ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΛΟΠΟΝΝΗΣΟΥ
University of the Peloponnese

MSc in Computer Science

Master's Thesis

Olfaction as a sensory interface and game mechanic in digital environments: Scentree, an Arduino-based olfactory display and its effects on User Experience and Memory

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University of the Peloponnese

Π.Μ.Σ. στην Επιστήμη Υπολογιστών

Μεταπτυχιακή Διπλωματική Εργασία

Η Όσφρηση ως αισθητηριακή διεπαφή και μηχανική παιχνιδιών σε ψηφιακά περιβάλλοντα: Scentree, μία οσφρητική διεπαφή βασισμένη σε Arduino και οι επιδράσεις της στην Εμπειρία Χρήστη και τη Μνήμη

Βασιλειάδης Βασίλειος

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Τρίπολη, 2026

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Βασιλειάδης Βασίλειος
Τμήμα Πληροφορικής και Τηλεπικοινωνιών
Πανεπιστήμιο Πελοποννήσου

Η παρούσα εργασία εκπονήθηκε σε συνεργασία με το εργαστήριο διάδρασης ανθρώπου υπολογιστή και εικονικής πραγματικότητας (HCI-VR LAB).

ABSTRACT

Keywords: **Olfaction, Olfactory Displays, Virtual Reality, CAVE, HCI, Immersive environments, Game Mechanics, User Experience, Memorization.**

This thesis examines olfaction as an interactive game mechanic in immersive digital environments, concentrating on how olfactory cues can alter user experience in terms of presence, immersion and realism within a CAVE (Cave Automatic Virtual Environment) environment (MobiCAVE). To do so, this thesis presents the design, development, and evaluation of Scentree, a modular, scalable and low-cost olfactory display designed for the MobiCAVE environment, along with its integration into the Unity game engine for real-time scent triggering. Furthermore, it elaborates on practical and technical considerations for integrating olfaction in CAVE experiences, such as scalability and reliable synchronization between virtual events and physical diffusion. Finally, drawing on the Proust phenomenon, this thesis highlights the potential of repetitive task training as a future direction for enhancing perceived memorization and recall of complex information through the sense of smell.

ΠΕΡΙΛΗΨΗ

Λέξεις Κλειδιά: Όσφρηση, Οσφρητικές Διεπαφές, Εικονική Πραγματικότητα, Ψηφιακά Περιβάλλοντα, Διάδραση Ανθρώπου-Υπολογιστή, Εμβυθιστικά Περιβάλλοντα, Μηχανικές Παιχνιδιών, Εμπειρία Χρήστη, Απομνημόνευση.

Αυτή η διπλωματική εργασία εξετάζει την όσφρηση ως διαδραστική μηχανική παιχνιδιών σε εμβυθιστικά ψηφιακά περιβάλλοντα, εστιάζοντας στον τρόπο με τον οποίο τα οσφρητικά ερεθίσματα μπορούν να μεταβάλουν την εμπειρία του χρήστη όσον αφορά την αίσθηση παρουσίας, την εμβύθιση και τον ρεαλισμό μέσα σε ένα CAVE (Cave Automatic Virtual Environment) περιβάλλον (MobiCAVE). Για να το πετύχει αυτό, η παρούσα διατριβή παρουσιάζει τον σχεδιασμό, την ανάπτυξη και την αξιολόγηση του Scentree, μιας πολυτμηματικής, επεκτάσιμης και χαμηλού κόστους οσφρητικής διεπαφής σχεδιασμένης για το περιβάλλον MobiCAVE, μαζί με την ενσωμάτωσή της στη μηχανή παιχνιδιών Unity για την ενεργοποίηση οσμής σε πραγματικό χρόνο. Επιπλέον, αναλύει πρακτικές και τεχνικές παραμέτρους για την ενσωμάτωση της όσφρησης σε εμπειρίες CAVE, όπως η επεκτασιμότητα και ο αξιόπιστος συγχρονισμός μεταξύ εικονικών γεγονότων και φυσικής διάχυσης. Τέλος, βασιζόμενη στο φαινόμενο Proust, η παρούσα διπλωματική εργασία αναδεικνύει τις δυνατότητες της εκπαίδευσης σε επαναλαμβανόμενες εργασίες ως μια μελλοντική κατεύθυνση για την ενίσχυση της απομνημόνευσης και της ανάκλησης σύνθετων πληροφοριών μέσω της αίσθησης της όσφρησης.

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1 Introduction

Multisensory interface development is a main area of research in the HCI field. Most digital environments, particularly video games have been trying to integrate multiple senses seeking to enhance immersion and improve realism and user experience. In practice however, visual, auditory and haptic modalities tend to be the main channels of interaction because of their efficiency [1],[2]. Olfaction despite its promising outcomes [3],[4],[5],[6],[7] remains underexplored.

Olfaction is also underexplored specifically from a game design perspective. In most implementations, smell is treated mainly as a component of 'naïve immersion', an atmospheric layer that merely confirms what is seen onscreen,rather than being designed as a structured game mechanic triggered by gameplay events [49].

This is particularly evident in virtual reality (VR), where efforts are constantly being made to improve multi-sensory fidelity to enhance presence, engagement, and perceived realism. Recent studies of Olfactory Virtual Reality (OVR) display present a variety of scent delivery mechanisms and reports encouraging perceptual outcomes across different application areas [8]. However, literature[8, 46] also highlights technical difficulties, such as latency, cross-contamination, and the difficulties of producing spatially targeted aromas in large room-scale immersive environments such as CAVE systems.

Past olfactory virtual reality mechanisms were either designed for head-mounted displays (HMD's) or desktop configurations where only a single user could receive odors[39]. Conversely, Cave Automatic Virtual Environments (CAVE) systems offer novel opportunities and difficulties for olfaction[46]. Those systems facilitate multi-user, collaborative experiences and address HMD-related ergonomic issues such as motion sickness[15]. The literature also highlights a significant lack of technologies that are reproducible and adaptable to CAVEs[8]. Most ubiquitous solutions are either based on commercially available expensive systems or on systems that are not designed for interactive synchronization with game engines[40].

1.1 The potential of olfaction

Psychology has shown that olfaction can be a sufficient mnemonic cue, enabling us to recall more vivid and strong autobiographical memories [7]. Encoding Specificity theory [9] explains that recall improves when cues present at retrieval overlap with those present during encoding, while Dual Coding theory [10] explains how combining modalities can strengthen memory by creating more than one route for retrieval. Multisensory integration theory [11] further clarifies how multiple stimuli become a single coherent experience: when sensory cues are temporally aligned and perceptually congruent, they are more likely to be bound and experienced as one event rather than separate signals. From a learning perspective, Cognitive Load theory [12] adds that integrating related cues across channels can reduce cognitive load, and Gestalt principles [13] describe the tendency to perceive structured wholes, which together help explain why well-coordinated multisensory cues can feel more unified and easier to process.

Multisensory interfaces have been proven to effectively optimize learning and improve the flow and user experience [14]. Olfaction as a distinct sensory modality that functions as an interactive element and a game mechanic that could enhance the memorization of complex information through repetitive task training remains underexplored. The current study gap refers to the olfaction's capacity as a game mechanic in combination with psychological theory aiming to enhance the perceived memorization of complex information and recall after a delayed period. This thesis also explores olfaction's effects on User Experience in terms of flow, realism and immersion.

1.2 Aim & Study Objectives

This thesis investigates the integration of olfaction as a structured game mechanic, rather than an ambient element, within a CAVE environment (MobiCAVE). To achieve this, the study addresses the following Research Questions (RQs):

1. RQ1 (Technical Feasibility): Can a low-cost, open-source, and extensible olfactory display be effectively developed and integrated within a CAVE environment (MobiCAVE)?

2. RQ2 (User Experience): To what extent does the inclusion of event-based olfactory cues affect user immersion, realism, and the sense of presence in virtual environments?
3. RQ3 (Cognitive Impact): Does the integration of olfactory stimuli enhance the perceived memorization and engagement of users during complex information tasks?

Therefore, this work presents the complete design, development, and evaluation process of Scentree, an Arduino-based olfactory display tailored for the MobiCAVE system[15].

1.3 Summary of Contributions

My thesis aims to contribute to multiple fields. In HCI & Game studies it demonstrates that olfaction can function as an interactive game mechanic rather than serving only as a background element to enhance immersion. Additionally, this thesis provides a technical contribution through the design of an affordable, extensible, and open-source Arduino-based olfactory display designed for a CAVE environment (MobiCAVE). Finally, this study offers a contribution in the field of Cognitive Psychology by highlighting insights into the role of olfaction in perceived memorization of complex information.

1.4 Thesis Structure

This thesis is organized into six chapters. Chapter 1 presents the motivation for this study, defines the problems and outlines the contributions of this thesis. Chapter 2 provides foundational knowledge on olfaction, sensory perception, game mechanics and user experience. Chapter 3 surveys prior research on olfactory integration in virtual reality, learning and memory and related HCI studies. Chapter 4 introduces a proposed framework for the development and evaluation of Scentree. Chapter 5 describes the MobiCAVE system and presents a proof-of-concept study to further evaluate the system. Finally, chapter 6 includes further discussion, limitations, future work suggestions and concludes.

2 Background

2.1 The Human olfactory network

Olfaction refers to the sensory modality which is responsible for the detection of gaseous odorants experienced as the sense of smell. Unlike the term “smell” which defines the experience, olfaction refers to the biological and cognitive processes of this sense [16]. To understand smell, we first must understand how our olfactory system works. Human sense of smell begins in a region above the nasal cavity, where odor molecules first come in touch with the olfactory epithelium. Sensory neurons lining this layer contain receptors that attach to chemicals in the air. Together these sensors can identify thousands of different odors since each one is tailored to detect molecular characteristics. Following activation, the olfactory bulb receives electrical signals from these neurons, organizes the data and then sends it to the brain for interpretation. This process is depicted in the accompanying figure, which demonstrates a representation of our olfactory system.

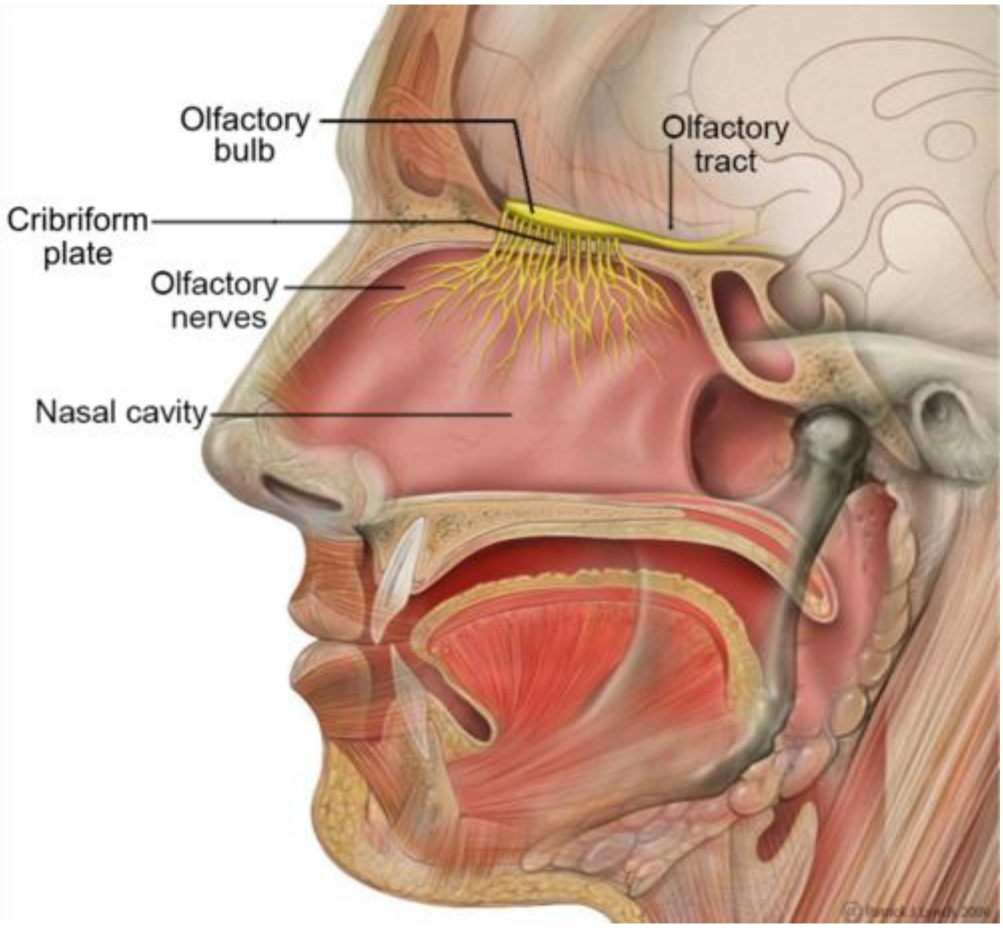

Figure 1. Representation of the human olfactory system. Image by Patrick J. Lynch, medical illustrator , Retrieved from (https://en.wikipedia.org/wiki/Olfactory_system#/media/File:Head_Olfactory_Nerve_Labeled.png) is licensed under CC BY 2.5.

Our olfactory system has around 6-10 million receptor cells, able to distinguish between 2-4k different smells [17]. The odor detection begins in the nasal chamber, where odors bind to the olfactory receptor cells in the epithelium. These receptor neurons transmit signals to the olfactory bulb where they are processed by the mitral cells. After this procedure is completed, the signals are sent to the brain cortex where neurons encode them and relay perception, resulting in the perception of smell [17].

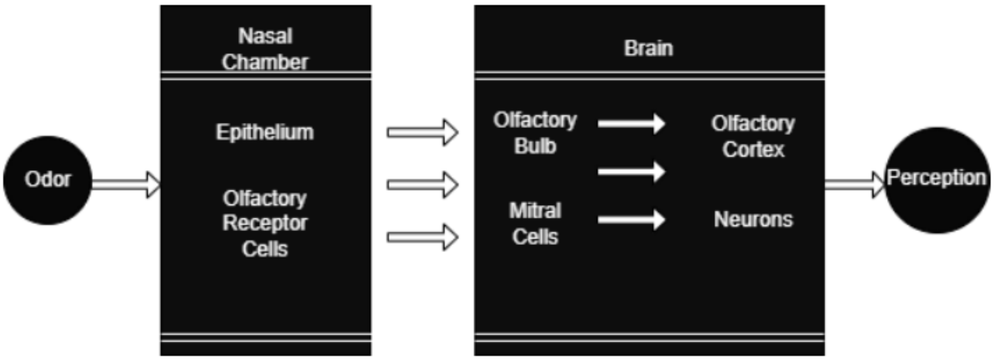

Figure 2. The Olfactory Pathway, Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

2.1.1 Olfaction & Memory

The perception of odor begins with the detection of volatile molecules, which activates a network of receptor cells & neural pathways. Primarily, olfaction has a direct connection to the limbic system of the brain. Areas such as the amygdala and hippocampus are critical for emotion and memory processing [18] . Unlike other sensory modalities, olfactory information bypasses the thalamus, leading to a more immediate and profound emotional response. As neurobiologist Robert Sandeep Datta (University of Cambridge) stated, when odorant molecules enter the nose and bind to their matching receptors, it is “like a key being inserted into a lock. Then a neurological procedure takes place for the molecules to lock into an odor-based memory. When we compare those memories with ones triggered by other senses, odor evoked ones tend to be more emotional, also discussed in the context of the Proust phenomenon according to which, smell, can evoke more vivid autobiographical memories [7].

2.2 Memory in Cognitive Psychology & HCI

Building on this overview of our olfactory system, the following section examines key theories from cognitive psychology and HCI that present principles for multisensory immersive design.

2.2.1 The Proust Phenomenon

The Proust phenomenon refers to the unique ability of smells being able to trigger more intense and vivid autobiographical memories [7]. This term originates from the novel “À la recherche du temps perdu” in which Proust evokes childhood memories by using madeleine cakes to create a peculiar scent. Studies have shown that memories tied to olfactory cues tend to be more emotional, vivid and sometimes older than those that are triggered by visual or auditory cues [18]. This is attributed to the fact that our olfactory system has direct neural connections to the hippocampus and amygdala, structures that are critical for memory and emotion [19]. This close anatomical link between olfaction and the limbic system provides a feasible mechanism as to why odors can act as effective retrieval cues. Therefore, in multisensory interactive environments, we expect congruent olfactory cues to support memorization and delayed recall by strengthening the association between content and context.

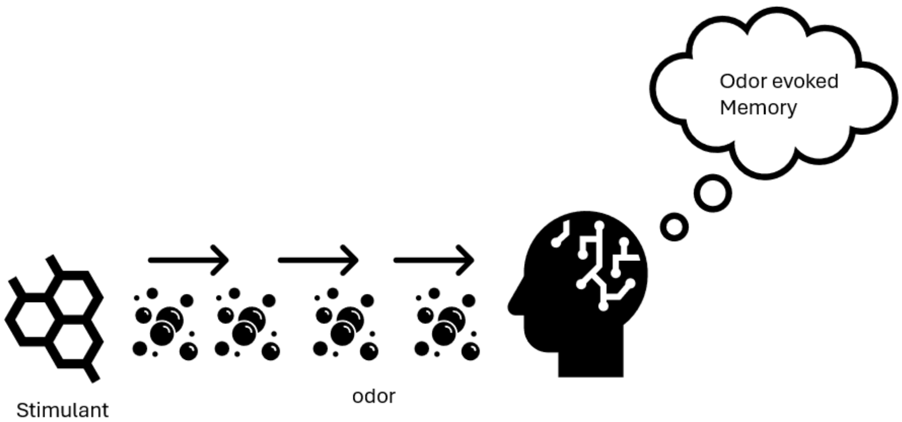

Figure 3. The Proust Phenomenon, Image by Vasileiadis Vasilis, is licensed under CC by 4.0

Existing bibliography highlights olfactory cues as powerful mnemonic signals, which could enhance both recall and the quality of memories. This motivates the way for links to theories about memory encoding and the importance of appropriate cues in successful recall, such as the theory of encoding specificity.

2.2.2 Encoding Specificity

The Encoding Specificity Principle was formulated by [9] according to which for more effective memory recall, the cue that was present during the time of the learning process, needs to also be present during the recall process. This theory strongly explains that, by associating an object with a specific odor, it can act as a powerful stimulus which improves memory recall. To further prove this theory, they conducted experiments where the use of specific cues dramatically increased the success of information retrieval. In terms of olfactory memory, another study has shown us that when odors are present during both the learning and recall process, they act as a powerful retrieval cue [4].

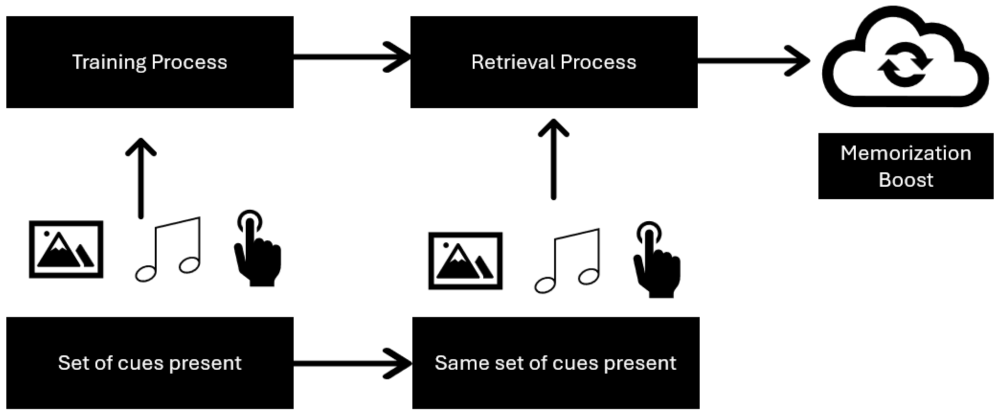

Figure 4. Encoding Specificity, Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

The encoding Specificity Principle helps explain how olfactory cues can support memorization. Following, the Dual Encoding Theory further extends this idea.

2.2.3 Dual Encoding

The Dual Encoding theory [10] suggests that information is stored in two independent but complementary systems, divided into verbal and non-verbal. The verbal system involves language and vocabulary and the non-verbal involves other sensory inputs like sounds, images and other sensory stimuli. Thus, simultaneous encoding in more than one channel increases the likelihood of successful information storage. According to this theory, when the same information is encoded in more than one channel, retrieval is more successful, because more retrieval channels are created. Prior work by Clark and Paivio [20], has shown that when you accompany a word with an image the retrieval is significantly stronger than when only one of the two exists.

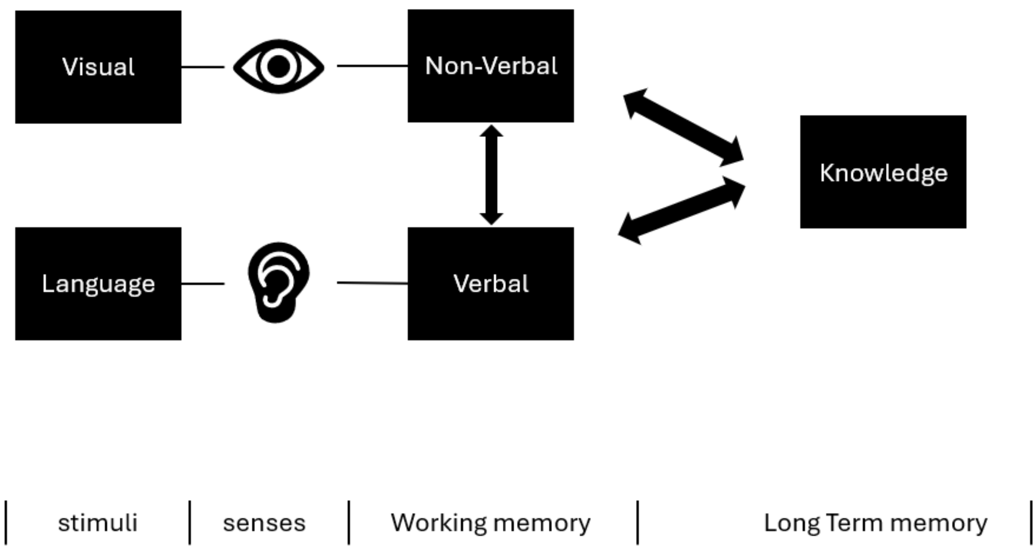

Figure 5. Dual Encoding, Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

Dual Encoding theory provides a powerful framework that enables us to conceptualize how the integration of multiple channels of information can enhance those processes.

2.2.4 Multisensory Integration

The theory of Multisensory Integration [21] suggests that the brain does not process the senses individually but combines them, using multiple channels from different sensory pathways to shape a more unified concept of the environment and create richer and more realistic representations. Research results [22], have shown that when compared to monosensory stimuli, utilizing information through multiple channels leads to richer memory traces, enhances the process of learning and can improve recall accuracy.

This theory can also be backed by the Cognitive Load theory [12]. Sweller states that our memory has limited capacity and overloading it can affect efficient learning. The use of multiple channels to present information allows it to be processed in different mechanisms and can result in reducing the overall cognitive load and making encoding easier.

Overall, the principles of the Gestalt theory, which is a school of thought, emphasize that the brain perceives things as a unified experience rather than perceiving them as a collection of individual parts. For example, the result of the combination of two different stimuli, an image and a smell can be perceived as a multisensory integration that enhances perception, memory and the sense of continuity in the experience.

In an educational setting, Di Fuccio et al. [23] studied digital and multisensory educational materials with tangible user interfaces and evaluated effects on retention in primary school learners. Separately, Ghinea and Ademoye [14] discuss enhanced multimedia and outline opportunities and challenges for using smell to influence user experience and perceived quality in multimedia systems.

Multisensory Integration blends the logic of the Dual Encoding Theory into a more holistic approach where inputs are arranged into cohesive experiences and cognitive load is distributed more efficiently. Designing digital games with the dual goals of improving memory and producing more realistic and immersive experiences requires an understanding of these mechanisms.

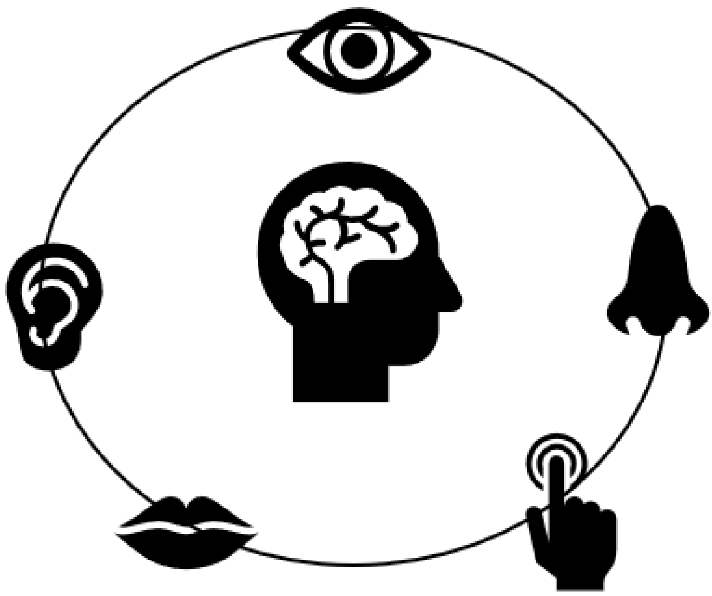

Figure 6. Multisensory Integration, Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

2.2.5 Repetitive Task Training

Repetitive Task Training refers to the active and repeated practice of a specific task that aims to improve functional performance [24]. Repetitive task training enables the user to be active in the process, by repeating actions even if its memory tasks, in contrast to other passive modalities. It is often used in the rehabilitation process of post-stroke patients. Repetitive Task Training gives us a structured framework emphasizing practice intensity and task relevance.

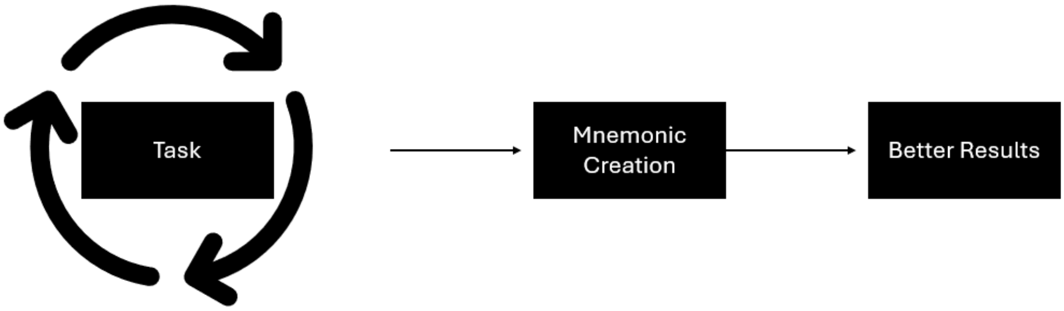

Figure 7. Representation of the Repetitive Task Training Process, Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

Taken together, the theories demonstrated that olfaction shows potential to function as a powerful memory mechanism in multisensory environments. Starting from the Proust phenomenon highlighting the ability of smells and their connection to memory. Next, the Encoding Specificity theory shows that by presenting the same cues during the learning and recall process we can enhance the access to storage information, while the dual encoding theory explains that using more than one channel to present information creates more enduring memory traces. Multisensory Integration, understood within the framework of cognitive load and Gestalt principles, provides us with a more holistic framework that enables us to lower the cognitive load. Ultimately, the Repetitive Training (RTT) model indicates that systematic repetition of such multisensory connections can theoretically result in faster and more efficient memorization.

2.3 Interface Design

Modern interface design increasingly considers interaction beyond the desktop, encompassing a wide range of human perceptual and motor capabilities. While designing immersive experiences, we must consider the representation and the processing of information by various sensory modalities based on this theory. Immersive experience design has overwhelmingly been dominated by visual, auditory and haptic modalities because of their efficiency [1], [2].

2.3.1 Olfaction & Game Design

In the context of game design, olfaction remains underexplored. Most studies are focusing on other sensory modalities despite the advantageous results that research has shown olfaction provides. For example, research has shown that olfaction can enhance immersion, the sense of realism and memory qualities through immersive gamified experiences. Recent research has used olfaction to change the mood of users [25], enhance immersion [26] and boost memory recall during sleep [27]. Very few studies have used olfaction as an interactive element that enables it to be considered an active game mechanic. Integrating olfaction alongside other sensory modalities in game design can better demonstrate its potential as an interactive channel and help address the current gap in how sensory modalities are theorized and operationalized as game mechanics.

2.3.2 Game Mechanics: Definitions & Classifications

To understand how olfaction can be integrated within the game mechanics spectrum, we have first to define the notion of game mechanics. According to the study by [28], there is not a globally accepted term when we are talking about game mechanics, presenting that there are 49 explicit definitions that form this concept of "game mechanics". Definitions with a lot of citations such as Salen and Zimmerman's *Rules of Play* [29] depict mechanics as "methods invoked by agents for interacting with the game world", while Sicart (2008) [30] depict them as "rules-based interactions" that shape the user experience. Some classifications help designers organize how player actions, system rules and feedback interconnect. The MDA Framework, for example [31] differentiates between mechanics, dynamics and aesthetics to define design intent. So, the most accepted term should be that "game mechanics are the ways the player interacts with the system". While this framework and definitions tend to be player centered and provide us with an abstract taxonomy, researchers [32] provided a taxonomy that works well as a design tool.

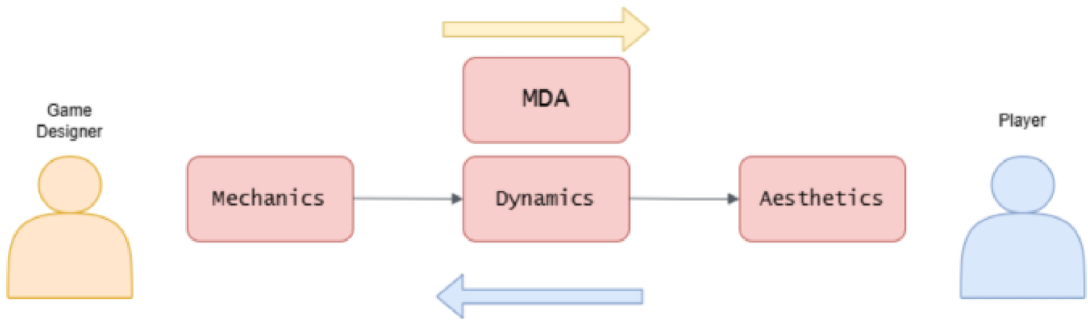

Figure 8. The MDA Framework, Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

2.3.3 Bramantoro's Classification

A study by [32], differentiates mechanics from theoretical taxonomies and offers a powerful design tool by constructing a six-category classification that breaks mechanics into six categories: Core, Meta, Feedback, Social, Narrative and Aesthetic each reflecting a unique aspect of how video games organize the user's interaction and experience. For example, Nine Sols uses audio feedback so players can hear when they successfully parried an attack. This example is using audio as a Feedback game mechanic. At the same time, it uses visuals as a Meta mechanic because to further unlock the map and explore the players need to collect certain items.

Table 1. Bramantoro's Classification

Core	**Meta**	**Feedback**	**Social**	**Narrative**	**Aesthetic**
Movement	Micro Transactions	Rewards	Multiplayer Modes	Lock/ Unlockable	Graphics
Jumping	Leveling System	Bonuses	PvP	Cutscenes	Audio
Shooting	Progression	Achievements	Leaderboard	Dialogue Trees	Virtual Goods
Puzzle-Solving	Skill Trees	Badges	Chat System	Character Development	Customization

Jumping	Challenges	Points	Party Tactics	Quests	Avatar Identification
Replayability	Resource Management	Score systems	Coordinate Actions	Storyline	Atmosphere
Gacha	Randomness	Feedback Messages	Gifting & Charity	Mystery	Style
Detailed Simulation	Base Building	Health Bars	Player-Created Content	Player Choice/Decision Making	Immersion
Turn-Based	-	Punishment	-	World-Building	-
Rewind	-	Collectibles	-	-	-
Player Inventory	-	-	-	-	-

Core Mechanics explains the basic movements and interactions that are necessary for gameplay.

Meta Mechanics contains the mechanisms that exist beyond the core gameplay including Leveling systems, micro transactions or resource management.

Feedback Mechanics, the third classification includes responses that inform the player of their performance, including rewards, bonuses or score systems.

Social Mechanics includes features involving multiplayer interaction such mechanics are multiplayer modes, PvP (Player versus Player), or Player created content.

Narrative Mechanics, these mechanics shape immersion through plot and character development.

Aesthetic Mechanics, the sixth and final classification, includes mechanics that focus on sensory and artistic choices of video games including graphics, audio quality, style & atmosphere and character customization that gives a video game its unique style.

2.3.4 Senses as game mechanics

I am putting forward a classification that incorporates sensory modalities into the game mechanics classification, drawing inspiration from Bramantoro's work. Given that Bramantoro is categorized according to functional role, the goal of this categorization is to correlate how each sense is used by each mechanic. This will help me discover the potential of olfaction by systemically integrating it rather than just using it as a passive environmental and immersion enhancer. It also allows me to think about and distinguish distinct sensory modalities as game mechanics in an organized manner. This classification offers a conceptual link between the necessity for structured mechanics in Game Design and HCI's focus on multisensory engagement.

Table 2. Senses as game mechanics classification

Sense/Mechanic	Core	Meta	Feedback	Social	Narrative	Aesthetic
Visual	Aim, Navigation	Unlocking Map, changing equipment	Screen Shaking	Emotes, Avatar Poses	Cutscenes	Graphic style
Auditory	Rhythm Input	Soundtrack collectibles	Audio alerts, 3D spatial audio(whispering)	Voice Chat	Soundscapes	Sound Design
Haptic	Gesture recognition	Using tools with tactile functions	Vibration	Haptic suits	-	-

Olfactory	Odor-object association	Unlocking scent pallets	Odors as signals	-	Odors triggering autobiographical memories	Immersion & Mood changes
Gustatory	-	-	-	-	-	-

Visual Mechanics

Starting from vision - which is the ruling modality in video games - can be integrated into all categories of mechanics easily. As a core mechanic it dominates tasks including aiming and navigation. As a meta- mechanic visual information helps the player observe things that aid in their progression, such as seeing a map or navigating the world and noticing changes in the atmosphere. Feedback mechanics depend on visual cues. From HUD indicators (a health bar) to on-screen messages for failure, success or checkpoints, rest points & danger zones. In the social layer, visual cues can aid communication among players. For example, players can use their avatar emotes to express themselves. Narratively, vision supports cutscenes while aesthetics is determined by colour, lightning and graphic style, all involving visuals.

Figure 9. Vision in Core Mechanics, Image by Antony Terence, retrieved from (https://www.videogamer.com/guides/helldivers-2-aim-down-sights-first-person/)

In helldivers 2 aiming is crucial since you must take out aliens to progress through and complete missions to liberate the planet. Aiming works as a core mechanic in this video game, thus the player must rely on their vision.

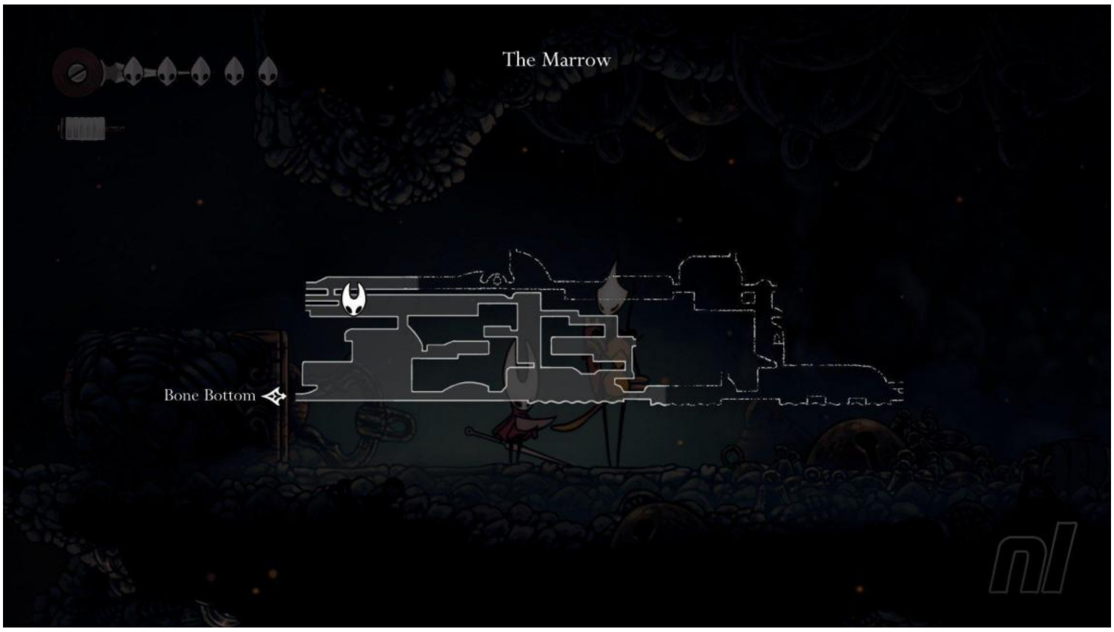

Figure 10. Vision in Meta Mechanics, image by Nintendo Life, retrieved from (https://www.nintendolife.com/guides/hollow-knight-silksong-where-to-find-shakra-compass-quill-and-map-locations)

In Hollow Knight Silksong, players when exploring the world of Pharloom tend to unlock a map of each area. By later purchasing a compass tool they can see their location on the map, so they know which path to take or just to be able to identify their location. Vision again works as a mechanic in the context of Meta information.

Figure 11. Vision in Feedback Mechanics, image by Muhit Rahman, retrieved from (https://intoindiegames.com/walkthroughs/tips-tricks/hollow-knight-silksong-boss-guide-widow/)

Hollow Knight Silksong provides us with a great example of how vision exists in feedback mechanics. Indicators in the form of rays are showing the players where an attack is going to land, so they need to move out of that way to not be hit. In this context vision plays a vital role in feedback mechanics.

Figure 11. Vision in Social Mechanics, Image by PUBG Corporation, retrieved from(https://www.gamesradar.com/pugb-emotes-player-unknowns battlegrounds/)

In PlayerUnknown's Battlegrounds (PUBG) players can communicate with their teammates using an emote wheel. This leads to faster communication and it's a way to visually communicate with cooperators.

Figure 12. Vision in Narrative Mechanics, image by XzParen, retrieved from (https://steamcommunity.com/sharedfiles/filedetails/?id=3354905432)

This example follows a narrative of the game Hollow Knight. The visual channel dominates in cutscenes.

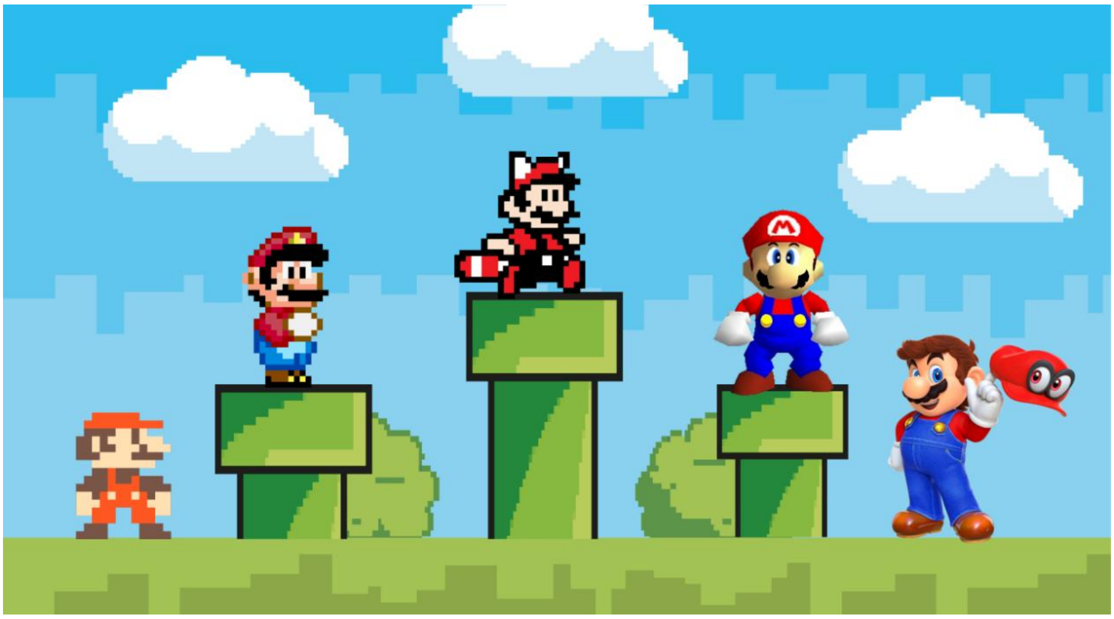

Figure 13. Vision in Aesthetic Mechanics, image by Pradeepsingh Rajpurohit, retrieved from (https://300mind.studio/blog/the-evolution-of-video-game-graphics/)

In this example we can see how visuals form aesthetics. All the games follow the story of Super Mario, but we can see the difference of aesthetic value in each different art style.

Auditory Mechanics

Sound works complementary and further extends the visual channel creating rhythm and mood into gameplay. As a core mechanic it introduces rhythm-based gameplay. As a meta mechanic, unlocking sounds are needed for progression. Feedback mechanics rely on sounds as alerts and notifications that enable the player to prepare for upcoming events. In the social mechanics layer, using voice communication (Voice Chat) enables players to strategically communicate, preparing better for upcoming events. In the narrative layer, soundscapes provide thematic resonance and finally on the aesthetic dimension, background music expands the feeling of immersion and realism.

Figure 14. Audio in Core mechanics, retrieved from (https://videogamesplus.ca/products/patapon-1-2-replay-jpn-import-multi-language-nintendo-switch-pre-order?srsltid=AfmBOooTGYTH7dhEUBJV_St0ULBAtWDghegE_stRDJpjIOfujXj-1oFI)

Patapon is a perfect example of a rhythm-based game. Players are pressing inputs based on the rhythm Patapons sing. Each rhythm shows different results.

Figure 15. Audio in Meta Mechanics, image by Team Cherry, retrieved from (https://www.sportskeeda.com/esports/how-unlock-needolin-hollow-knight-silksong)

In the meta mechanics layer, Hollow Knight Silksong provides the players with melodies that when played using their weapon extend their progress.

Figure 16. Audio as a feedback mechanic, Image by Quick, retrieved from (https://megaman.fandom.com/wiki/Warning?file=MMXCMWarning.png)

Megaman provides us with a powerful example of how sounds further extend the visual channel. In the feedback layer, when the player enters a boss's room, they are presented with a warning notification visually and an audio signal start playing. This works complementary to the visual channel and further affects the user's perception.

Figure 17. Audio in Social Mechanics, image by VR CHAT Inc. Retrieved from (https://store.steampowered.com/app/438100/VRChat/)

VR Chat is probably the best example of using audio as a social mechanic. In VR Chat players can interact with each other and talk by using the Voice Chat option. This leads to communication between players further extending player experience.

Figure 18. Audio in Narrative Mechanics, retrieved from (https://www.shacknews.com/article/135588/cold-resistance-armor-zelda-totk)

In the game The Legend of Zelda: Tears of the Kingdom, players are met with nice soundscapes that form the narrative of the game. As shown in Figure 19 when the players enter a snowy field, their footsteps and the whole acoustic layer shift to match the landscape they have entered. Walking is now heard as “walking in snow”, or when Link doesn’t wear heavy clothing, they can hear him getting cold. Audio further extends the narrative layer by adding those details.

Figure 19. Audio in Aesthetic Mechanics, retrieved from (https://daily.bandcamp.com/features/katana-zero-score)

Katana Zero is a hack and slash game where players need to clear a stage without getting hit. Since the games' pace is fast the Background Music (BGM) provides energetic soundtracks altering the mood of the player and forming the aesthetic of this game.

Haptic Mechanics

Haptic interaction uses motion and touch to "insert" the player in the gameplay. As a core mechanic, gesture recognition is fundamental components of gameplay. In the meta layer, the player can use tactile functions to progress through the game. As a feedback mechanic, haptic functions mimic weight, impact or damage via pressure sensors and vibrations. In social mechanics, using haptic suits, especially in a VR environment can lead to better engagement since users can "feel" other player actions.

Figure 20. Haptic functions in Core Mechanics, retrieved from (https://www.nintendo.com/us/store/products/1-2-switch-switch/?srsltid=AfmBOormv4XZYhqa2F8jk09iE4riihtAYRW3E7SW9as2L5PhxgepGqeS)

1-2-Switch makes use of motion controls and gesture-like physical activities. Players are encouraged to look at each other instead of looking at the screen by the game's emphasis on real-world actions, which are executed with the Joy-Con controllers.

Figure 21. Haptic functions in Meta Mechanics, retrieved from (https://www.digitalfoundry.net/articles/digitalfoundry-2024-the-last-of-us-part-2-remastered-ps5-tech-analysis)

In the Last of Us Part 2, Players can use their Dualsense's touchpad to play the guitar, adding haptic modalities as a meta mechanic to the game.

Figure 22. Haptic in Feedback Mechanics, retrieved from (https://mashable.com/article/horizon-forbidden-west-how-to-use-motion-controls)

Horizon Forbidden West utilizes Dualsense's Triggers to add tactile feedback. When aiming, players can feel the "pressure" of the bow which returns to normal after they fire the arrow. This technique gives players the feedback of how much they "powered" their bow before firing.

Figure 23. Haptic feedback in Social Mechanics, image by VR CHAT Inc. Retrieved from (https://store.steampowered.com/app/438100/VRChat/)

Recently players of VR chat are using haptic suits to enable haptic feedback, feeling the actions of other players such as a touch or a hug. Thus, we can add haptic feedback in social mechanics.

Olfactory Mechanics

In this work, olfactory cues are designed as diegetic signals as the emitted scent is congruent with the location in the virtual scene, instead of it being an abstract reward for interaction. This diegetic mapping supports immersion by maintaining perceptual coherence between visual context and olfactory feedback. Prior work also suggests that adding olfactory cues can increase users' sense of presence in virtual environments; for example, Munyan et al. report higher self-reported presence when olfactory stimuli are included [36]. Accordingly, this interaction can be modelled as a feedback loop as shown in Figure 25.

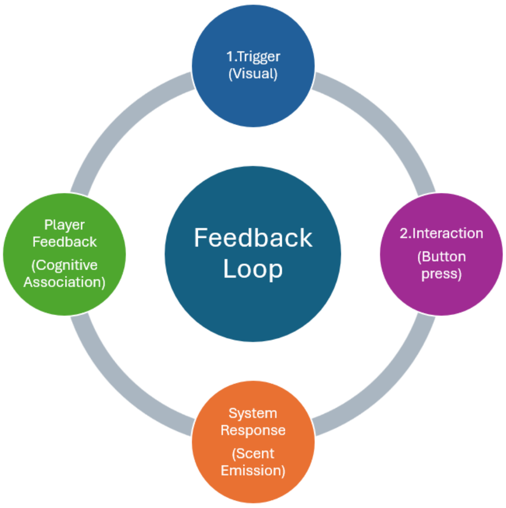

Figure 24. Diegetic olfactory feedback loop in a virtual environment: a visual trigger leads to interaction (button press), which activates scent emission and results in cognitive association that supports immersion and guides subsequent player behavior. Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

Olfaction is yet to be fully integrated into video game design, yet it offers great potential. As a core mechanic, odors can be utilized to drive navigation or memory tasks. As meta mechanics, odors can work as Unlockables as seen with audio cues, to help players progress. Feedback mechanics can use smells to notify players of dangers or other changes during the gameplay. Narratively, referencing the Proust Phenomenon, smells can evoke strong autobiographical memories and finally in the aesthetic layer, olfactory mechanics offer ways to enhance presence and immersion in virtual environments.

By mapping each sensory modality onto Bramantoro's classification, this framework illustrates how senses can function as structured game mechanics. However, understanding game mechanics is only part of the picture, since assessing their impact also requires examining how these design choices shape the user experience. User experience theories, such as flow, immersion and presence, and realism and aesthetics, provide a basis for exploring olfaction's role in shaping perceived realism, flow, and immersion.

2.4 Olfaction & User Experience

User experience (UX) provides a structured framework for describing how users perceive, interact with, and interpret digital environments. In contrast, game mechanics define the rules of interaction, while user experience focuses on their subjective qualities, including how engaging, immersive, and meaningful they feel to the user. User experience is particularly important in the context of multisensory integration, because additional sensory channels can both reduce cognitive load and substantially influence perceived immersion, flow, and realism. Accordingly, this section examines how olfaction can affect these user experience dimensions.

2.4.1 Flow theory

The concept of *Flow* was first introduced by Csikszentmihalyi (1990) [48]. Csikszentmihalyi describes it as a state where the user is completely absorbed in the task they must perform. This state can be achieved when the user's skills and the challenge are at the same level. When the challenge is easy boredom occurs and when it is too difficult frustration takes place. Players must always be in a state where the experience is not boring or frustrating. The Flow theory has been widely used in game design to maintain user engagement.

In contrast to visual text or UI prompts that demand focused attention and may interrupt the flow of gameplay, olfactory cues can serve as a channel of low-demand background information, which does not require constant visual attention [50]. In this sense, smell can act as a cue mechanism that supports the user's perception by providing an associative anchoring point (e.g., linking a work situation or goal to a distinct odor), which can reduce perceived cognitive load during complex or informationally dense activities. In the context of Flow, it can help users cope with higher challenges without feeling overwhelmed, thereby supporting the balance between challenge and skill that characterizes Flow.

Nevertheless, olfaction can also be a "Flow Breaker" if the technique is not reliable. High latency or prolonged odors can disturb the temporal alignment between visual events and olfactory feedback, which may create cognitive dissonance and disrupt the continuity of the experience. For this reason, Scentree's low-latency activation and deliberate activation approach based on the interactive kiosk were treated as design requirements not only for realism and usability, but also for maintaining an uninterrupted Flow state during interaction.

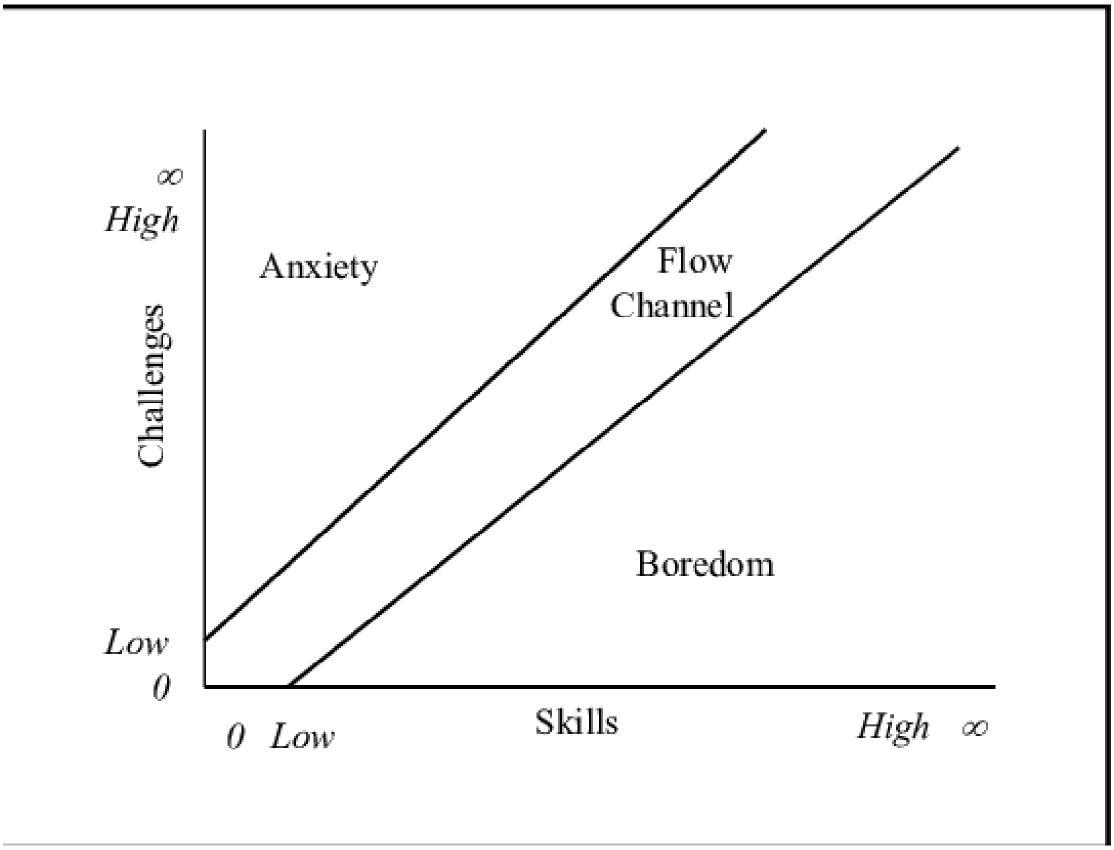

Figure 25. The Flow, Image by Mihaly Csikszentmihalyi, retrieved from (https://supplychaintrend.com/2012/04/01/is-your-supply-chain-in-flow/)

Sensory elements can affect the Flow state too [33], [34]. In the context of multisensory integration, richer sensory cues can speed up awareness of in-game conditions and rules, lower cognitive load and help players stay focused in the activity. Olfaction shows promise, because it can act as an additional layer of information, enhancing the Flow state cognitively and experientially.

2.4.2 Immersion & Presence

In HCI and Game studies immersion & presence are two closely related, yet different concepts that are frequently examined. Immersion refers to the level of absorption and involvement a user feels when they are interacting with a digital environment [34]. Immersion is a state which lowers the awareness of external distractions leading to more attention in the activity. Alternatively, presence is the sense feeling present within the virtual world [35]. On the one hand, immersion focuses on attention, while on the other hand presence focuses on perception. The use of olfaction in digital environments has shown that it can potentially enhance both immersion and presence. In a study by Munyan et al. [36], a smoke-related olfactory cue was delivered during exposure to a virtual environment to examine whether scent influences the user's sense of presence and the authors noted higher self-reported presence when olfactory cues were included.

3 Related work

Previous sections focused on theories from Cognitive Psychology, HCI, Game Design and User Experience and proposed a structured framework for understanding senses as game mechanics. However, integrating olfaction into virtual environments requires technological mediation too. Vision and sound are native to most hardware, rather than olfaction which depends on custom, specialized devices able to store, synchronize and transmit scents to digital media. Such devices are called Digital Scent Technologies.

Digital Scent technologies (DST's) are technologies that enable us to sense, transmit and receive scent enabled digital media, such as movies, music and video games. Odor dissipation and control is made much easier due to the small size and individual nature of these devices. There were already a few devices for such use, which I will start describing in the next section of this historical evolution.

DSTs were first introduced by Digicents, a firm that developed a device known as Ismell [37]. The construction is made up of pots filled with variously scented oils. According to the code given by the computer, these oils were evaporated by heating a combination of pots and were then diffused with a fan. Its creators thought that this device could produce any scent by combining a few fundamental scents.

Figure 26. Digiscents, Ismell Device, image by Laurian M Jones Moore, retrieved from (https://www.researchgate.net/figure/ISMELL-SYSTEM-BY-DIGISCENTS_fig1_284106797)

Aromajet, a different company, developed the Pinoke prototype scent dispenser. This gadget can be placed in front of the desk or worn. The device releases the desired smell in the right quantity thanks to the computer's digital codes. When this device was being designed, VR games were taken into consideration. Additionally, they created the more customizable Scentkiosk scent dispenser, which lets users mix and match different scents to create their own aroma [37].

Figure 27. Aromajet, Pinoke, image by Alexandra Branzan Albu, retrieved from (https://www.researchgate.net/figure/The-Pinoke-prototype-by-AromaJet_fig40_266216435)

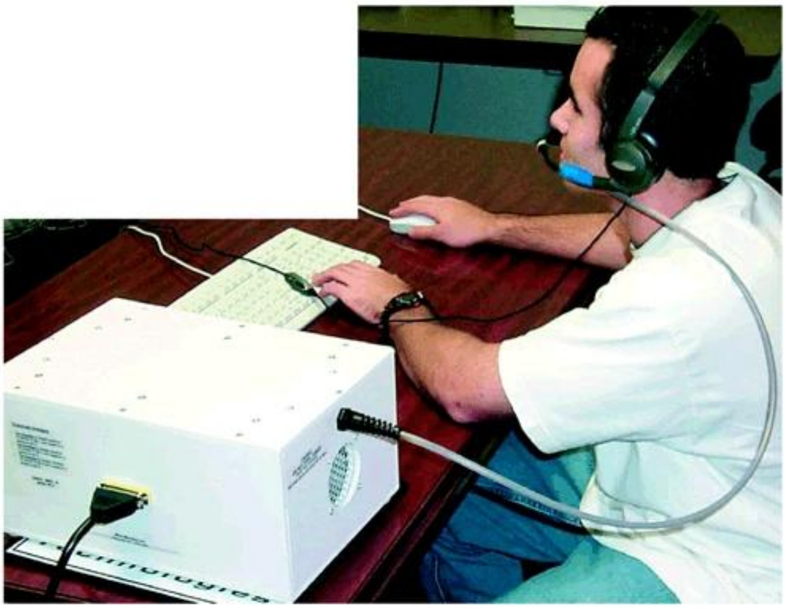

Figure 28. Aromajet, Scentkiosk Scent Dispenser, image by Laurian M Jones Moore, retrieved from (https://www.researchgate.net/figure/ScentAir-

ScentKiosk-Scent-Dispenser-This-system-can-deliver-three-scents-to-a-user-for_fig1_3422717)

In July 2003, Trisenx introduced a beta version of their scent dome technology. The device's aroma cartridge contains 20 distinct smells. To produce new scents, you could blend the perfumes in any quantity, and a tiny fan spread the fragrances out of the top smell cartridge [37].

Figure 29. Trisenx, Scented Dome System, image by Laurian M Jones Moore, retrieved from (https://www.researchgate.net/figure/Trisenx-Scent-Dome-This-system-produces-a-mixture-of-20-scents-but-currently-has-no-way_fig2_3422717)

3.1.1 Later Innovations

Later improvements in technology have enabled the use of olfaction in virtual reality and virtual environments. The term created in this field of research is known as Olfactory Virtual Reality (OVR). To better understand those technologies, a definition of Virtual Reality is needed.

Virtual reality (VR) is a computing technology that transports users into a virtual environment where they navigate and interact [38]. To submerge in such environments, we need to enhance immersion by using technologies such as HMD's that transmit visual and auditory spatial signals to the user. HMD’s (Head Mounted Displays) are Head-worn devices often used in Virtual Reality that display visual and audio information.

Virtual reality technologies have revolutionized the way we interact with digital environments. Multisensory experiences like VR are limited to two or three senses such as visual, audio and haptic. Since our perception and emotional attachment to settings are greatly influenced by olfaction it makes sense to incorporate it into virtual reality systems.

3.1.2 Olfactory Virtual Reality (OVR)

The field in which olfaction is researched in virtual reality is called “Olfactory Virtual Reality” (OVR) and the devices used to conduct experiments are called OVR displays. OVR displays are devices made to show scents in precise and regulated ways. They can mimic the smell of flowers [39] or even smoke in a fire scenario simulation by releasing olfactory cues [36]. By adding olfaction in VR users can become more immersed in the digital environment, something that enhances their emotional impact and sense of realism.

3.1.3 OVR Display Classification

Based on a classification by [8] Olfactory Virtual Reality (OVR) displays are categorized based on three parameters: 1) delivery methods, 2) presentation approaches and 3) application areas. Delivery methods refer to the process where the odor evaporates and is delivered to the user. Three methods of delivery are available: 1) delivery via heat, 2) delivery via airflow and 3) delivery via atomization.

The heat-based delivery method is mimicking the natural dispersal of scents by using heat to vaporize scent molecules and release them as a stream. By guiding air currents to carry scent molecules towards the user, airflow delivery is accomplished. Finally, the atomization method is achieved by breaking liquid components into mist droplets by using ultrasonic vibrations.

OVR displays are divided into three categories based on their presentation approach: 1) ubiquitous, 2) handheld and 3) wearable.

Ubiquitous devices rely on fixed installations to allow the creation of ambient scents. Handheld devices refer to devices often connected to a virtual reality controller enabling users to interact directly with smells by directing the controller to their nose. Finally, wearable devices integrate smell emitters into specific objects, such necklaces so users can interact with scents without being fully aware.

The third category of this classification proposes that OVR displays can be categorized based on their application area. Seven key areas have been highlighted by previous research: 1) Gaming, 2) Health, 3) Perception, 4) V-Commerce, 5) Education, 6) Engineering, 7) Cinema.

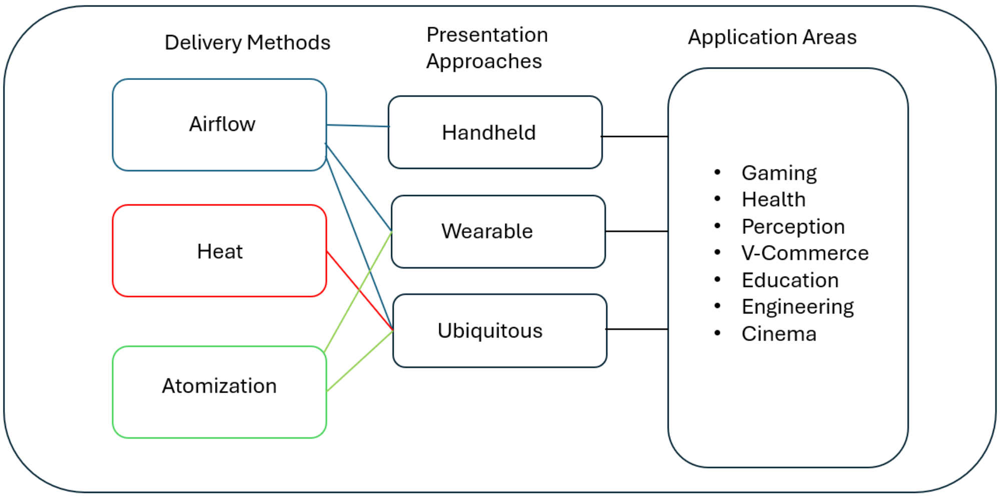

Figure 30. Olfactory Virtual Reality Display Classification, Image by Vasileiadis Vasilis, licensed under CC BY 4.0

A wide range of olfactory displays has been proposed for introducing scent into immersive virtual environments, with many ubiquitous approaches focusing on releasing multiple scents to the setting during an experience. [26] Presented an olfactory display developed to provide scents for their game "Tainted". This device was built around an Arduino Mini Pro that drives four ultrasonic mist generators. Each generator contains a vial which is filled with a fragrance solution, where a fan helps distribute the scent in the environment. The device is activated through communication with the Unity game engine so that the generators can be triggered in real time via digital output signals. Although their device enabled real time scent diffusion, it imposed notable drawbacks. For it to comply with the game's narrative, the authors relied mainly on floral or fruity fragrances, which over time reduced the user’s ability to reliably discriminate between odors after prolonged exposure. Tsaramirsis et al. [40] presented an olfactory display capable of providing up to twenty-four different aromas. Their device is using an Arduino mega to control four MG996R servo motors that mechanically press spray bottles, allowing up to four scents at a time to be released concurrently. The Arduino is also paired with an L298N motor driver that handles two 12V fans, which can either direct scents towards the user or work in reverse to clean the air and mitigate cross-contamination. Their system is expandable and does not require any additional programming. To scale it up all it needs is to add additional servo motors and scents. To integrate their system within the Unity game engine they created a C# application which enabled scent distribution in different events. Reported limitations include residual cross-contamination whenever scents are triggered in close time, the absence of ready-to-use assets and files for automated scent triggering and limited control over persistence duration and conflicts among overlapping scent releases.

Handheld devices enable the recreation of scenarios where objects are brought close to the user’s nose in a manner that resembles actual sniffing. Niedenthal et al. [41] presented a handheld olfactory device add-on which can be mounted to the HTC Vive controller to support a VR wine tasting scenario. Their prototype seats four scent reservoirs with aromas vaporized in chambers and 3D printed stepless rotational valves are driven by Tower Pro SG90 RC servos to blend odors. Each odor has two valves, one on the inlet that allows the container to close when no scent is going to be released and one on the outside. To deliver the scent to the users’ nose a single fan is used to generate air flow. To initiate scent release, a button is being pressed, or a proximity sensor can be used to gauge the distance from the HMD. Scent release can be activated by pressing a button or by using proximity to measure the distance from the HMD. The limitations they noted include miniaturization, weight issues with a battery addition, the device’s limited capacity to store only four scents and Limitations to this device include miniaturization, the device’s limit to store only four odors, weight issues if they add a battery and that the device is mainly suitable for deliberate sniffing rather than ambient delivery.

Wearable olfactory displays refer to devices that can be worn in the body or be directly mounted on an HMD. These devices enable scents to be directly delivered to the user's nose. Wearable olfactory displays are often developed to be lightweight, compact and easy to carry, which makes them suitable for mobile or headset-based use. [25] introduced a wearable olfactory display designed as a necklace they called "Essence". To vaporize oils, which are stored inside a small container, this device is utilizing a piezoelectric transducer connected to a cotton filter. To maintain its compact size, most of the electrical components it uses are placed at the rear of the necklace, while the front section contains only the piezoelectric transducer, the 7ml container and the cotton wick. The rear part of the system includes an AT-mega32u4 microcontroller, a 3.7 V lithium battery reported to power the system for roughly 27–28 hours under a default duty cycle of releasing scent for 1 second every 20 seconds to allow previous odors to dissipate, and a Bluetooth Low Energy (BLE) board for wireless connectivity. In addition, the authors investigated context-aware triggering driven by smartphone data such as GPS and date/time data, as well as physiological signals like heart rate with an E4 wristband and electrodermal and brain activity using MUSE EEG headband. Limitations they reported include the necklace's limit to only storing one scent at a time, its refill procedure, desensitization and the limits of frequency and intensity of scent. An additional study [39] proposed a wearable olfactory device that could be mounted in virtual reality glasses. Their device is running on Raspberry Pi 3 Model B microcontroller and uses a piezoelectric transducer to vaporize fragrant solutions, while a rechargeable lithium battery is used to support portable operation. Their design also incorporates a voltage regulator and an atomizer driver board, which enables the atomizer to be managed through the controller's GPIO. Lastly, a Wi-Fi module that uses a REST stack is employed to support communication with smartphones. Overall, the prototype is presented as a low-cost, lightweight approach for introducing smell into virtual settings, but it is still limited by single-scent output and a single-user distribution strategy. Even though wearable olfactory displays are compact and portable they have several different drawbacks including technical and ergonomic limitations. The plethora of devices developed are designed for use by a single user and are limited to presenting only one scent at a time, limiting their ability to be integrated in large scale immersive setups such as CAVEs. Additionally, recent research has highlighted that the addition of weight to an HMD can increase load on the user which results in neck pain and reduced comfort after extended use.

Despite wearable olfactory display's compact design and easy portability, they are restricted by technical and ergonomic limitations. Most of them are designed for a single user and can deliver one scent at a time which limits their use in immersive environmental setups. Also, studies have shown [42] that adding weight to an HMD can increase the load on the user, resulting in neck pain and reduced comfort after prolonged use.

3.1.4 Olfactory Displays for CAVE systems

The integration of olfactory stimuli in CAVE environments has been the subject of recent research. At the time of writing this thesis only five studies were found that examined the integration of olfaction in such settings. Among them, two studies used regular diffusers to emit scents of chocolate and coffee [43], [44], one used samples from human sweat [45] and two studies implemented engineered olfactory systems [46], [47].

Duong et al. [43] investigated how engaging multiple sensory channels influences consumer's emotional responses during an in-store experience. To investigate this, they utilized an omnidirectional CAVE system called "Curtin Hive" and recreated a chocolate retail environment using 360° panoramic content, while introducing a chocolate odor through scent diffusers. Shin et al. [44] examined the restorative effects of "open window" experiences within busy environments by building a CAVE-style installation with projections across the walls, ceiling, and floor to deliver a 270° VR simulation centered on coffee brewing. In their setup, the coffee aroma was produced using an essential-oil diffuser.

Quintana et al. [45] used a 6-sided CAVE-like system to immerse participants in a virtual bar to test whether exposure to odorants linked to fear will affect impression formation through contagion and confirm whether these effects may be detected in an ecologically valid context. Sweat samples were gathered and attached to respirator masks worn by female participants during immersion to display odors.

Similarly, Truong et al [47] examined how multisensory environmental cues affect startle responses. They developed MS.TPAWT, an extended-reality locomotion system that integrates environmental cues into a CAVE-based treadmill. The system centers on a large treadmill placed inside a steerable wind-tunnel structure to reproduce wind effects, and it additionally incorporates scent diffusers for odor delivery, heat emitters for temperature simulation, and mist generators for fog-like conditions, allowing users to navigate virtual worlds while receiving coordinated, environmental sensory cues. In another study, Ischer et al [15] created an olfactory display for a CAVE-like virtual reality environment which is called "Brain and Behavioural Laboratory-Immersive system" (BBL-IS). This system is a four-walled projection-based system utilizing high resolution projectors and uses motion tracking from 8 infrared cameras to capture the user's movements. To trigger odors, it uses the GeVRE toolkit for Unity 3D so it can control odor dissipation based on the user's position and movements. Their olfactory display consists of 32 computer-controlled solenoid valves that are connected to a filtered air supply. The valves are also connected to a bank of glass vials that contain up to 28 different scents. To deliver precise and low-intensity scent pulses directly to the users it contains polyurethane tubes and a nasal cannula. Lastly, the device has dual air-extraction systems to minimize cross-contamination. The researchers identified several limitations to this implementation. This system is too expensive and cannot be easily reproduced. Also, they noted that it is uncertain whether systems like this offer clear advantages over classical experimental setups and finally the third limitation refers to the system's reliability which depends highly on experimental results.

Overall, many olfactory virtual reality (OVR) systems have been introduced for desktop and VR use, presenting a variety of techniques enabling scent production and control. However, most of those devices are targeting HMD or desktop settings, often supporting only one scent at a time and are usually dedicated towards a single user. In contrast, relatively few studies have integrated olfactory displays into CAVE installations, and the solutions reported in the literature tend to be expensive and difficult to replicate.

4 System Architecture Guidelines

4.1 Design Principles

A key design goal was to avoid a "sensory gap," a mismatch in timing and intent between sensory channels that may disrupt the user experience. In multisensory interactive systems, the perceived quality of the experience depends not only on the addition of more modalities, but also on ensuring that these form a coherence that users can interpret as a unified interaction [21,22].

Because of this, the system was designed to achieve multisensory coherence through the concurrent activation of visual, auditory, and olfactory events. Practically speaking, olfactory signals aren't emitted as a continuous environmental layer but are triggered at specific moments that correspond to important actions and feedback in the world, so that the odor signal is temporally aligned with the audiovisual content. The aim of this alignment is to enhance immersion by reducing perceptual conflicts between channels and facilitating a consistent mapping between virtual events and physical odor diffusion.

To implement this principle, the system's architecture prioritizes deterministic event handling and reliable synchronization between the Unity application and the olfactory hardware. The design also considers the practical limitations of olfaction in CAVE environments by focusing on cues based on events that can be controlled and evaluated, instead of attempting continuous or spatially complex scent delivery that can lead to cross-contamination. Altogether, the principle of multisensory integration guides both interaction design and technical implementation, making sure that smell works as a structured part of the experience that matches the additional audiovisual elements to support immersion.

4.2 System Architecture

Scentree, provides a mobile and completely reproducible approach for integrating olfactory stimuli into the MobiCAVE environment. Its purpose is to provide olfactory feedback based on user interactions within the virtual setup. Because CAVE installations differ from HMD and desktop setups, mainly in terms of room-scale spatial constraints and support for multiple concurrent users, there is a need for a distinct design approach. Scentree was developed specifically to address these requirements. To begin with, it can be positioned anywhere within the MobiCAVE without requiring structural modifications. Additionally, although it can deliver up to four scents simultaneously, it can store an unlimited set of scents through its detachable and refillable containers. Finally, it is made to be easily integrated into Unity 3D projects.

At the functional level, it links events in the digital environment with the physical emission of scent. When a user is interacting with an object in the digital space, Unity transmits a character to the Arduino via serial communication and then Arduino receives the signal and selects which piezoelectric transducer to use and triggers the corresponding relay channel. Because each piezoelectric transducer's driver board houses its own built-in button necessary to start emission, the relay module, instead of switching the power supply to isolate the button, emulates three presses to switch between emission and idle states. This strategy enables reliable switching between transducer states and supports near-immediate scent release following user interaction.

The system's architecture is divided into two tightly coordinated subsystems, that is the hardware and software subsystems. The hardware subsystem includes an Arduino Uno R3 capable of handling communication with the Unity 3D environment and the relay's activation, as well as the relay module, used to emulate button presses to activate the appropriate piezoelectric transducer and four piezoelectric transducers, are mounted in a detachable container for scent emission. Each transducer possesses a driver board of its own and is powered from a USB Hub with USB. The hub can be supplied either directly by a PC USB port or, as in the current setup, through an external power source. The software subsystem consists of Unity-side components that (1) establish and maintain communication with the Arduino, (2) detect interaction events and send commands for Arduino interpretation, and (3) the Arduino firmware implementing the activation protocol that translates incoming signals into relay/transducer actions.

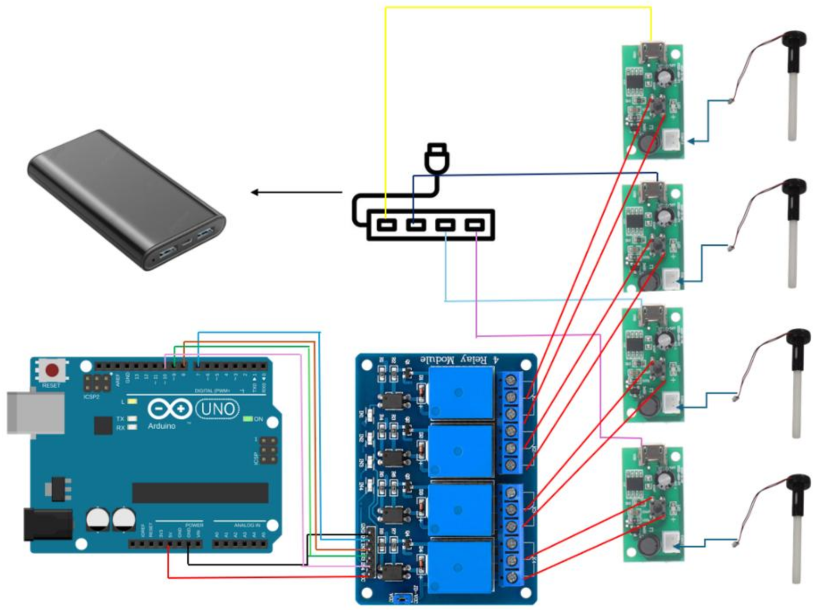

Figure 31. Wiring Diagram of Scentree, Image by Vasileiadis Vasilis, licensed under CC BY 4.0

4.3 Hardware

Scentree is made from a set of inexpensive modules that together form a fully modular and mobile olfactory display. Built around an Arduino Uno R3, which receives commands from Unity and interprets them, resulting in the activation of the corresponding channel of a 5V 4-channel relay module. Each relay channel is also used to emulate physical button presses that control a sole ultrasonic piezoelectric transducer. Odor diffusion is handled by four ultrasonic piezoelectric transducers, where each one includes its own PCB driver and ultrasonic element, needed to atomize a liquid into mist. To keep the operation separate and avoid cross contamination, every transducer is mounted on its own detachable container that contains its unique scented fragrance. For control that does not interfere with the driver board's onboard power regulation, we modified the driver board by soldering two jumper wires onto the button contact pads, then rerouted these wires into the relays COM/NO ports, enabling the simulation of the button's press . This design supports scalability, since expanding the scent set can be achieved by simply adding additional transducer modules, relay channels, and detachable containers.

To provide power to the transducer a multi-port USB hub connected to a 10,000 mAh external power supply is used. Using an external supply improves portability and, critically, helps separate the higher-current transducer load from the Arduino/relay control circuitry. The Arduino Uno is powered independently via a USB connection to the PC running the Unity application. Combined, these elements create a compact, flexible, and reproducible system capable of real-time, interaction-driven scent diffusion in virtual experiences.

Table 1. List of components needed to build Scentree.

Component	Quantity	Specifications	Purpose
Arduino Uno R3	1	ATmega238P, 5V, USB Serial	Receives signals from Unity and controls the relay module
4-Channel Relay Module	1	COM/NO contacts, 5V	Emulates button presses
Ultrasonic piezoelectric transducer module	4	5V, Ceramic Atomizer, Onboard Control PCB	Generates Scented mist
Piezoelectric transducer Driver Board	4	Integrated tactile button pads	Need to modify their button pads
Plastic container	4	Plastic, 50-70 ml	Store scented liquid
Multi-port USB-HUB	1	5V Output	Power the transducer driver boards

External Power supply	1	5V DC Output, USB A ports	Provide portability and power the USB hub
USB A to MicroUSB Cable	4	5V Power delivery	Connect the transducer to the PCB
USB A to USB B Cable	1	Default Arduino Cable	Connect Arduino to PC
Dupont Jumper Wire kit	1	Flexible wire	Wire the Arduino with the Relay
Dupont Jumper Wire for Soldering	8	Insulated Copper	Solder to button pads for modification

4.3.1 3D-Printed Enclosure and Mechanical Design

To improve portability, safety, and repeatability of the hardware deployment, a custom enclosure was designed and fabricated using 3D printing. The enclosure was modelled in Shapr3D and exported as STL files, which were then prepared for fabrication in Creality Slicer. The final parts were produced using a Creality Ender 5 Plus 3D printer.

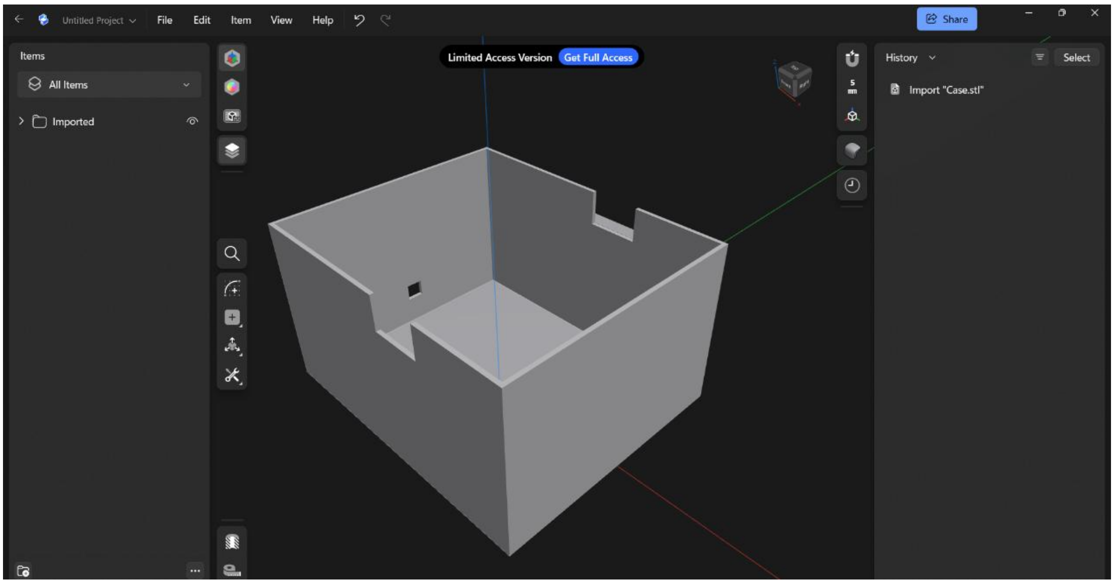

Figure 32. The case model created in the Shapr3D software. Image created by Vasileiadis Vasilis, is licensed under CC BY 4.0

The structural design was created to encapsulate the system and maintain its flexible physical layout during operation. More specifically, the enclosure provides stable mounting for the system components and helps to protect the electronics and wiring from accidental exposure during use. This is particularly important in CAVE, where the device may be approached or handled during setup, demonstrations, or experimental sessions.

All enclosure parts follow a snap-fit assembly approach, which avoids the need for extra parts to hold things together during installation. This design choice reduces assembly time, simplifies maintenance procedures, and supports rapid disassembly during system refilling, cleaning, or servicing. Additionally, snap-fit assembly helps maintain consistent placement of internal components across sessions, which is beneficial for repeatable experimental development. Finally, the enclosure design strengthens the reproducibility of the overall system by enabling the mechanical packaging to be replicated and adapted in future deployments.

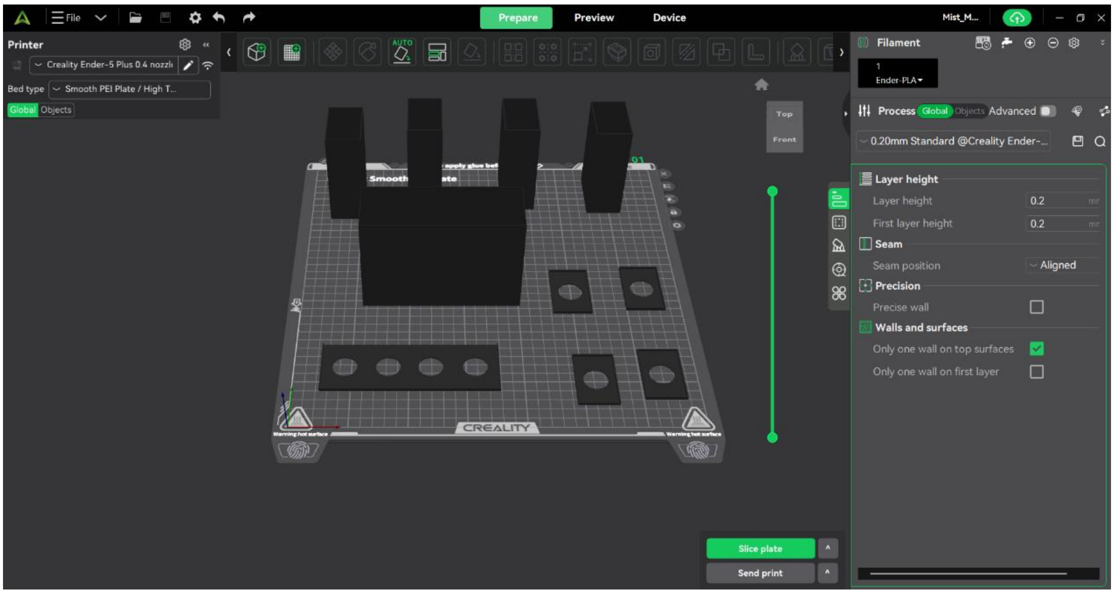

Figure 33. Parts, edited in Creality Slicer for 3D Print. Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

4.4 Firmware

The Arduino firmware implements a byte-oriented serial protocol over USB at 9600 baud, enabling real-time communication with the Unity engine. Incoming ASCII characters in the range “1” to “4” are mapped to the relay module’s four channels via Arduino digital pins D7–D10, which connect to the relay inputs IN1–IN4. Consequently, each command sent from Unity can immediately trigger the corresponding relay channel and then emulate a button press on the corresponding piezoelectric transducer driver board.

During initialization, all relay outputs are set HIGH, so the system remains in an idle state. The serial interface is then initialized, followed by a short 2-second delay to allow USB host enumeration. During operation, the main loop continuously monitors the serial receive buffer. When a valid character (“1”–“4”) is detected, the firmware converts it to a zero-based index and calls the associated channel activation Protocol. This protocol performs a three-press sequence mimicking the physical button press on the transducer driver board, ensuring consistent state transitions regardless of the device’s prior state:

- First press: Activates the piezoelectric transducer and initiates scent emission.
- Second press: Stops emission after a short interval.

- Third press: Returns the transducer to an idle state.

Timing behavior is defined through constants set at the beginning of the sketch:

- PRESS_DURATION = 500 ms (press length)
- ON_TIME = 5000 ms (emission duration after the first press)
- INTER_PRESS_DELAY = 300 ms (delay between the second and third press)

Algorithm 1. Pseudocode of Arduino's main logic

```
Require: Relay Module Pins = Arduino Digital Pins[7, 8, 9, 10] -> [IN1, IN2, IN3, IN4]
Require: PRESS_DURATION = 500 ms, ON_TIME = 5000 ms, INTER_PRESS_DELAY = 300 ms
procedure SETUP
    for i ← 0 to 3 do
        Configure relayPins[i] as OUTPUT
        Write HIGH to relayPins[i]
    end for
    Initialize serial at 9600 baud
    Wait 2000 ms
    Log "Arduino ready"
end procedure
function LOOP
    while true do
     if serial has data then
      command ← read one character
      if command ∈ {'1','2','3','4'} then
        index ← command - '1'
        Log "Activating piezoelectric transducer " + (index + 1)
```

```
            ACTIVATETHREEPRESS(index)
            end if
        end if
    end while
end function
procedure BUTTON EMULATION(index)
    pin ← relayPins[index]
    PRESSBUTTON(pin, PRESS_DURATION)
    Wait ON_TIME
    PRESSBUTTON(pin, PRESS_DURATION)
    Wait INTER_PRESS_DELAY
    PRESSBUTTON(pin, PRESS_DURATION)
end procedure
procedure PRESSBUTTON(pin, duration)
    Write LOW to pin
    Wait duration
    Write HIGH to pin
end procedure
```

This firmware approach provides deterministic control over each piezoelectric transducer over a simple serial protocol, that ensures repeatable operation and precise timing. Since the time variables are set as fixed parameters, the firmware can be reconfigured to meet different experimental settings. This implementation code was written in the Arduino IDE and is compatible with all ATmega328P-based microcontrollers. To evaluate the system automatically we used the same activation protocol with an additional logging addition. Just barely prior to the execution of the three-press activation sequence, the firmware initializes and increments an internal test counter and records the test execution time using the millis() function. Once the iteration is complete, it calculates the total duration and transmits start and end messages over serial, which includes the test and channel ID’s, as well as the measured duration. This addition enables us to keep the original logic, while providing additional data to support further analysis.

4.5 Arduino-Unity Communication

Communication between Unity and the Arduino is using Unity’s built-in package .NET System.IO.Ports. and is handled through a serial USB connection that operates at 9600 baud. The project was configured with the .NET API so that the SerialPort class is always present both during compilation and runtime. Moreover, through this design, the serial interface enables Unity 3D to transmit single-character ASCII commands that manage Scentree directly in real-time. Within Unity 3D, a dedicated C# script, Arduino_Listener, is attached to an empty game object, in charge of activating and maintaining the serial connection. At launch, it opens a predefined (hardcoded) Port at 9600 baud rate, logs and reports the connection status, provides a way to write characters to the serial stream while making sure the port is properly closed upon the application's exit. This exact serial interface is used additionally in an Auto_Tester script within the evaluation environment designed for the auto test. AutoTester periodically sends trigger commands via the Arduino_Listener and listens for timing messages from the Arduino. These messages are then recorded to a CSV file which is stored locally and contains the performance data we use for the quantitative evaluation of the system.

Algorithm 2. Pseudocode of The Unity’s Arduino_Listener Logic

Require: portName = "COM5" (Hardcoded), baudRate = 9600

1: serialPort ← null

2: **procedure** START

3: CONNECTTOARDUINO

4: **end procedure**

5: **procedure** CONNECTTOARDUINO

```
    try
    serialPort ← NewSerialPort(portName, baudRate)
    SetReadTimeout(serialPort, 50)
    SetWriteTimeout(serialPort, 50)
    Open(serialPort)
    if IsOpen(serialPort) then
        Log("Connected to Arduino on " + portName "COM5")
    end if
    catch e
    LogError("Failed to connect: " + e.Message)
end procedure
procedure SENDCOMMAND(command)
    if serialPort ≠ null and IsOpen(serialPort) then
        try
        Write(serialPort, command)
        Log("Sent command: " + command)
        catch e
        LogError("Serial write error: " + e.Message)
    else
        LogWarning("Serial port not open!")
    end if
end procedure
procedure ONAPPLICATIONQUIT
    if serialPort ≠ null and IsOpen(serialPort) then
```

```
            Close(serialPort)
    end if
end procedure
```

At the same time, interactive objects are the bridge between user actions and hardware activation through the Arduino_Listener script that is assigned to them. Additionally, to objects meant to emit scents, another dedicated C# script named Interactive_Object, was created and assigned. This script exposes a public int set as mistMakerId (1,2,3,4) and monitors for input, so that when the correct key is pressed [E], it casts a raycast forward of the camera up to a configurable distance. If the ray hits the targeted object, the script sends the corresponding ID as a single-character ASCII command to the Arduino via Arduino_Listener. Then Arduino initialized the correct channel in the relay, activating the corresponding piezoelectric transducer, initializing the activation protocol, thereby beginning scent emission.

Algorithm 3. Pseudocode of The Unity's Interactive_Object Logic

```
Require: arduinoListener (reference to ArduinoListener), mistMakerId (1-4)
Require: interactDistance = 3.0, interactKey = Key.E
playerCamera ← null
procedure START
    playerCamera ← GetMainCamera()
    if playerCamera is null then
            LogError("No MainCamera found!")
    end if
    if mistMakerId < 1 then
            mistMakerId ← 1
    end if
    if mistMakerId > 4 then
```

```
            mistMakerId ← 4
    end if
end procedure
procedure UPDATE
    if GetKeyDown(interactKey) is true then
            ray ← NewRay(playerCamera.position, playerCamera.forward)
    if Raycast(ray, out hit, interactDistance) is true then
      if hit.collider.gameObject is this.gameObject then
        if arduinoListener is not null then
            command ← ConvertToString(mistMakerId)
            arduinoListener.SendCommand(command)
            Log("Interacted with cube (ID " + mistMakerId + ")")
          else
            LogWarning("ArduinoListener not assigned on " + this.name)
          end if
        end if
  end if
 end if
end procedure
```

4.6 Automated System Evaluation

To evaluate the system's quantitative indicators of reliability and time behavior, a dedicated test environment in Unity was developed, which uses a minimal scene with four interactive objects each mapped to one of the four physical scent channels controlled by the Arduino-relay subsystem. To support automatic multiple iterations a dedicated C# AutoTester script was developed which triggers the button presses without user intervention. For each trial, AutoTester transmitted a single-character ASCII command requesting activation of the corresponding channel. As Arduino received the command, it executed the activation protocol and measured the total duration of the activation sequence using the millis() function.

The Unity test scene was configured to run 200 activations, targeting 50 trials per channel, with a 1s interval between trials to approximate a realistic physical button press. The resulting dataset was processed in Excel to compute trial success rate, per-channel mean and standard deviation of activation time, and the overall observed timing range. Finally, a one-way ANOVA was performed to check whether mean activation duration differed significantly across the four channels. These quantitative results are reported in the following section.

4.6.1 System Evaluation Results

The system performed a total of 201 tests on the four aroma channels within the automated test environment. Nearly 50 trials were performed on each channel with an exception on channel 3, in which it was observed that 51 trials were performed after Arduino had reset. However, we chose to include this trial since its timing aligns with that of the others on the same channel. For all channels, the overall mean time was 6800.692 ms with a total standard deviation of 0.72414 ms, indicating highly accurate and consistent timing behavior. To assess the presence of consistent timing differences across channels, a one-way ANOVA was performed. The ANOVA resulted in SSbetween = 0.8023 and SSwithin = 104.0733, with d fbetween = 3 and d fwithin = 197, resulting in $F(3, 197) = 0.50622$ and $p = 0.678432$. Since $p > 0.05$, there are no statistically significant differences in the mean activation duration between the four channels, validating that all outputs have statistically equal time performance.

Channel	Trials	Mean (ms)	SD (ms)
1	50	6800.6	0.72843136
2	50	6800.74	0.75078191

3	51	6800.66667	0.68313005
4	50	6800.76	0.74395523
Total	201	6800.692	0.72414

5 Implementation

5.1 The MobiCAVE system

MobiCAVE [15] is an interactive Virtual Reality CAVE (Cave Automatic Virtual Environment) system built to support immersive, shared experiences. MobiCAVE presents a simplified yet effective implementation of CAVE technology enabling portability and is utilized for public use cases. Its construction consists of a surround-screen setup with an estimated diameter of 3.5 meters and height of 3 meters. The display surface is assembled by 15 ultra-slim monitors organized in a borderless layout with 0.9mm bezels. These monitors are mounted on a custom-made aluminium truss structure and can be reconfigured to accommodate different spatial constraints. Moreover, the system's output is driven by a high-performance workstation with several synchronized graphics processing units, enabling effortless operation of all 15 screens from just one computer. Also, a high-resolution projector which is mounted at the top of the truss structure to deliver floor projections onto a special reflective material, while at the same a depth-sensing camera allows motion capture for position tracking, spatial mapping, object detection, and full-body tracking. Finally, spatial audio immersion is achieved with a surround sound system.

The system is designed in such a way to scale room-sized installations while supporting use in various lighting conditions, multi-user collaboration, and shared participation. MobiCAVE, utilizes mobility, since it's made for easy installation/uninstallation for exhibitions that require traveling, easy maintenance so maintenance costs are minimized and finally it utilizes power efficiency since it operates at low noise to assist communication between participants. Unlike conventional VR setups requiring HMDS and controllers to operate, MobiCAVE enables users to interact with their movements through a motion capture system that allows for navigation within the virtual environment. This approach gets rid of equipment barriers, resulting in fast changeovers between participants while also allowing attendees to participate in the player's actions in real time which creates a shared social experience.

5.2 Integration within the MobiCAVE

5.2.1 Unity Scenario Overview

To explore Scentree's practical application, a proof-of-concept virtual museum exhibition application in Unity was developed for use inside the MobiCAVE system. Interaction was implemented in Unity through (a) proximity-based informational cues (UI text) and (b) kiosk-based interactive events that trigger scent release via the Unity–Arduino serial interface described in Section 4.5. The application, called "Smelling Ancient Greece", introduces four areas on the theme of ancient Greece (Ancient Greek Baths, Gymnasium, Symposium, Altar). Users in this setting can: (1) freely explore and navigate the exhibition space, (2) view exhibits, and (3) interact with objects in each themed area within the virtual museum.

On the implementation level, the kiosk interaction is handled by the Unity scripts Arduino_Listener and Interactive_Object (Algorithms 2–3). Each themed area is mapped to one of the four physical scent channels of the olfactory device (Channel IDs 1–4), simplifying configuration and reducing uncertainty during development. When the user activates the kiosk, the mapped channel ID is transmitted as a single-character ASCII command through the serial interface, following the same command protocol described in Section 4.4. On the hardware side, the Arduino interprets the received character and executes the predefined activation protocol that emulates button presses on the transducer driver board, initiating scent emission on the corresponding channel.

The intended user flow is:

1. The user navigates into a themed area.
2. The user approaches an exhibit to receive contextual information via on-screen text.
3. The user walks to the area's kiosk and performs an explicit activation action.
4. The user receives the corresponding scent output from Scentree for that area.

Moreover, by approaching certain objects in the scene, an on-screen text appears, providing a short description of the object the user is facing. Technically, these descriptions are triggered through collider-based proximity checks on predefined exhibit objects. This cueing mechanism ensured that the olfactory stimulus was contextualized by the visual narrative and that the user was aware of which scent channel corresponded to each area.

Figure 34. Interactive kiosk interaction prompt in the Ancient Greek Baths area used as an explicit user action to trigger the corresponding Scent. Image by Vasileiadis Vasilis, licensed under CC BY 4.0.

5.2.2 Technical Level Design

Beyond the interaction logic, the virtual museum layout was designed as a technical level design task, the spatial arrangement of rooms, exhibits, and interaction points was not arbitrary but driven by Scentree's physical constraints and the realities of scent diffusion in a shared CAVE environment. In particular, the design aimed to reduce cross-contamination between odors and to support a predictable "reset" period where air can clear before a different channel is triggered.

To achieve this, the museum was organized into four spatially distinct "scent zones", each corresponding to exactly one scent channel (Baths, Gymnasium, Symposium, Altar), and each containing a dedicated kiosk as the single activation point for that zone. The kiosks were placed inside their respective zones so that scent triggering happens when the user is already situated in the intended narrative context, rather than in transitional spaces.

Between zones, the layout incorporates transition areas functioning as "safe zones": spaces with no scent-triggering kiosks and no olfactory events, intended to (a) minimize accidental activation while users are moving and (b) provide spatial separation that helps residual odor dissipate before the user reaches a different themed area. Exhibits associated with different scent channels were kept physically separated by these transition spaces, and zone boundaries were treated as design constraints during placement of walls, entrances, and points of interest. Figure 32 presents a top-down map of the museum and visualizes the zoning strategy.

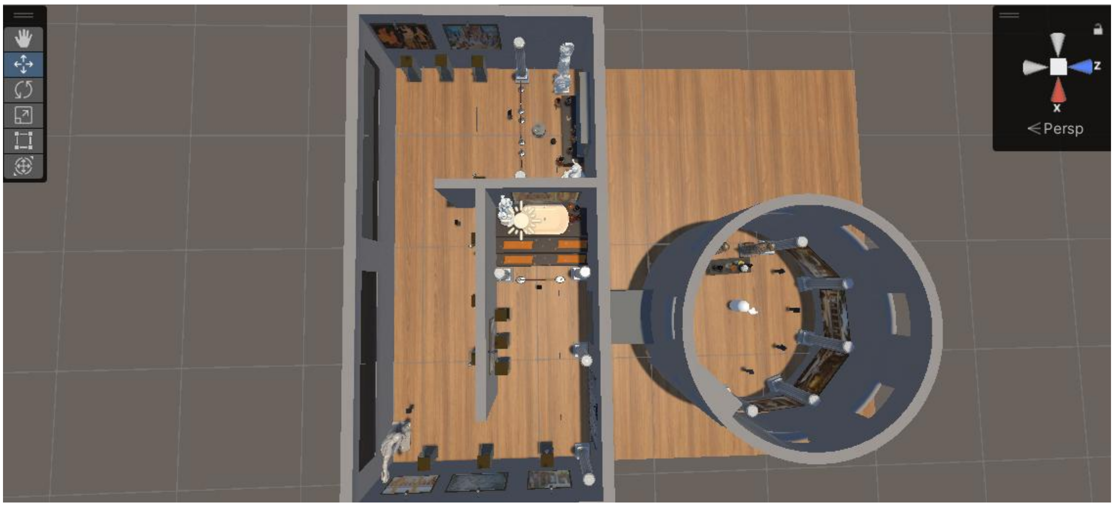

Figure 35. Top-down view of the "Smelling Ancient Greece" Unity Museum layout, showing the spatial arrangement of themed areas and the separation between zones to support controlled scent triggering and reduce cross-contamination. Image by Vasileiadis Vasilis, licensed under CC BY 4.0

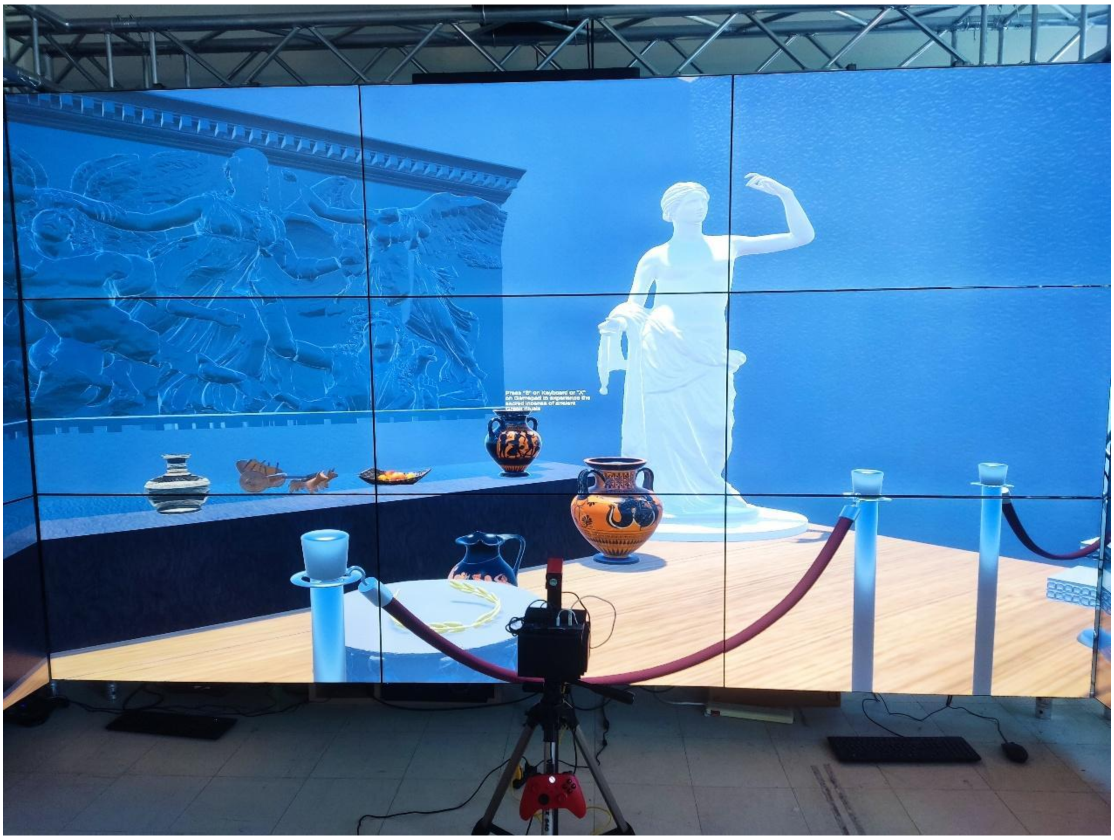

Figure 36. Scentree olfactory display within the MobiCAVE environment, image by Vasileiadis Vasilis, is licensed under CC BY 4.0

5.3 Methodology

A user study with voluntary participation was conducted to further evaluate system performance which resulted in N=51 participants. This sample included 42 male and 7 female participants, 1 non-binary/other participant and 1 participant who preferred not to disclose their gender. The study took place within the MobiCAVE installation with the virtual museum scenario. Each session lasted approximately 10-15 minutes per participant, including briefing, interaction with the virtual exhibition and questionnaire completion. The user study was organized around the following **Evaluation Questions (EQs)**, which operationalized the thesis Research Questions (RQs) introduced in Chapter 1.

1. **EQ1**: Does the system operate as intended?
2. **EQ2**: Does Olfaction enhance overall User Experience?
3. **EQ3**: Is the interaction scheme easy and intuitive?
4. **EQ4**: Do scents help participants memorize information better?

EQ1 and EQ3 primarily address RQ1 (Technical Feasibility) by evaluating system reliability, synchronization, and interaction practicality in the MobiCAVE environment, while EQ2 addresses RQ2 (User Experience) and EQ4 addresses RQ3 (Cognitive Impact) in terms of perceived memorization and engagement.

During the experiment, each participant first was asked to fill in a pre-experiment questionnaire providing basic background information such as demographics, prior familiarity with VR systems, prior experience with olfactory enhanced VR applications, self-reported sensitivity to scents and possible causes influencing their sense of smell. After they completed the first questionnaire, participants were introduced to the task and were allowed to navigate the virtual scene, so they experienced the four themed areas and their associative smells. After completing the experience, they were asked to fill in a post-experiment questionnaire assessing perceived system performance, as well as perceived intensity and comfort. To match the two questionnaires anonymous participant IDs were used.

Figure 37. Users Interacting with MobiCAVE, image by Vasileiadis Vasilis, is licensed under CC BY 4.0

Data collection combined subjective ratings with objective system measurements:

1. Post-experience Likert ratings: Items were used to quantify (1) the perceived performance of the system (EQ1), (2) immersion impact (EQ2), (3) usability (EQ3) and (4) effects on perceived memorization (EQ4).
2. Open-ended responses: Three short-text questions urged participants to answer what they liked most, what they would change or improve and additional comments.
3. Objective timing measurements: System-level timing data from the automated test environment and Arduino logs were used to support EQ1 alongside perceived synchronization and reliability ratings from participants.

To operationalize these research questions, specific outcome measures were defined for each domain. For EQ1, technical efficacy was assessed by examining timing consistency and perceived synchronization (including any noted delays), alongside scent dissipation rates as a proxy for cross-contamination efficiency. Additionally, perceived intensity and comfort were measured to ensure that olfactory stimuli were distinct yet non-intrusive. For EQ2, the evaluation focused on the impact of olfaction on user experience, specifically measuring perceived immersion, presence and the congruency between visual and olfactory cues. Additionally, EQ3 addressed usability by assessing the intuitiveness of the kiosk-based trigger mechanism and the overall user acceptance of the proposed interaction scheme. Finally, EQ4 addressed perceived memorization by measuring whether participants reported that the addition of scents helped them remember the information presented in the virtual museum. The experimental findings are presented in the next section.

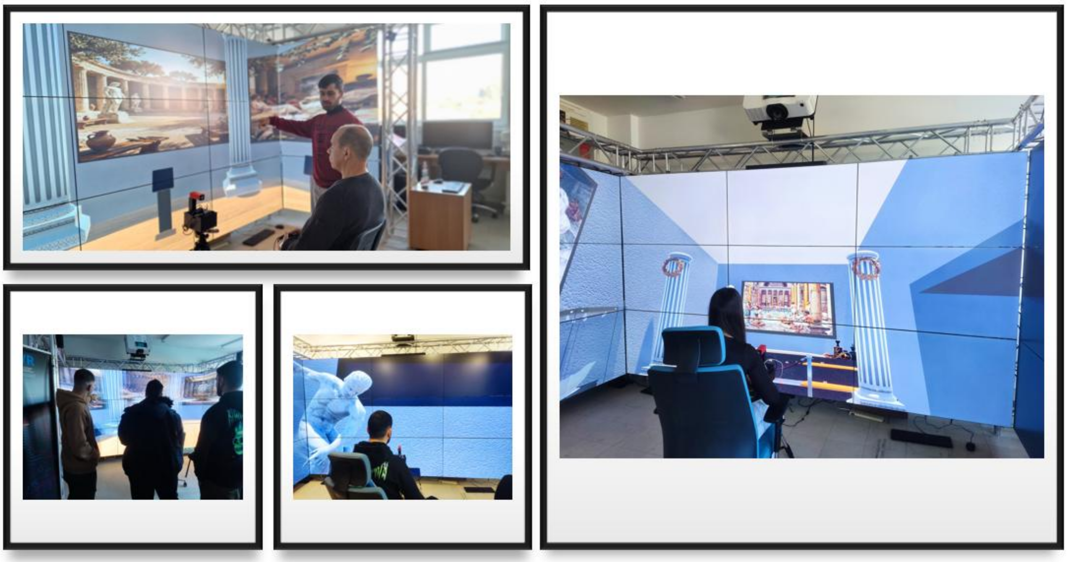

Figure 38. Users Experiencing Scentree within the Virtual Museum Setup. Image by Vasileiadis Vasilis, is licensed under CC BY 4.0

5.4 Experiment Results & Statistical analysis

The user study results are structured around the four defined evaluation questions, as summarized in Figure~35. For each Likert-scale item (1=Strongly Disagree, 5=Strongly Agree), descriptive statistics are reported in terms of Mean (M) and Standard Deviation (SD).

In general, participants recognised the system as technically reliable and well-synchronized. Odor diffusion was assessed as significantly synchronized with virtual events (M=4.47, SD=0.7), while perceived or mismatches were quite low (M=1.90, SD=1.20). In addition, participants agreed that the aromas dissipated adequately before the next activation (M=3.67, SD=1.29), declaring the cleaning interval was effective, despite some residual odor being occasionally observed. The intensity of the fragrances emitted was deemed appropriate (M=4.35, SD=0.69), and participants also seemed to largely disagree that the smells were unpleasant or too strong (M=1.98, SD=1.10). These subjective findings coincide with the objective timing performance reported in Section~4.5.1, confirming that Scentree operates with sufficient accuracy.

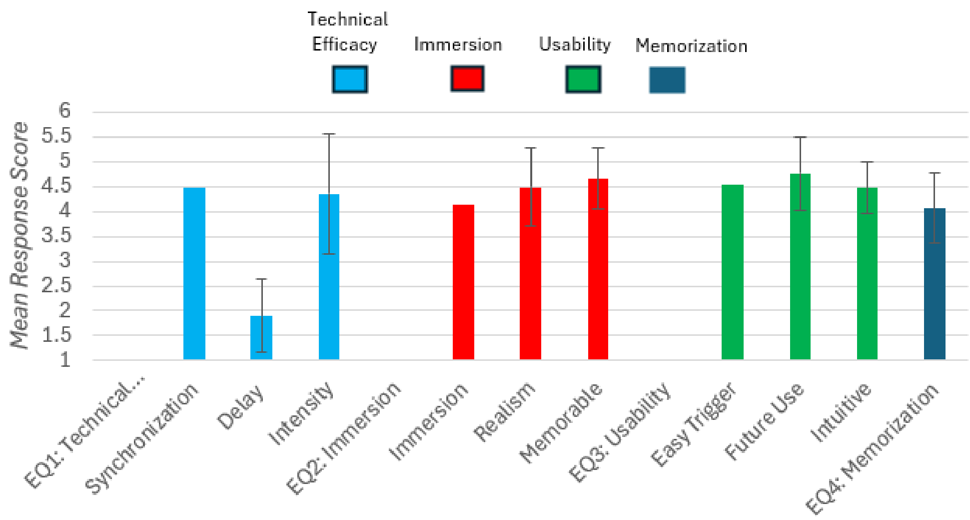

Figure 39. Mean Likert-scale ratings (1-5) with standard deviation error bars for the post-experiment questionnaire, image by Vasileiadis Vasilis, is licensed under CC BY 4.0

Furthermore, olfactory stimuli appear to have contributed significantly to the overall sense of presence and immersion. Participants reported feeling immersed in the virtual museum environment (M=4.14, SD=0.78) and had a strong sense of "being there" (M=4.02, SD=0.84). The combination of visual elements and odors was considered realistic (M=4.49, SD=0.61), with odors that were deemed especially suitable for the ancient Greek settings (M=4.25, SD=0.84). Additionally, participants reported that scents contributed to making the experience memorable (M=4.65, SD=0.56), supporting the hypothesis that multisensory stimuli enhance engagement. Participants also agreed that the addition of scents helped them memorize information better (M=4.06, SD= 0.94), suggesting a positive perceived effect on memorization.

The kiosk-based interaction scheme proved to be particularly user-friendly. Participants noted that it was easy to understand how to activate the scents (M=4.53, SD=0.73) and rated the button-pressing interaction as simple and intuitive (M=4.47, SD=0.70). Acceptance among users was very high, as participants expressed a strong interest in using similar scent-enhanced VR experiences in the future (M=4.76, SD=0.51) and agreed that the scents had improved the overall virtual exhibition experience (M=4.55, SD=0.54).

While objective memory performance was not assessed in this study (e.g., through standardized recall or recognition tests), participants' self-reported responses indicate a clear **subjective/perceived memory improvement**. Participants frequently stated that the olfactory cues helped them remember exhibit-related information and made the content feel more vivid and easier to encode. Such reports are consistent with prior work on odor-evoked autobiographical memory and the so-called Proust phenomenon, which highlights the strong association between olfaction, emotion, and memory. Therefore, the present findings should be interpreted as evidence of enhanced perceived memorability and engagement, rather than a demonstrated improvement in objective memory retention.

6 Discussion

The results indicate that the device achieves its primary goal, to provide repeatable real-time olfactory triggering, suitable for use in CAVE environments. The result from the automated testing environment shows rich results of consistent behavior between the functionality of the system's four odor diffusion channels, and the one-way ANOVA did not return statistically significant differences in the average activation duration across the four channels ($F(3,197) = 0.50622$) and ($p = 0.678432$). This is especially relevant for multisensory VR experiments, where timing variations could introduce unintended experimental bias and reduce perceived synchronization. In addition, considering the strong perceived timing and synchronization ratings reported in the post-experiment questionnaire, these findings support the conclusion that the Arduino–Unity serial interface and the activation protocol provide time-consistent scent delivery.

6.1 Limitations & Future Directions

Furthermore, our results demonstrate limitations that are specific to CAVE-based olfaction rather than the weakness of the control logic itself. While users rated the system technically reliable and the interaction logic simple and intuitive, responses related to odor diffusion suggest that, hardly, olfactory traces may persist in the space, clearly pointing to the future directions of research, suggesting for focus on diffusion and cleaning to avoid cross-contamination, while at the same time maintaining time consistency. Also, we need to explore scent as a clue in different game genres, such as puzzle games. Overall, the results indicate that Scentree is a reliable and scalable device for olfactory research in CAVE environments

6.2 Conclusions

This thesis explored olfaction as a structured event-based game mechanism in an immersive CAVE environment (MobiCAVE) rather than as a purely atmospheric enhancement. It presented the design and implementation of Scentree, a flexible and low-cost Arduino-based olfactory display, and demonstrated its real-time integration with Unity for reliable scent activation within the MobiCAVE environment. The overall results show that such integration is technically achievable and reproducible in Cave environments.

In terms of User experience and perceived impact, the findings suggest that synchronized olfactory stimuli can enrich perceived realism, immersion, and presence in an immersive virtual environment, while supporting perceived memorization and engagement of participants. At the same time, the study emphasizes the need for objective and cognitive measures and careful control of olfactory constraints CAVE environments, such as odor persistence and cross-contamination. In summary, this thesis contributes to both a practical system and a design direction, supporting the view that olfaction can function as an interactive game mechanic in immersive environments and inspiring future research that combines strong cognitive evaluation with more advanced diffusion control strategies.

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