders. The ranking of hedonics before viewing, from highest to lowest, was as follows: rose perfume ($M = 6.33$, $SD = 0.84$), lavender soap ($M = 6.06$, $SD = 0.8$), Blood 2 - Psychological ($M = 3.56$, $SD = 1.67$), Dirt ($M = 3.17$, $SD = 1.67$), Blood 1 - Physical ($M = 2.39$, $SD = 1.24$), and Blood 3 - Combination (M = 2.33, SD = 1.14). The ranking results were generally consistent with the definition and setting of scent clues. Rose perfume and lavender soap exhibited pronounced pleasant attributes, while the three blood scents showed varying degrees of unpleasantness. The scent of dirt yielded unpleasant results in the test. We further investigated user perception changes of scent pleasantness after virtual viewing, as outlined in Section 6.4.3.

Table 3. Recognition accuracy of six odor types.

Sample	Scent clue	Recognition accuracy (%)
1	Blood 1 - Physical	50.00
2	Blood 2 - Psychological	96.00
3	Blood 3 - Combine	52.38
4	Lavender-flavored soap	86.96
5	Dirt	77.78
6	Rose-flavored perfume	85.71

7.1.3. Odor recognition accuracy

In this test, participants achieved an average accuracy rate of 76% in identifying the six odors before virtual viewing (see Table 3). We found that the main identification confusion occurred between Blood 1 and Blood 3. We suspected the poor dilution between shrimp oil and water (Blood 1 - Physical), leading to rapid volatilization. As a result, the remaining scent types in Blood 1 and 3 become similar, leading to users' confusion.

However, participants also indicated that the distinction between blood and other non-blood scents was significant, making them easily distinguishable, and other scents exhibited high recognition rates. Considering that the three blood odors are not used in the same viewing session, we believe the scents do not interfere with each other during the virtual viewing, thus ensuring the distinctiveness and differentiation of scent information. The highest odor recognition accuracy provided by the four ScentClue odors is approximately 86.61% when choosing Blood 2 - Psychological.

7.2. General rating of virtual viewing experiences

Generally, participants were relatively satisfied with incorporating scents into the video-watching experience ($M = 5.67$, $SD = 0.92$), and they found the addition of scents to be highly attractive in VR video-watching ($M = 6.05$, $SD = 1.11$). Considering that users may need to simultaneously process various types of information such as visual, audio, olfactory, and the entire storyline during the viewing process, accurately quantifying the scent recognition rate might be challenging (like the accuracy test in Session 1), and the resulting error might be significant. Therefore, we assessed users' satisfaction with perceiving and recognizing the four scent clues through a scale. We found that even with visual, auditory, and narrative elements involved, participants still perceived and recognized the four scent clues well in each viewing session (see Figure 7).

Besides, we also speculated the reasons for the slightly lower recognition rate of Scent Clue 4-Rose-flavored perfume compared to other scent clues. These reasons include: (1) Release sequence. Since Scent Clue 1 - Blood and Scent Clue 2 - Lavender are strongly contrasting scents set at the beginning of the short film, they raise users' recognition threshold, which lowers their satisfaction with recognizing Scent Clue 4, released later. (2) Information difficulty. Scent Clue 4 contains the most challenging information, which might reduce users' satisfaction due to their inability to identify the scent information.

Figure 7. Results of general satisfaction with odor perception and recognition for the four scent clues: Scent clue 1-Blood ($M = 5.88$; $SD = 1.18$); Scent Clue 2-lavender-flavored soap ($M = 5.83$; $SD = 1.10$); Scent Clue 3-Dirt ($M = 5.56$; $SD = 1.76$); Scent Clue 4-Rose perfume ($M = 5.33$; $SD = 1.19$).

We also observed that even with unpleasant scents, users' immersion, character understanding, story comprehension, and emotional engagement significantly improved during the odor stage, particularly in the second and fourth dimensions (Figure 8). However, we did not find significant differences among the three blood scents, indicating that their formulations did not adversely affect the virtual viewing experience. Additionally, we noticed a significant difference in emotional fluctuations between Blood 1 - Physical and Blood 3 - Combine. We hypothesize that this is because users perceived Blood 1 as having a" metallic" scent and Blood 3 as more" pungent," leading to lower acceptance of Blood 3 and thus affecting their emotions.

From the perspective of genre compatibility, we found that including scent cues enhances user engagement in suspense-themed stories from various dimensions. (1) ***Curiosity and initiative exploration***. P13 remarked," *Compared to rose and lavender, dirt is not a common scent in perfume. I actively seek the meaning of the dirt scent and pay more attention to and contemplate its corresponding plot.*" P12 added," *Scents play a significant role in creating atmosphere, and appropriate intensity stimulates people's desire to explore, triggering a series of associations.*" (2)***Enhance efficiency.*** We observed that participants could efficiently differentiate between characters based on scents, especially in the early sessions of the story, and quickly capture critical information in the storyline." *Each character has a different scent, like a clue,*" reported P7. P5 mentioned," *Like changing background music when the plot enters the next node, changing scents can also serve the same purpose, but it is more natural than music.*" (3) ***Boost confidence.*** Users can validate their judgments through scent information, enhancing confidence, which is particularly important for suspenseful decryption. P14 stated," *Previously (without scent), when I saw the hand-washing, I speculated whether she had been to the scene to wash something. When the scent appeared later, I was sure that she was the one who had been to the scene!*" (4)***Enhance immersion and watch willingness.*** Participants watched the same video four times, but they did not express discomfort or boredom. On the contrary, they believed that adding scents would increase the desire to re-watch and re-explore (P4) and gradually deepen their understanding of the storyline clues.

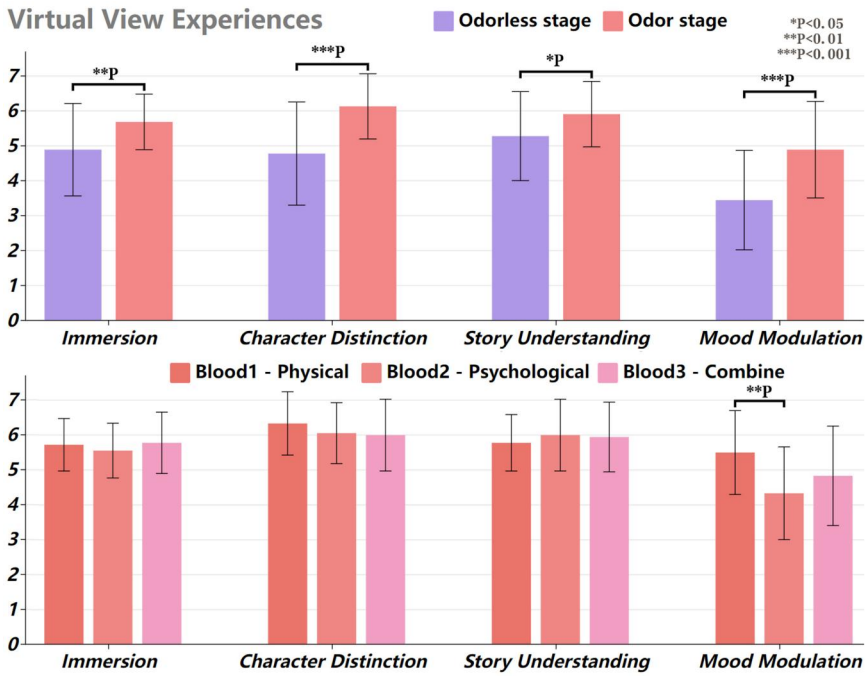

Figure 8. Comparison of two experimental conditions in an immersive virtual viewing experience. Experimental condition 1: with or without odor (top chart); experimental condition 2: three different unpleasant odors (bottom chart).

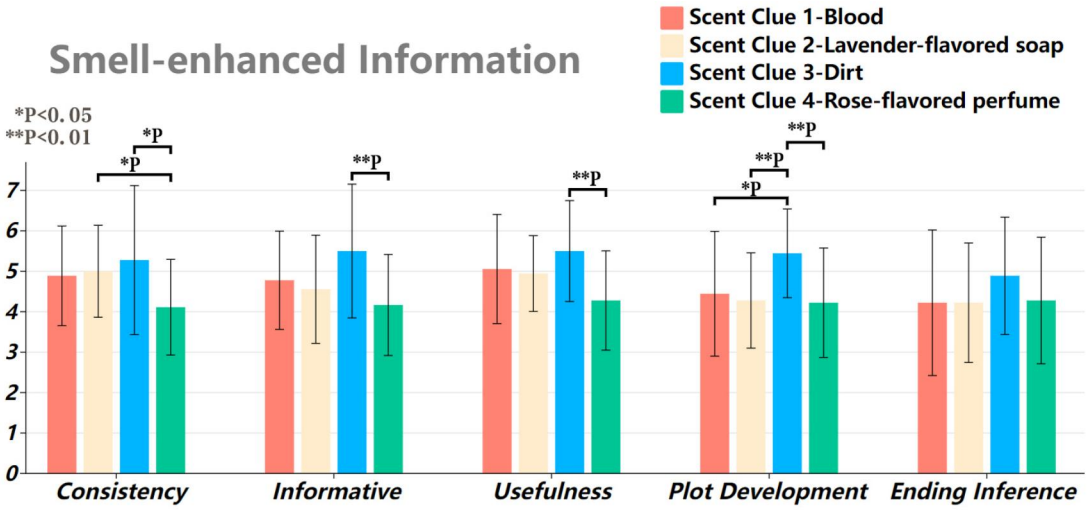

Figure 9. Evaluation dimensions and results of four smell-enhanced information for four key scent clues.

7.3. Understanding smell-enhanced information

7.3.1. Story ending judgment

The participants believe smell-enhanced information positively impacts consistency with audiovisual cues, richness, and usefulness, driving the story forward and drawing conclusions about the ending (see Figure 9). Users can deduce the culprit based on their understanding of scent information, with suspect A (Scent Clue 1 - Blood) being implicated eight times, suspect C (Scent Clue 3 - Dirt and 4 - Rose perfume) six times, and suspect B (Scent Clue 2 - lavender soap) being involved in the crime with C three times.

Based on participants' feedback, we found that due to the film's short duration and fast pace, users focused primarily on distinguishing characters and understanding their stories during the odorless viewing stage, leaving less mental energy for deducing the culprit, often leading to vague or speculative conclusions. However, with the help of scent cues, they found it easier to differentiate characters and plotlines, becoming more confident in their reasoning about the culprit. For example, P4 and P12 changed their final choices based on the influence of scent cues on characters, and six participants believed that the scents validated their reasons for selecting the culprit from different perspectives.

Furthermore, based on Figure 9, the difficulty of setting scent information may also affect users' recognition satisfaction of scent clues during viewing (when the scent is assigned information), thereby impacting the overall

understanding of the story. For example, the evaluation dimension of Scent Clue 4 from an informational perspective is lower than other scent clues (e.g., informative, plot development).

However, we also found that even though participants had their own judgments about the murderer at different viewing sessions, scent clues scored lower in the final ending compared to other evaluation dimensions. This may be because the story has an open-ended conclusion, lacking a clear resolution to validate their judgments (P6).

7.3.2. Understanding pre-defined clues

We found that users can accurately perceive the preset scent clues and information, including environmental cues, character status, and interpersonal relationships. For example, regarding scent clue 1 - Blood, users P2, P5, P7, and P11 associated the metallic and pungent scent with the environment of an abandoned factory. P4 inferred from the scent's stench and decay that it might be related to the crime scene, thereby deducing that suspect A had been to the scene and had contact with the victim, leading to the identification of suspect A.

Comprehension difficulty. Furthermore, users found scent clue 3 - Dirt to be the easiest to understand and perceive ($M = 5.50$; $SD = 1.25$), followed by scent clue 1 - Blood ($M = 5.05$; $SD = 1.35$), scent clue 2 - Lavender soap ($M = 4.94$; $SD = 0.94$), and scent clue 4 - Rose perfume ($M = 4.28$; $SD = 1.23$). Most users indicated that the earthy scent of scent clue 3 was the easiest to comprehend, suggesting that it accurately simulated the scent of the scene and was accompanied by static close-up shots in the visuals, enhancing the consistency between visual and olfactory experiences. In contrast, the rating for scent clue 4 (Rose-flavored perfume) was lower, likely because the information conveyed by this clue was more indirect, requiring users to infer the deceased's habits (wearing perfume) simultaneously and the contact with the suspect, thus making it more challenging to understand. Furthermore, based on Figure 9, the difficulty of setting scent information may also affect users' recognition satisfaction of scent clues during viewing (when the scent is assigned information), thereby impacting the overall understanding of the story. For example, the evaluation dimension of Scent Clue 4 from an informational perspective is lower than other scent clues (e.g., informative, plot development).

7.3.3. Ways to obtain the clues

We found that participants accessed olfactory information through various means, including olfactory-visual-auditory cues, the sensation of the odor, timing of odor release, and odor pleasantness. Even with the same odor clue, participants interpreted it from different perspectives. For instance, when presented with Scent Clue 3 - Dirt, P4, P7, and P8 associated the damp and musty scent with outdoor scenes, such as moss and outdoors, inferring information about the character's outdoor activities. On the other hand, P6, P13, and P15 did not specifically identify the scent but noted the timing of its release, which led to increased attention to visual (scene) and auditory (dialogue) cues, helping them obtain critical plot information. Participants believed that the visual elements guided the interpretation of olfactory clues. For example, participants P1 and P7 stated," *In the black-and-white scene, I only noticed the red bloodstains and linked them to the blood odor (Scent Clue 1 - Blood).*" P1 and P14 associated Scent Clue 2 -Lavender soap with the scene of Suspect B's emotional outburst, empathizing with the character's excited mood to identify the culprit. Likewise, when olfactory cues lacked visual or auditory associations, participants perceived them as ambient scents, especially with abstract or unfamiliar olfactory clues (e.g., Scent Clue 1 - Blood). Participants also used the pleasantness of the scent to gather olfactory information; P1 considered Scent Clue 4 -rose Perfume as a pleasant, sweet scent, correlating it with the suspect's mood (glee) to infer the perpetrator.

7.4. Storytelling with differentiated hedonic odors

7.4.1. Extended smell-enhanced information

We found that users have two perspectives and focus when recognizing and understanding scent clues. (1) The odor type. Users are more inclined to associate this information with visual or dialogue cues like scene details and dirt on shoes. The odor type more directly affects users' understanding of the entire story. (2) Odor hedonics. Users tended to relate hedonics to abstract information such as character image ($p = 10$), characteristics ($p = 7$), emotions ($p = 5$), and the atmosphere of the story ($p = 8$). They show confidence in the suspect when combining their understanding of the story and the pleasantness of the scent. Therefore, the impact on character impression comes more from the recognition and understanding of the pleasantness of the scent rather than the scent itself. Users tended to categorize odors based on their pleasantness, so in terms of information, the pleasantness of odors can also lead to diverse interpretations regarding the authenticity of clues, the positive or negative aspects of characters, the goodness or badness of character traits, and the positivity or negativity of character emotions.

For instance, (1) ***Authenticity of Information***: P2 associated Scent Clue 1- Blood with flashback scenes, stated," *At that moment, I even doubted whether this memory was fabricated.*" (2) ***Character Image and Personality***: P7 perceived rose-flavored perfume (Scent Clue 4) as a pleasant sweetness, portraying Suspect C as calm, composed, and a harbinger of justice. Both P7 and P13 inferred complex character traits and images of suspects from the intricate scent of blood, deepening their confidence in identifying Suspect A. P6 expressed uncertainty in identifying a suspect but remarked," *I feel they all have motives and evidence against them, but I would choose Suspect A because her scent is different from the others, giving me a hint.*" (3) ***Character Emotion***: Users empathized with characters' emotional fluctuations through scent. P1 correlated the pleasant lavender-flavored soap (Scent Clue 2) with Suspect B's outburst of anger, perceiving a contrast in information and suggesting

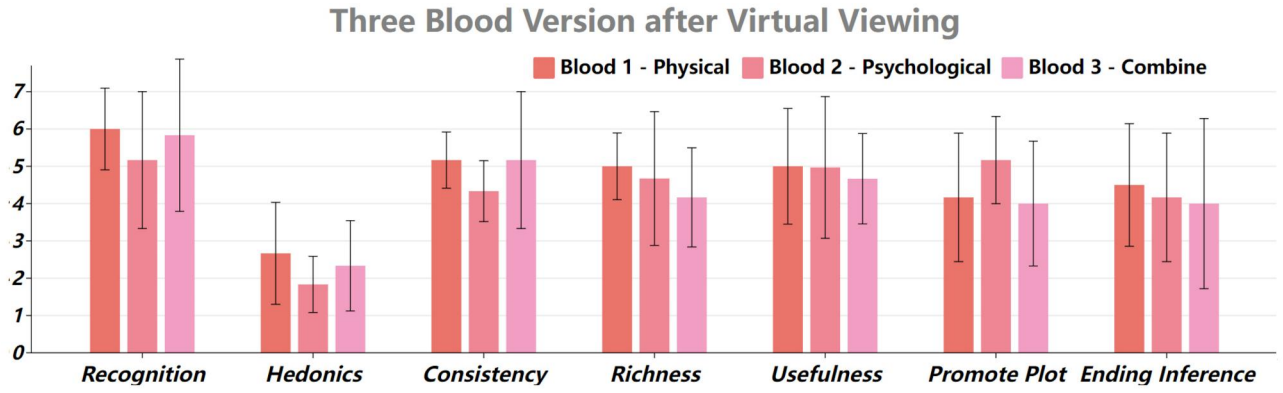

Figure 10. Three blood comparison after the virtual viewing.

that Suspect B's outburst concealed inner satisfaction. (4) ***Atmosphere Enhancement***: Different pleasantness levels of scents contributed to atmosphere and immersion. Regarding Scent Clue 1 - Blood, P11 commented," *The scent appeared from the beginning, evoking a primal fear, the smell of death, making my hair stand on end, somewhat resembling the scent of a corpse or someone about to die; I quickly sensed the suspenseful atmosphere.*" P14 felt," *The scent of that person (Suspect A) hit me like they were about to kill me.*" P16 suggested," *I think this scent could be lighter and played continuously as background scent, enhancing the atmosphere.*"

7.4.2. Experiencing unpleasant odors

In addition to creating expanded information through unpleasant odors, we found that users exhibited higher sensitivity and stronger orientation towards unpleasant odors during viewing. They paid greater attention to the odor information behind them and formed more profound impressions, stimulating their exploratory desires. For example, P18 mentioned," *This odor (Scent Clue 1 - Blood) is not as common as the other odors (lavender and rose), so I would be inquisitive about it.*" Almost all users considered Scent Clue 1 - Blood and Scent Clue 3 - Dirt the most memorable odors.

Odor intensity. Additionally, we found that users were generally satisfied with the current odor intensity settings ($M = 4.89$; $SD = 1.45$), considering them acceptable as long as the concentration was appropriate, even if they did not enjoy the sensations caused by unpleasant odors (such as nausea). P14 mentioned that" *alternating between pleasant and unpleasant odors was exciting and helped reduce the nausea caused by unpleasant odors.*" However, six users mentioned that the intensity of the Blood odor was relatively strong, with one user stating," *I would want to skip scenes associated with the appearance of blood.*" This issue may be due to individual differences in odor sensitivity among users. Since Blood was the first odor released, it may have garnered higher odor perception and attention from users.

Three blood versions. Regarding simulating the sensation of real blood, we found that seven users considered the most fitting version of Blood 2 - Psychological, which used shrimp oil. Compared to the other two versions, it had lower pleasantness and performed better in terms of richness of information ($M = 5.17$; $SD = 1.21$), usefulness ($M = 5.5$; $SD = 1.26$), assisting in story comprehension ($M = 5.17$; $SD = 1.07$), and concluding reasoning ($M = 4.17$; $SD = 1.57$), although the differences were not significant (see Figure 10). For Blood 1 - Physical, users tended to perceive it as related to chemical products, associating it with factory-related scene information (with the most commonly used descriptors being" *metallic*" and" *pungent*"). Blood 3 - Combination performed relatively poorly, which we attributed to their lower recognizability.

7.4.3. Hedonics changing within different odors

We observed changes in the hedonic ratings of different odors before and after viewing (Figure 11). Specifically, the hedonic ratings of lavender soap (Scent Clue 2) and rose perfume (Scent Clue 4) decreased, while the four unpleasant odors tended to approach and increase, with the Blood 2 - Psychological showing a decrease. There may be a mutual influence between pleasant and unpleasant odors. However, the results did not demonstrate a clear linear relationship due to the small sample size, limited data, and the inability to standardize odor experiences (such as variations in users' odor sensitivity). Additionally, we found that users believed pleasant odors could alleviate the negative feelings caused by unpleasant odors, thereby enhancing the hedonics of unpleasant odors (P10). For example," *With the scents of perfume and soap, the smell of blood does not seem unpleasant anymore.*" Additionally, some users expressed that exposure to unpleasant odors could enhance the hedonics of pleasant odors, suggesting an" *increase in the frequency and duration of pleasant odor release*" (P5).

We speculated that the reasons for the change in hedonic perception may include: (1) visual and auditory stimuli during viewing occupy some attention, leading to a decreased sensitivity to odor perception, thereby affecting the perception of pleasantness; (2) combining narrative and plot development, users focus more on functionally understanding the hidden information behind odor clues rather than perceiving the odors themselves; (3) we set up five releases of unpleasant odors and four releases of pleasant odors during viewing (see Table 2). Different pleasant odors' frequency, order, and concentration indirectly affect pleasantness perception. For example, the decrease in pleasantness after viewing the"

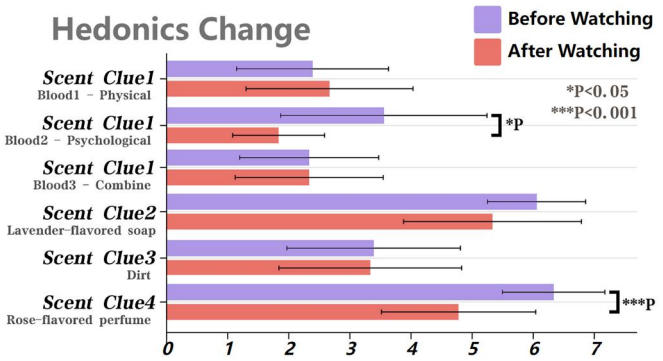

Figure 11. The change in hedonic ratings of six odor types before and after the virtual viewing.

Blood 2 - Psychological" may be related to the higher concentration that was released; Scent Clue 4 - Rose perfume follows closely after the releases of Scent Clue 1 - Blood and Scent Clue 2 - Lavender Soap. The perception of the pleasantness of the rose may be less noticeable due to the strong contrast with the first two odors, leading to a decrease in perceived pleasantness.

7.5. Scent-Releasing, viewing parameters and advice

Generally, users perceived odor release timing, frequency, and immediacy as appropriate ($M = 5.61$, $SD = 0.98$). One user mentioned that the odor release frequency was slightly fast during the first viewing of the odor version, as it required simultaneous memorization of the plot and recognition of odors. Users found the release to be quiet and noise-free ($M = 6.67$, $SD = 0.49$), and the wearing of the odor-release device ($M = 5.33$, $SD = 1.28$) and the weight of the device ($M = 6.17$, $SD = 0.79$) to be relatively comfortable. The placement of the odor release device ($M = 5.67$, $SD = 1.19$) was also reasonable. However, two users mentioned feeling cool when the mist touched their chin or face, which may be due to differences in user posture and height affecting the distance between the odor-release device and the nose. Users also noted that unpleasant odors could be perceived as having a higher concentration, leading to lingering odors (P6, P16), and suggested that the concentration of unpleasant odors be appropriately reduced. Some users ($p = 3$) believed that even while watching a 2D video, the virtual experience in VR could provide higher concentration levels, avoiding distractions from external stimuli, especially in puzzle and suspense genres. P13 and P16 believed that the VR cinema setting enhanced immersion, with P13 stating," *I hope to be able to choose seats like in a real cinema, which would be cool.*"

8. Discussion

8.1. Themes, scenarios, and interactions

Through two sessions of testing and experimentation, we have validated that even when users have not previously learned the correspondence between odors and information, they can still acquire preset odor clues (e.g., environmental cues, character states, and relationships) and make judgments. Moreover, users can gain more complex information by combining odorous clues of different hedonic qualities, such as discerning the veracity of information, understanding the positive or negative portrayal of characters, and inferring character traits and emotions. They can even enhance the immersion of the viewing experience by utilizing the hedonic qualities of odors to match the theme and ambiance of the narrative (e.g., using blood odor for a murder theme). This feature highlights the pivotal and valuable guiding role that odors can play in narrative comprehension and inference, enhancing the engagement and significance of odors as an emerging medium. Particularly in suspenseful mystery genres, users can be intrigued and swiftly grasp complex character relationships through unpleasant odors, thus gaining confidence and enhancing immersion in the viewing experience.

In this work, we have undertaken an initial exploration of crime-themed suspenseful mystery story design. However, we recognize that numerous other popular, appealing, and attractive themes and visual styles can be further explored, unearthed, and integrated. For instance, we can devise a survival horror story set in a cyberpunk style that combines futuristic and technological elements or a war story with distinctive odor features (e.g., like the movie DUNE with its featured spice). Additionally, there could be exploratory game simulators that simulate the olfactory systems of humans or animals (e.g., dogs), mimicking odor inhalation, storage, and search processes. Providing featured theme odors could enhance the immersion and memorability of specific narratives. However, the compatibility of specific themes and odors would require targeted experimentation and testing. We also envision expanding our audience from regular users to particular groups and scenarios, such as those requiring frequent tedious training and learning (e.g., Alzheimer's patients and perfumers undergoing olfactory training). The narratives and timing of odor occurrences can be tailored based on the training objectives, providing participants with a coherent, progressive, and novel training experience.

Meanwhile, although our testing content serves as a starting point with a 2D short film, there are numerous possibilities for expansion in terms of interaction. We can integrate odor-enhanced immersive experiences into narrative-driven VR games (e.g., Sam and Max), interactive movie-style games (e.g., Detroit: Become Human), and immersive performances (e.g., Sleep No More). Users can actively choose virtual characters and perspectives within the story, experiencing varying odor information, concentrations, and release frequencies. They can also customize exclusive odors for characters based on their preferences (e.g., selecting orange-flavored soap for Suspect B). We recommend incorporating control functions for odor release, enabling users to pause or replay odors in real-time during the experience to ensure sufficient time for smelling and reflection. Additionally, we can enhance the exploratory nature of the experience by linking odor release to user-initiated interactive actions, such as clicking or approaching specific objects or scenes

(e.g., exploring items with olfactory clues). Due to individual differences in odor sensitivity and usage scenarios, we suggest allowing users to adjust appropriate odor concentrations (especially for unpleasant odors) and device placement according to their preferences.

8.2. Odor selection and learning as clues

Incorporating odors as clues, the acceptability and recognizability of the odors themselves are crucial. Common daily odors benefit in evoking cognitive resonance among users, such as specific products from popular consumer brands (e.g., Safeguard soap from Brand P&G) or familiar floral and food essential oils (e.g., lavender, rose, oranges). They are easier to identify within visual scenes and can assist in reducing the learning curve associated with odors. Their olfactory information often entails abstract and ambiguous associations for less common but potentially highly recognizable odor types (e.g., dirt and blood). We can supplement user learning and definition-building by integrating audiovisual elements to establish character traits, images, relationships, or scene details within the narrative. It is essential to ensure sufficient learning and memorization time when using such odors as clues. For instance, in visual media (e.g., movies and short films), their appearance should be adequately echoed before and after, with appropriate timing and frequency of odor release, or in gaming experiences, by establishing an" odor backpack" where users can repeatedly experience and remember odors. Furthermore, we can adjust the difficulty of odor clues and information based on the general populace's familiarity with odors. However, it is crucial to consider odor usage's regional and cultural specificity when selecting odors. For example, in Singaporean culture, the smell of bananas can be associated with ghosts and horror (Ranasinghe et al., 2019).

Moreover, to explore the potential of users' understanding of scent clues, we intentionally set Scent Clue 4 - Rose as a clue with only a scent unrelated to visual and auditory information. The results show that users found it difficult to perceive this information. Therefore, we recommend that when presetting scent clues, at least one non-olfactory sensory information should be combined, such as close-up shots, linguistic hints in dialogue, or matching sound effects.

Additionally, although users in the testing of *ScentClue* showed relatively good acceptance of unpleasant odors, selecting acceptable unpleasant odors remains more challenging compared to pleasant ones. We suggest seeking the consent of target users before using unpleasant odors, conducting acceptability tests through rapid experiences, and simultaneously retaining alternative options that can be replaced with pleasant odors. We also recommend that such odor experiences be confined to small spaces or personal use (e.g., room space) rather than public spaces (e.g., cinema) to reduce unnecessary odor residuals and emissions. Meanwhile, apart from the explored shrimp oil and some fragrance ingredients, we can further explore the potential of unpleasant odor materials, such as using safe and non-toxic chemical reagents under professional guidance. We also need to exclude odor types that may cause physiological and psychological nausea reactions (e.g., prank odors). We suggest rigorous selecting and testing of target odors, including concentration tests at different dilution levels, testing with the target user group, and ventilation testing.

8.3. Scent release settings

8.3.1. Precise scent release for narrative

In *ScentClue*, all piezoelectric atomizers operate at the same duration (100 ms/s for odor concentration, except Blood for 60 m/s). However, to better depict narratives, we can provide varied, more detailed, and precise olfactory experiences based on factors such as the tension of character performances, key story points, scene transitions, and visual expressiveness. For instance, we can intensify odor concentration during moments of heightened emotion in characters to evoke empathy and provide a more immersive experience. Additionally, we can increase odor concentration during gradual zoom-ins or close-up shots to emphasize critical information in the visuals. We can also release short but more pungent odors to highlight pivotal narrative points or use longer but milder odors to represent environmental scents or character traits. Further work is required to explore the specific correlations and rationality between visual elements and odor-release parameters.

8.3.2. Releasing unpleasant odors

Through experimentation, we have found that concentration is a crucial metric influencing users' acceptance of unpleasant odors. Therefore, we recommend choosing lower dilution concentrations when using unpleasant odors and allowing the target audience to test and adjust their smells. Considering the alleviating effect of pleasant odors on unpleasant ones, we suggest cross-utilizing two types of pleasant odors and potentially increasing the frequency of pleasant odor releases. Additionally, incorporating functional odors, such as lavender, known for its mood-calming properties, can mitigate potential adverse reactions to previously encountered unpleasant odors, particularly after a movie or game. Furthermore, to maintain a tranquil, immersive virtual experience, we have chosen piezoelectric atomization as a compromise for odor release. However, liquid-based odorants may result in more prolonged residual effects than airflow-based methods. Thus, in future endeavors, we will continue iterating on odor release methods (using pumps or heat and fans), and further testing is required to fine-tune the specifics of odor release parameters.

8.4. Limitation, iteration, and future work

Currently, *ScentClue* focuses on exploring the informational potential of different hedonic odor cues by offering open-ended conclusions. Refining and adjusting the story logic will be necessary in future endeavors. For instance, the conclusion could be structured as a closed-loop narrative with a sole culprit, integrating interactive multi-threaded

experiences to allow users to further observe the accuracy of odor cues in conveying information. Moreover, we will optimize the frequency of odor release and the number of releases for odors with varying hedonic qualities (reducing the frequency of Blood releases) to observe if users can still obtain relevant information. Additionally, the current test film is only three minutes long; thus, in future work, we still need to observe and test the concentration, frequency, and residual effects of odor release when users watch or engage with longer videos or games (e.g., for an hour). Furthermore, immersive experiences through panoramic multimedia viewing are crucial for enhancing immersion. We will continue iterating on the form of multimedia video materials (production of panoramic videos) to delve deeper into the interplay between user attention, odor cues, and odor release parameters.

9. Conclusion

In this paper, we have designed and implemented the *ScentClue* system, which comprises a murder-themed narrative design, four key scent clues encompassing pleasant and unpleasant odors, a neck-worn odor delivery device, and a UE-based virtual movie viewing environment. We have validated the usability of the *ScentClue* system and the immersive viewing experience enhanced by olfaction. Additionally, we have confirmed the effectiveness of scent clue settings; users could receive predetermined olfactory cues and attain a more intricate, immersive, and compelling storytelling experience through the hedonic quality of different scents. Finally, we discussed the potential applications and interaction modalities of *ScentClue*, proposing areas for improvement in scent clue design, material selection, and scent-releasing parameters, as well as addressing the limitations and future work of *ScentClue*. We particularly emphasized the potential and considerations when utilizing unpleasant odors.

Notes

1. https://www.tcm.com/tcmdb/title/89236/scent-of-mystery/overview
2. https://www.fragrantica.com/

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