Topic: Is a comprehensive smell display device tractable and what challenges need to be solved to develop such a display?

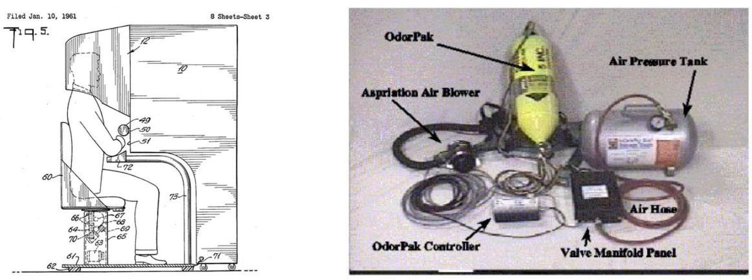
Overview

The research and development of olfactory displays is still in its infancy. One of the first identifiable applications of the idea of olfactory displays dates back to Heilig's Sensorama Simulator patented in 1962 (Fig. 1a), where scents were first introduced to the theatre experience [1, 2, 3]. One of the first portable olfactory displays was created in 2001 by Cater (Fig. 1b), which delivered scent through tubing to an oxygen mask [2, 4]. Despite its early conception, relatively little progress had been made due to a lack of understanding of the mechanisms of human olfactory perception. Nevertheless, much regarding the olfactory system remained unknown until the Nobel prize for discovering the principles of odor recognition and memorization in 2004 [5, 6]. Subsequently, olfactory studies and technologies have started gaining more attention in recent years. The COVID-19 symptom of anosmia (loss of smell) has also accelerated studies on human olfaction [7, 8, 9]. This paper reviews a selection of influential works done in the field of olfactory displays in the past two decades in order to understand the unsolved challenges faced by scientists in the current state of olfactory display research.

This paper will attempt to provide an answer to the topic question by investigating the following sub-topics:

1. The mechanisms and features of olfaction & olfactory perception

2. The current state of olfactory display research



(a) Sensorama Simulator by Heilig 1962. Figure from [1]

(b) Portable olfactory display by Cater 2001. Figure from [2]

Figure 1: Early olfactory displays

1 Olfaction & Olfactory Perception

Though the sense of smell is a sensory stimuli we are intimately familiar with, it is still one of the most unexplored sensory modalities to date [10]. A bare-bones smell display could be created by simply delivering scents to the user's nose. However, in order to develop a comprehensive smell display, a basic understanding of human olfactory perception is crucial for recreating the sensory experience of smell. This section will briefly summarize several key features of human olfaction relevant to the development of olfactory displays.

1.1 Concerning olfaction or the sense of smell

It is commonly believed that humans are less sensitive to smells than other animals such as dogs or rodents. However, Shepherd [11] has claimed that we are in fact good smellers due to humans having superior brains and biologically different nasal cavities compared to other mammals. Contrary to popular belief, the human olfactory system is capable of distinguishing over a trillion smells [2, 10, 11]. Moreover, humans adapt to scents in their environment over time. According to Cheok and Karunanayaka [10], humans become accustomed to unpleasant smells faster than pleasant smells and are alerted when unpleasant smells change.

Unlike visual stimuli, olfactory information can be processed without a deliberate and conscious shift in attention [2]. Hence some consider olfaction a secondary stimuli (with less importance) of lower priority (in terms of developing the corresponding human-computer interaction (HCI) technologies). Notably, visual stimuli have been found to have strong effects on olfactory responses [12, 13].

1.2 The human olfactory process

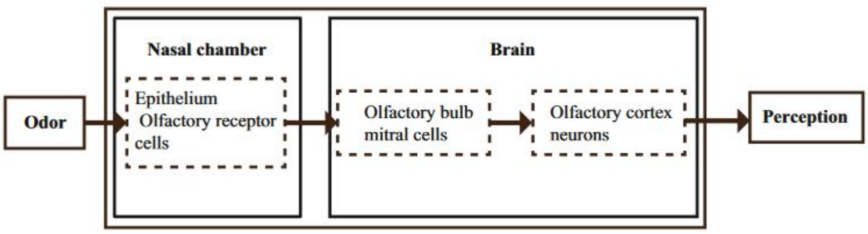


Figure 2: Diagram of the olfactory process. Cheok et al. 2018.
Source: Figure taken from [10]

A diagram of the olfactory process is shown in Figure 2. Odors—volatile chemical molecules—inhaled either through the mouth (retronasal) or nostrils (orthonasal) are eventually transported to the nasal chamber to bound with nasal receptors [10]. Through a series of biological and chemical processes, a nerve impulse (electrical signal) is relayed to the olfactory bulb in the brain, which creates our perception of smell [10]. In addition to the olfactory system, trigeminal nerves in the nasal cavity also contribute to our sense of smell [14]. For instance, the "cool" feeling of mints and the "hot" feeling of spices are examples of these two nervous systems working in tandem [9, 14].

1.3 Describing & classifying odors

While color can be measured using a spectrophotometer via photon absorption, a counterpart to standardize the description and classification of odors does not exist [15]. Throughout the years, various use-case specific systems have been developed (and proven useful within specifications) involving dozens to as many as hundreds of descriptors and attributes [15]. Unfortunately, these systems are not compatible since the same vocabulary used might not be describing the same scent (in terms of experiencing the same smell, intensity, etc.) [15]. Moreover, the nature of olfactory perception further complicates the description and classification of odors. From a psychological perspective, it has been reported that past experiences such as memory and emotions can significantly influence our description of odors [15]. From a physiological perspective, individuals have different degrees of odor sensitivity [16]. From a chemical perspective, though there were attempts to identify a set of primary odors (similar to the primary colors), later studies have begun reaching the consensus that color is instead a "continuum" [15, 16]. Chastrette has reported various numerical and statistical approaches for mapping a "color space" in 2002 [15], however it does not appear that these studies ever reached "mainstream" as they were not adopted by more recent studies on developing olfactory displays. Nevertheless, although a universal standard for describing and classifying scents does not exist, Braun [16] identified valence (the pleasantness of the smell), intensity, and familiarity as the "most widely agreed upon" dimensions of odor relevant in HCI research.

2 Olfactory Displays

This section presents an overview of the current state of olfactory display research through summarizing a selection of works published in the past 20 years. It is worth noting that most papers included in this report are portable olfactory displays designed for improving presence and immersion in virtual environments [17, 18]. Developed display devices & prototypes are classified into categories based on their mechanism and respective goals. Through the review and analysis of the current state of research, we will identify the major unsolved challenges of olfactory display development.

2.1 Displaying scents via odor delivery

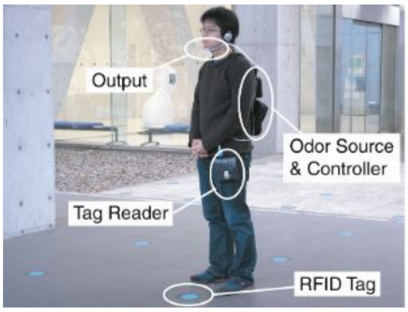
As shown in Fig. 2, the first stage of the human olfactory process is odor. Naturally, through the delivery of the corresponding chemical molecules to the users' nostrils, it is possible to recreate the experience of smell. Odor delivery is popular in the field of olfactory display research due to its non-intrusive nature. Odor molecules are typically delivered either directly via micro-droplets in liquid form or in a gaseous state after nebulization [16, 19].

2.1.1 Head-mounted/Body-mounted olfactory displays

The majority of head-mounted olfactory displays can be classified into the following categories:

2.1.1.1 Tube-based delivery

Tube-based olfactory displays deliver the nebulized odor molecules via a tube which is connected to a gas/nose mask worn by the user, similar to the previously mentioned system developed by Cater [2, 4]. Since the tubing would enable a greater flexibility in distance, tube-based delivery olfactory displays can be mounted to the body of the user through a backpack system (as shown in Fig. 3a), which enables the integration of larger and more complex diffusion equipment for generating a wider variety of scents. However, as a trade-off, the more cumbersome equipment could also impact user movement and lower comfort. For instance, the gas/nose mask might not even fit the user, a problem encountered by [20] during user studies (equipment shown in Fig. 3b). Moreover, a longer tube would also increase the latency of the system. Since the generated scent would take longer to reach the user's nose, the higher latency would lower immersion and presence.



(a) Backpack mounted olfactory display. Yamada et al. 2006. Figure from [21].

(b) Tube-based delivery olfactory display. Bahremand et al. 2022. Figure from [20]

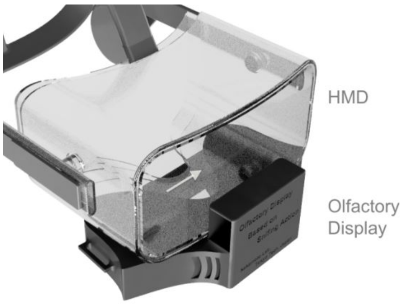
Figure 3: Tube-based delivery olfactory displays

2.1.1.2 Open air delivery

Open air olfactory displays are typically more compact than tube-based systems. Several studies in recent years devised prototypes in this category [13, 22, 23, 24, 25, 26]. As shown in Fig. 4a & b, these devices are designed to be mounted onto VR headsets as an extension. The generated scent is delivered to users via airflow from small fans integrated in these displays. Other form factors include necklace wearable devices, such as the device shown in Fig. 4c. These devices are relatively light-weight compared to tube-based systems. However, due to physical constraints, it is not possible to fit complex diffusion equipment into these head-mounted devices. Therefore, the number of scents generated by similar systems is limited. Certain commercial products such as the ION by OVR Technology[1] opt for a cartridge system to expand the number of available scents. However, it is debatable whether such a system would be easy to use in practice, as one would have to manually swap cartridges in between scenes. Nevertheless, such devices are more accessible for the general consumer as they are relatively simple, highly portable, and less costly compared to other olfactory displays.

[1] `https://ovrtechnology.com/`

(a) Head-mounted olfactory display. Javerliat et al. 2022. Figure from [22].



(b) Head-mounted olfactory display. Kato and Nakamoto 2019. Figure from [24].

(c) Necklace type olfactory display. Egan et al. 2017. Figure from [26]

Figure 4: Open air delivery olfactory displays

2.1.2 Handheld olfactory displays

2.1.2.1 General handheld olfactory displays

Most scent delivery systems have a certain degree of latency between when the scent is released from the device and when it reaches the user's nostrils. If the users were to bring the olfactory display to their nose instead, this latency could be significantly reduced. Past studies have found that the timing of odor release is crucial for maintaining presence [16]. Several works have attempted to construct handheld olfactory display prototypes. For example, as shown in Fig. 5a [27] created a compact olfactory device attachable to the VIVE controller. Other devices such as [28, 29] could be compact enough to serve as handheld devices depending on the specific use-case. Nevertheless, it is fairly evident that handheld displays are typically designed to be compact, lightweight, and easily to handle. This poses a tight constraint on the form factor of said devices, as it would be physically impossible to include a large number of odors (chemicals) and complex diffusion mechanisms in a small device.

2.1.2.2 User triggered handheld olfactory displays

User triggered handheld olfactory devices can be traced back to the 1970s, when scratch and sniff cards [30] were included as a part of the cinema experience where the audience was expected to scratch the cards based on contents of the film. In modern virtual environments, user triggered olfactory displays have the advantage of having its behavior, such as the timing of odor release, tied strongly to the user's actions. Moreover, Cornell et al. [31] suggest some might even respond to environmental odors negatively (i.e. odors outside of their control). Niedenthal et al. developed a prototype oflactory display based on this idea, where the trigger of the VR controller is tied to the release of the smell [7] as shown in Fig. 5b. Participant feedback from the wine tasting game developed by the researchers were fairly adequate, although not stellar (users rated the device 5.3 out of a 7 Likert scale for the device's responsiveness) [7]. Nevertheless, user triggered olfactory displays' biggest advantage is also one of their greatest flaws. As the system is designed for releasing scents in quick bursts and incapable of generating environmental scent over time. Moreover, the influence of trigger-based displays on immersion and presence is questionable, since humans are not capable of switching the sense of smell on/off in real life.

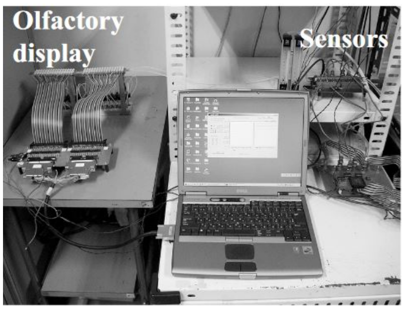
(a) Handheld olfactory display. Niedenthal et al. 2019. Figure from [27].

(b) Trigger-based olfactory display. Niedenthal et al. 2023. Figure from [7]

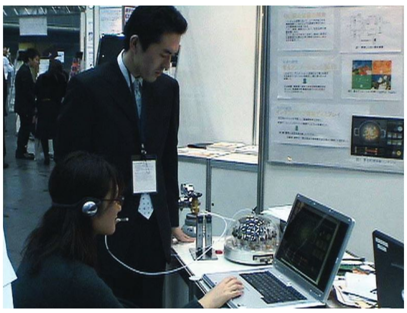
Figure 5: Handheld olfactory displays

2.1.3 Stationary olfactory displays

Most stationary olfactory display research indexed are older works from the 2000s. The olfactory display shown in Fig. 6a contains 32 tubes of odor sources [32]. As stationary olfactory displays have no restraints on size, the odor generation and diffusion equipment can be as complex as necessary, thereby enabling a larger variety of scents. Other stationary olfactory displays utilize air cannon devices [3, 33, 34] for delivering odor to the users, as shown in Fig. 7.



(a) Nakamoto and Minh 2007. Figure from [32].



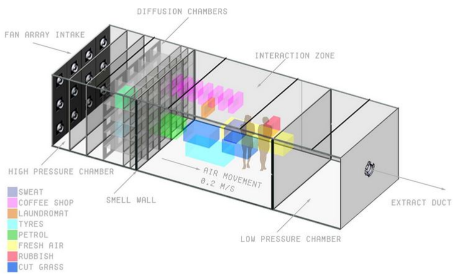
(b) Nakamoto et al. 2008. Figure from [35]

Figure 6: Stationary olfactory displays

2.1.4 Ambient scents

While most recent olfactory displays are designed to recreate the experience of scent for individual users, there had also been many efforts in the past to introduce odors to ambient environments. According to Spence [36], the first use of olfaction in cinema dates back to 1908, where cotton saturated with the floral scents were held in front of a fan to deliver the smell to the audience. Kaye [2] has complied a list of projects in the 1990s attempting to introduce olfactory displays to theatres with limited success. These projects remained experimental primarily due to financial concerns such as a lack of funding and high operation costs. In recent years, [36] claims that cinema with olfaction remain "one-off novelties" designed for "attracting media attention". In general, the tractability of the current technology is not sufficient for long term investment, operation, and maintenance in theatres. Although it is also worth noting that a temporary loss of smell has been recorded when individuals are overloaded with visual information [37]. Spence [36] speculates that audiences are less likely to be conscious of ambient scents when deeply engaged in a movie, hence the lukewarm feedback from moviegoers (for scented cinema events). Nevertheless, as olfactory responses have been shown to influence presence in virtual environments [17, 18], attempts have also been made in incorporating smells into room-like virtual environments. Cave automatic virtual environments (CAVE) [38] are room-based virtual environments where the relevant visual information (view) is projected onto the walls of said room. Certain stationary olfactory displays could be compatible with a CAVE, such as projection based scent delivery systems capable of delivering odors across a larger distance [3, 8, 28, 34, 33] as shown in Fig. 7. As shown in Fig. 8, the project by Haque et al. [39] is a room-based virtual environment where various scents are released based on the movement of the users. Participants were able to navigate paths in the virtual environment based on pleasant and unpleasant smells delivered by the ventilation system [39]. In general, delivering scents in an ambient environment is more challenging than its portable/localized counterparts, as the increase in scale could pose significant challenges in terms of practicality and tractability.

Figure 7: Air cannon delivering smoke (scent). Yanagida et al. 2004. Figure from [3].



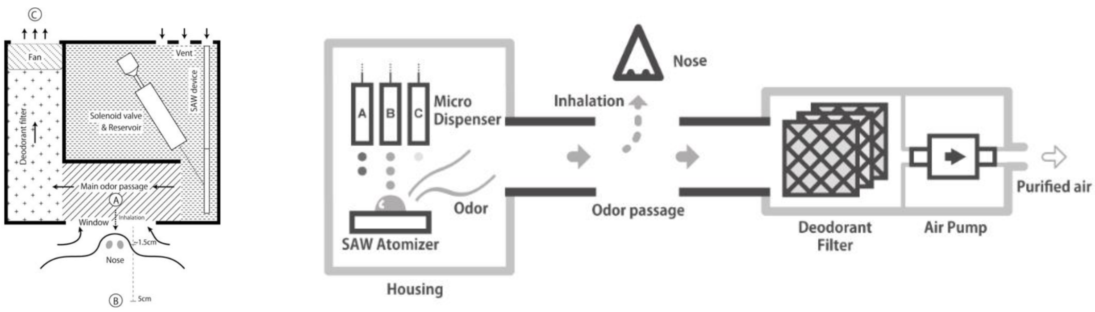
(a) An olfactory display in an room-like environment.

(b) Ventilation system of the scents of space project.

Figure 8: Scents of space by Haque et al. 2002. Figures from [39].

2.1.5 Residual scents

As chemical molecules disperse into the ambient environment after the continuous delivery of various scents, users might be inhaling a mixture of residual scents instead of the intended scent. A key challenge of olfactory displays is the reduction and eventual elimination of residual odors. While a significant portion of studies avoid addressing the effects of residual scents directly, certain papers developed prototypes that target this specific problem. In order to eliminate residual scents, previously released odors must be collected and removed, which in essence resets the air around the user to "fresh air". For instance, the prototypes by Kato and Nakamoto are implementations of this idea [23, 24]. As shown in Fig. 9, the constant air flow in the olfactory system ensures ventilation by transporting/removing previous odors and introducing fresh air. Previous odors are then collected, thereby removed from the ambient environment, with deodorant filters. Moreover, the approx. 98% reduction in residual molecules based on carbon activation rate reported by [24] indicates that this mechanism is fairly effective for head-mounted olfactory displays. Nevertheless, the effects of residual scents on user experience is also highly dependent on the quantity of odor released. For example, the handheld device developed by [27] is designed to release odor in short bursts near the user's nostrils for less than a second. The minute amount of odor released and subsequent actions of the user moving the graspable device away from their nose will induce sufficient airflow to render the effects of nearly negligible. As for larger, room-like ambient environments such as [39] (shown in Fig. 8) or CAVEs, the ventilation system must be up-scaled accordingly, which in turn increases the complexity of the system and related costs.



(a) Kato and Nakamoto 2018 Figure from [23].

(b) Kato and Nakamoto 2019. Figure from [24].

Figure 9: Olfactory displays for reducing residual odor

2.2 Displaying scents via electrical stimulation

As shown in Fig. 2 and described in Sec. 1.2, nerve impulses are delivered to the corresponding areas of the human brain, i.e. the olfactory bulb. If one were to replicate these nerve impulses, which are electrical signals, and deliver them to the brain, then it would be possible in theory to recreate the sensory experience of smell. One of the earliest identifiable cases of inducing smell via this method was found in 1954 [40]. Penfield and Jasper discovered that patients were able to experience the smell of "foul odors" during their research on epilepsy [40]. Later studies have investigated the induction of smells via stimulating the olfactory bulb directly, primarily for the treatment of anosmia [19, 41, 42, 43, 44]. While this method has seen varying degrees of success [19], it is intrusive in nature due to the need for implants, as shown in Fig. 10. A small portion (approx. $10-20\%$) of study participants have reported the feeling of numbness and pain due to the electrical stimulation [19]. Moreover, implant operations require specialized/trained personnel and high costs, thereby rendering this method unserviceable outside of laboratory settings and impractical for commercial purposes. Nevertheless, there have also been approaches to circumvent the intrusiveness of electrical stimulation methods, such as the prototype developed by Brooks et al. [9], which targets the trigeminal nerves instead through inserting their device through the nose, as shown in Fig. 11. However, triggering the trigeminal nerves alone cannot recreate the sensations of smell induced by the olfactory bulb [9]. Although this approach is quite limiting, it might be suitable as a complimentary device to other non-intrusive olfactory displays for enhancing trigeminal sensations. In general, electrical stimulation for displaying scents is not tractable with current technologies, therefore most existing literature on olfactory displays opt for alternative methods.

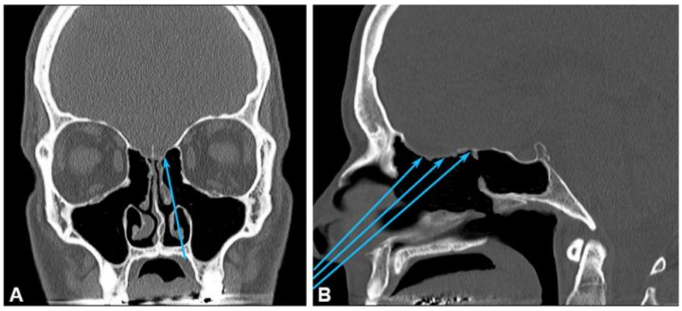


Figure 10: Location for implants for stimulating the olfactory bulb by Holbrook et al. Source: Figure taken from [43]

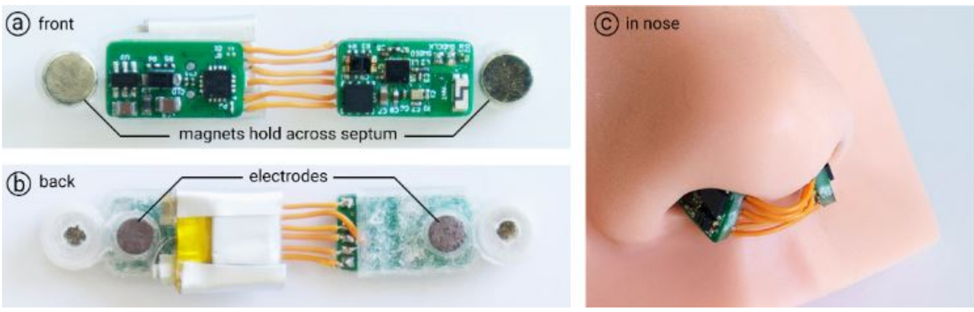


Figure 11: A implant for stimulating the trigeminal nerves by Brooks et al. Source: Figure taken from [9]

2.3 Related Technologies

Other technologies are also relevant to olfactory display research. This section will cover said technologies briefly, as they are out of the scope of this paper but nonetheless worth mentioning.

2.3.1 Computational fluid dynamics (CFD)

Studies have been conducted on the flow of gaseous particles in controlled environments and the diffusion of odor particles [45, 46]. However, performing CFD in real time is computationally costly. Moreover, the subject is out of the field of expertise of most computer scientists involved in olfactory display research.

2.3.2 Electronic nose

Electronic noses are indispensable to the capture and recreation of natural scents, which are typically composed of a mixture of volatile chemical molecules. Although current electronic noses are capable of categorizing detected chemicals, they are unable to capture the nuances of a smell, such as its intensity [5, 47, 48]. In addition, current sensor materials are consumables with relatively short lifespans [48].

Discussion & Challenges

This section will outline the unresolved challenges of olfactory display development.

From the perspective of olfaction and olfactory perception:

- The current industry lacks of a standardized system and vocabulary for describing and classifying odors. This problem is also evident in the majority of works on olfactory displays, which renders most studies difficult to reproduce [5] and incompatible with existing findings.

- As the human nose is not reliable and consistent, due to differences in personal experience, memory, preference, and physiology, individuals might experience a different sensation despite smelling the same scent. An olfactory display aiming to capture and recreate the same experience for all users would be challenging to develop.

- As a set of primary odors likely does not exist, it would be physically impossible to fit over a trillion combinations of scents into an olfactory display. Any display developed can only attempt to cover as much of the human olfactory spectrum as possible. However, this might change as the human olfactory system becomes better understood in the future.

From the perspective of olfactory display research:

- The current state of olfactory display research appears disjointed. Although this is understandable as the field of olfactory displays is in its infancy. Nevertheless, many of the prototypes and solutions devised (or designed to address specific limitations) are not compatible with other existing devices. Therefore, it is challenging to create an olfactory display with few flaws.
- Current olfactory technology (especially odor generation mechanisms) lack compactness. Existing portable solutions must sacrifice scent variety for practicality. While less portable solutions are likely to support a larger number of scents, such systems are typically complex and inaccessible for the general consumer (due to high cost and low usability).
- Electrical stimulation based devices are unlikely candidates for household olfactory displays until more advancements could be made in the related fields (of biology, anatomy, and medicine).
- Related technologies such as electronic noses could provide considerable aid to olfactory display research as they mature in the future.
- Olfactory display research is highly interdisciplinary, involving several fields across disciplines such as computer science, electrical engineering, mathematics, physics, biology, and psychology. Researchers with an understanding of all or most the related fields are rare [5].

Conclusion

In conclusion, as it stands, a comprehensive smell display is not tractable with the current research and technology. In fact, it is questionable whether a fully "comprehensive" display would ever be possible due to physical limitations and the lack of a set of primary odors. Nevertheless, it is not impossible to imagine a smell display capable of rendering many odors appearing in the near future. With increasing attention on the field of olfactory displays in recent years, a future where smell displays are tractable is hopeful.

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