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Information Olfactation: Harnessing Scent to Convey Data

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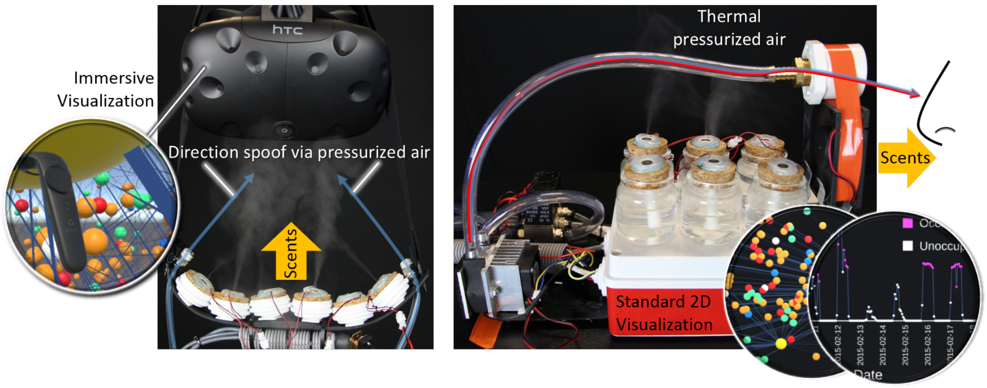

Fig. 1: Our two six-scent olfactory displays for information olfactation; the left shows the mobile setup, which is intended to be hung on a virtual reality head-mounted display (HTC Vive depicted) and used for immersive analytics applications, and the right shows the tabletop unit, which is to be used for more traditional 2D visualization setups. The prototypes have different capabilities; the mobile version has two pipes for varying the directionality of scents, whereas the tabletop unit can control the air temperature.

Abstract—Olfactory feedback for analytical tasks is a virtually unexplored area in spite of the advantages it offers for information recall, feature identification, and location detection. Here we introduce the concept of *information olfactation* as the fragrant sibling of information visualization, and discuss how scent can be used to convey data. Building on a review of the human olfactory system and mirroring common visualization practice, we propose olfactory marks, the substrate in which they exist, and their olfactory channels that are available to designers. To exemplify this idea, we present VISCENT: A six-scent stereo olfactory display capable of conveying olfactory glyphs of varying temperature and direction, as well as a corresponding software system that integrates the display with a traditional visualization display. Finally, we present three applications that make use of the viScent system: A 2D graph visualization, a 2D line and point chart, and an immersive analytics graph visualization in 3D virtual reality. We close the paper with a review of possible extensions of viScent and applications of information olfactation for general visualization beyond the examples in this paper.

Index Terms—Olfaction, smell, scent, olfactory display, immersive analytics, immersion.

1 Introduction

The rich cinnamon of mom's apple pie cooling on the kitchen table; the refreshing tang of a fir tree permeating the house during a childhood Christmas; a beloved dog's wet fur as he cuddles next to you in bed after an evening walk in summer rain. *Olfaction*, the chemoreception that gives rise to the sense of smell, is a powerful memory stimulant and can yield unexpected associations. Marcel Proust (1871–1922) famously wrote in *In Search of Lost Time* about how a single bite of a *madeleine* (a small cookie from the Lorraine region of northeastern France) gave rise to vivid childhood memories of the narrator's aunt sharing the same cookie. Beyond memory, smell (and its close relative, taste) is a powerful sense used for detecting danger, testing (and enjoying) food, and receiving pheromones to yield social response. But can smell be used to convey data? To our knowledge, this question has not yet been satisfactorily investigated in the visualization community.

In this paper, we explore the design space of olfaction in humans as a multimodal mechanism to convey information in a data visualization as a complement to the traditional visual system. Our exploration begins with a review of the olfactory system in humans. Mirroring visual marks and their visual channels traditionally used in data visualization [73], we derive a design space consisting of *olfactory marks*—the building blocks of scent, including fragrance, bouquet, and airburst—as well as their *olfactory channels*, including intensity, direction, air flow rate, burst frequency, and climate. Then, we summarize existing approaches to designing olfactory interfaces, and use these as well as real-world examples to present a case for *information olfactation*: The use of interactive olfactory representations of data to amplify cognition. To showcase the potential of information olfactation, we present VISCENT, a prototype system consisting of both hardware and software components. The viScent hardware rig is a six-fragrance olfactory display with stereo output (i.e., supporting both nostrils, which is important for scent direction) as well as temperature control. The corresponding viScent software framework allows for rapidly building information olfactation applications that harness the rig. We also present three examples that we have developed using viScent; one immersive for Virtual Reality (VR), and two using standard 2D visualizations.

While we do not suggest that smell will ever replace vision (or even sound or touch) in a data visualization, our investigation of this topic gives strong indication that smell can be used as a natural complement to vision for ambient and passive effects [47], such as *smell glyphs*. In particular, we see the primary utility of olfactory displays such as ours for *immersive* [13] and *ubiquitous analytics* [28], the new flavors of visual analytics that endeavors to optimize the flow [17] and fluidity [29] of the user by immersing them in the analytic environment. For such situations, we suggest that an olfactory display can provide a powerful and hitherto unused sensory modality with significant potential to improve the presence and flow of the analyst [31, 90, 103]. Our contribution is thus (i) what we believe to be the first definition of the information olfactation topic, and (ii) a prototype hardware and software framework for building information olfactation applications, which we demonstrate with three concrete applications that combine visualization with olfactation. Because these contributions are mainly in the

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areas of engineering and theoretical framework, we do not include a user study in this paper; instead, we provide an in-depth foundation of empirical research from the domain of cognitive and neuropsychology.

2 Models of Olfaction in Humans

Humans are able to distinguish between a vast number of discrete fragrances—over one trillion, by one estimate [8]. There are two perspectives on olfactory perception relevant to interface design: A chemical-topographic model, and a fragrance classification model.

2.1 Chemical Topography

All of our senses create a spatial mapping of the world around us, and olfaction is no different [27, 46]. How this is done in olfaction, however, is an ongoing area of research that is still not fully explored [5, 19, 27]. To some extent, an initial landscape of smells is created through dimensionality reduction.

The epithelial tissue inside the nasal cavity is lined with millions of olfactory sensor neurons, each with an odorant receptor. There are approximately 1,000 different types of odorant receptors [75, 82], each able to detect a range of molecule formations. A large amount of dimensionality reduction is done in the epithelium alone [75]; The sensor neurons are all connected (synapsed) to the olfactory bulb in the brain via smaller bundles of nerves called the *glomeruli*; it is through this bundling that the dimensionality of the information received from the olfactory sensor neurons is further reduced [75].

The brain classifies sensory input as a distinct fragrance, but only after several steps. Olfactory receptors first detect high-dimensional information about the composition of volatile molecules in the air. The pathways leading from the olfactory sensor neurons to the olfactory bulb then perform heavy preprocessing to reduce the complexity of this information in the both the epithelium and the olfactory bulb. Thus, an initial landscape of smells is created by the nervous system before entering cognition. It is perhaps as a result of this preprocessing that odor-in-the-head recollection—the internal re-creation of fragrances in the absence of external stimuli—is subjectively considered very difficult in comparison to visual or aural memories [45].

2.2 Fragrance Classification

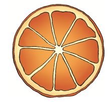
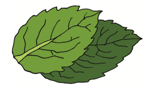
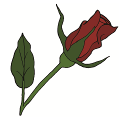
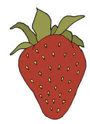
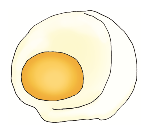
The notion that people group odors into fragrance categories is not a new one, but what those categories entail has historically been subjective and culture-dependent [53, 88]. It is only recently that robust empirical research supporting fragrance classification models has appeared, both in psychology [11, 51] and in interface design [74]. Castro et al. [11] introduce the classification framework we use in this paper (Table 1) [11]. Classifying olfactory input as a distinct fragrance is an important part of the olfaction process in humans; it allows us to assign meaning to smells and use the contextual information we associate with specific odors in our decision-making processes [88]. While the estimate of "one trillion" distinct odors is contested as representing the upper, rather than lower, bound of human olfactory discrimination [33], it still presents a powerful argument toward the use of fragrances for analysis of high-dimensional data.

2.3 Model Synthesis

While dimensionality reduction of detected odors is done before the information reaches the cortex, relative to other animals, a greater degree of odor processing is done consciously [88]. Categorical clustering of odors into broad types may be considered a further reduction in dimensionality that is done by humans: By creating associative classes of odors, we simplify the data our odor receptors collect from the air around us, perceived by our conscious brain as a distinct fragrance, into a conceptual grouping of fragrances [11, 88].

Human perception of olfactory stimuli is an exercise in dimensionality reduction and cognitive filtering. From the chemo-topographic model, we understand that there are spatial and, as we will discuss (in section 3.4), *temporal* substrates of information that are detected and interpreted by the human olfactory system both consciously and unconsciously. From the classification model, we understand that human olfaction is dependent on association and context.

Table 1: Castro's Fragrance Classes [11]: The basis for smell glyphs.

Odor Class	Visual Glyph	Example Scent Glyphs
Citrus		Oranges, lemons, limes, grapefruit, tangerine
Acerbic-Synthetic		Alcohol, kerosene, leather, ammonia, tar
Leafy		Peppermint, teas, licorice, eucalyptus
Floral		Roses, lavender, violets, other flowers
Fruity-Non-citrus		Strawberries, other berries, pears, mango, pineapple
Woody		Mushrooms, cedar, earthy/dirt, "green vegetables" (e.g., bell pepper), beans
Spicy-Smoky-Nutty		Tobacco smoke, coffee, almonds, popcorn, cloves, spices, burnt things, butter
Heavy-Rotten		Eggs, smoked fish, garlic, vinegar, beer, wet dog, blood, cadaver, feces

3 A Task Taxonomy for Information Olfactation

Obrist et al. [78] have proposed ten categories for describing the user's experience in the context of olfactory interfaces, including past association and memory recall (categories 1 and 2), stimulation and attention (categories 3 and 4), identification and detection (category 5), aversion (category 6; e.g., the scent of a decaying corpse), feeling intruded upon (category 7), associations with other people (category 8), and smell affecting mood, behavior, and expectations (categories 9 and 10) [78]. While this model offers solid foundation for framing the ways a user may receive and experience olfactory feedback, it does not extend into the realm of recommending signifiers for affordances related to tasks relevant to olfactory displays to convey information [77].

In this section we discuss the features of odor detection in human sensation and perception that we believe to be most relevant to information olfactation design in the context of the varieties of task that are signaled or augmented by odor. We define *information olfactation* to specifically refer to the design, creation, and transmission of olfactory stimuli to convey information. Following the introduction of data edibilization [98]—a design space for encoding data into taste—information olfactation represents the next piece of the multisensory information visualization puzzle [65, 86]. Human beings, like all animals, rely on odor not only to receive, but also to send information, although the latter of these is typically done unconsciously [21]. We make a distinction not only between the odor reception as it affects user experience, but also between information olfactation and this unconscious olfactory communication.

3.1 Information Recall

Decades of research indicate that odor detection is a potent trigger for eliciting memories of prior experience [1, 9, 43]. In fact, there is evidence that odor may be a better mode for eliciting recall of certain classes of information than visual or verbal/word cues [4, 45]. Olfactory signals that retrieve information from human memory tend to evoke stronger emotion than other sensory stimuli [35, 45].

The caveat that this applies to only certain classes of information warrants elaboration: There is a difference in the age distribution of memory formation (olfaction-associated memories tend to be from earlier stages of life relative to visual- or aural-associated ones), and olfaction-associated memories tend to be more sensitive to pairing with events affecting a greater emotional intensity than those with other sensory associations [44, 101]. With that distinction made, these relationships go both ways. Memories created in association with olfactory signals experience less decay over longer spans of time than visual or aural ones [45], and olfactory signals that retrieve information from human memory tend to also evoke stronger emotion than other sensory stimuli [35]. In the short-term, there is also some evidence of an "olfactory working memory" which can be updated with new information as the individual is exposed to stimuli, and which depends heavily on the individual verbalizing to create a semantic association (i.e., naming the perceived odor out loud) [49].

Task performance may be improved when fragrances are contextually out of place: The smell of motor oil while walking through an orange grove would aid in forming a stronger memory than the smell of oranges in the same context [43]. An immediate suggestion must be made in light of this observation: While there is some evidence supporting the existence of associations specific odors have with colors [63] and with shapes [38], *natural* (for want of a better word) contextual association between specific odors and visual marks and channels for abstract information are largely unexplored. How *should* a bar chart smell, for example? Or a force-directed graph? As such, with respect to odor-vision concept pairs, the visualization (olfactation) community is free to develop design standards.

3.2 Object Localization and Tracking

Using scent to locate objects is a feat we typically associate with other animals—the drug-sniffing dog, the bloodhound put to work tracking a deer or an escaped criminal, the truffle-sniffing pig, or the shark scenting a drop of human blood in the ocean. Human beings, however, are also capable of successfully tracking objects by scent, and their tracking ability improves with practice [81]. The intuition is reasonable: Imagine that someone, distracted, misses the garbage can when throwing away the remains of their meal, and it rolls unnoticed behind a couch. This person, within the ensuing days, would likely be able to detect and locate the remains for disposal by smell.

The olfactory system's structures for delivering stimuli to sensor neurons affects perception [52], and the dual-nostril structure of the nose is an important mechanism for tracking objects [32, 81]. Bilateral scent detection is an important feature of olfactory system structure for navigation not only in humans, but in mammals in general [12] (and, incidentally, in robotic sensor systems as well [36, 58, 87]). Directionality detection by scent is also associative: Visual stimuli simulating leftward motion presented with a specific odor, for example, leads individuals to associate that odor with leftward motion [59]. This effect is significant enough that it can affect the way we see objects in motion when the direction of that motion is ambiguous [59].

3.3 Feature Detection and Discrimination

Section 2.2 involved a review of empirical and theoretical work on the process by which olfaction represented the ability of people to distinguish between many different, distinct odor types [8, 11]. If each odor type, as described by any number of fragrance classification schema, is mapped to a particular feature of a dataset, it stands to reason that it should improve task performance with regards to making distinctions between objects in a view [8, 11]. Dmitrenko et al. [24], in evaluating the abilities of drivers to discern between different odors conveying semantic meaning, found that deriving meaning from different types of odor was well within the range of human olfactory ability. Human ability to discern between different odors is dependent not only on long-term memory associations but also upon the use of working memory, which is strongly influenced by vocalizing semantic codes for a given odor [49]. To give a real world example, the detection of certain types of smells by firefighters—burnt rubber or grease, for example—is a means of evaluating the scene of a fire [53]. We argue, then, that feature detection is a task that may be augmented by olfactory feedback in analytical environments; it is a task that fits the associative nature of human olfaction, and is a clear area for application of the classes listed in Table 1.

3.4 The Smell of Time and Somatic Sniffing

Imagine the very first moment you enter your favorite café or bakery: The smell of the freshly-brewed coffee and baked goods are likely at the fore of your mind. Consider how the relative priority of the ambient aromas changes after your first fifteen minutes of sitting down; likely, you hardly even notice most of the smells you detected upon entering the building. It is equally likely that you will be able to pick out the specific aroma of a freshly-baked pie if it passes near your table, or, worse, the stink of a garbage can with a tuna sandwich from yesterday being knocked over near where you are sitting.

In this scenario, walking through the entrance and encountering the bouquet of fragrances results in a spike of activity in certain parts of your brain lasting between 15 and 30 seconds; after this period, the activity for these regions begins not only to return to its original level, but, for a subset of the regions, to be actively suppressed below a baseline level [79, 92]. You have habituated. In the orbitofrontal cortex, however, there is ongoing activity that lasts as long as your exposure to the fragrances. This ongoing activity may facilitate associative memory creation [79, 92], and it also allows for the discrimination between old and new odors in the air in a single sniff [55].

Among ventilation-breathing organisms, olfaction is typically a cyclical process: There is a short period of time when air is exhaled during which the breather is receiving little to no external odor data, and a short period of time when air is being inhaled during which the breather is receiving a new sample of information from the air around them. This cyclical process of passive (autonomic) odor detection is often referred to as a "sniff cycle," which has been proposed as a standard "unit of smell" [55, 97]. It may be argued that this cycle may also mark a unit of human perception of the passage of time.

Beyond this passive approach to odor detection, the breather can perform *active smelling* via somatic (voluntary) sniffing [32, 91]. It is worth noting that this act of voluntarily sniffing, independent of the autonomic nervous system and external stimuli, is a feat unique to humans [89]. While voluntary sniffing on the part of the user is one way to get around the suppression of olfactory perception, all is not lost in terms of the olfactory interface designer's ability to counteract habituation. In empirical studies of olfactory perception, intermittent nine-second-long bursts of odor molecules produce a sustained level of activity in the parts of the brain that typically show suppressed activity after post-exposure adjustment during the autonomic sniff cycle; participants of an empirical study using this staggered burst approach experienced no habituation to the odor being tested [79].

The olfactory display designer must account for temporal perception and object discrimination through habituation, the sniff cycle, and active sniffing [67, 89]. Furthermore, temporal order of stimuli exposure matters, and not merely order of odors in isolation, but their order relative to other stimuli [52]. In other words, the perception of time through odor is cross-modal.

3.5 Human Olfaction is Cross-Modal and Associative

Odor affects the way we see objects, and vision affects olfaction [34, 35, 38, 59]. Research in neuropsychology has pondered the question of "seeing smell" for over a century, and structures of the brain seem to support the notion that there is a direct connection between these senses [20, 35]. This relationship is further validated by the recent development of convolutional neural networks to detect the presence of olfactory features in images [57]. Empirical cognitive psychology studies have explored techniques for producing odor associations with the effect of causing people to favor perceiving objects as moving in one direction over the other [59], or to be able to "smell" whether shapes are rounded or angular [38]. The latter study by Hanson-Vaux et al. [38] found that lemon, for example, smells angular; a finding that appeared in human-computer interaction (HCI) work as users' predisposition to create spiked sculptures with lemon-scented material [48]. Interfaces taking advantage of the cross-modality of odor are able to, for example, change the taste of the food the user is eating using visual and olfactory cues [76].

Beyond dimensionality reduction, olfaction is associative in that it is how we make sense of smells; we use scent and our memory thereof to identify people, animals, food, threats, and other objects in the world around us [53, 78, 88]. Further, these associations and the cross-modality of our senses affect the things that we create and the way we interact with the objects around us, particularly those that we have shared, or intend to share, with others [48, 78]. The evidence is clear: Odor has the power to modify how we experience vision, time, and space [20, 34, 38]. It can aide in our ability to find things in the world around us and in our own heads [1, 81]. We argue that the range of tasks that olfactory displays can impact make olfaction worth considerating for any analytical environment that extends beyond vision.

4 Olfactory Interface Mechanisms and Applications

Olfactory displays may essentially be described as the superclass of interfaces for information olfactation. An olfactory display unit is a device that is capable of being programmed to create an olfactory stimulus by emitting odorous molecules (chemo-stimulation) or creating a sense of smell (electro-stimulation). In this section, we categorize olfactory displays based on their mechanism of producing an odor stimulus, then discuss existing applications of olfactory feedback in design for information transmission. Broadly, these mechanisms include ultrasonic atomization, atomization through Venturi Effect, evaporative diffusion, and electro-stimulation.

4.1 Ultrasonic Atomization

Ultrasonic atomization systems employ a ceramic diaphragm vibrating at an ultrasonic frequency to convert a liquid solution (often aromatic essence oils) into a mist that eventually diffuses into the surroundings. Atomizers may be embedded in wearables to create personalized olfactory displays [3]. Ultrasonic atomization has also been used in designing tabletop olfactory systems for peripheral awareness [6]. Smell-based interfaces have employed this technology to create interactive peripherals for olfactory tagging [7] and engaging experiences in art museums [62]. Integrating ultrasonic atomization with ultrasonic transducer arrays offers potential for mid-air odor control [40].

Ultrasonic atomization (our mechanism of choice) and atomization through venturi effect (Section 4.2) both begin emitting odor molecules instantly. However, the scent may need some time to travel to the user based on the relative position of the display point of origin to the user with both of these methods.

4.2 Atomization through Venturi Effect

The Venturi effect is the reduction in fluid pressure that results when a fluid flows through a constricted section (or choke) of a pipe. When pressurized air blows past through the orifice of a cartridge holding a solution, it lowers the pressure within the cartridge, sucking up the liquid and converting it into fine mist. The application of atomization through Venturi Effect may be observed in a variety of appliances that many people use in their everyday lives: Consumer goods and industrial appliances, from perfume bottles to air brushes, make use of this principle. Design of interfaces for peripheral awareness have employed this technology in encoding information into smells such as mapping rise or fall in stock market information to distinct smells, or designing reminder systems with a task mapped to a smell [53].

4.3 Evaporative Diffusion

Evaporative diffusion is attenuating the rate of diffusion of a solution through controlling parameters such as air flow and temperature. Air flow may be enhanced by adding a fan. Temperature may be attenuated by placing a heating element to heat up the solution. Vaporization through attenuating air flow has been employed in designing olfactory displays for immersive media—accompanying VR [42] and large displays [80]. Heat-assisted vaporization has also been used in creating scent notifications for peripheral awareness [25]. Evaporative diffusion has a very long delay between events intended to trigger diffusion and the perception of an odor by the user when compared with the other mechanisms discussed here.

4.4 Electro-Stimulation

Electro-stimulation is the direct activation of receptor neurons through controlled electrical impulses. In the case of olfactory stimulus, this would mean that an electrical impulse must be passed directly to the odor receptors on the epithelial tissue deep in the nasal cavity. In other words, an electro-stimulation interface would require that wires be inserted deep into the nose and contact be made with odor receptor neurons. Because there are roughly 1,000 types of odor receptors, developing a method for conveying a consistent class or molecular composition of smell is nontrivial with this approach.

While this area remains less explored because of these practical considerations, there is evidence that the digital stimulation of smell for multisensory communication is a possibility for interface design [39]. There are several benefits this approach relative to the others, as it sidesteps the need for an aromatic solution, which has the potential to present allergy risks to users, and it does not require that the air be cleared of diffused odor molecules to discontinue the stimuli.

Electro-stimulation is instantaneous: The odor receptor neurons are directly stimulated by the display system in real time. However, it is quite invasive, requiring that electrodes be placed inside the user's nasal cavity. It also has a low resolution; in the current state of the art, simulating any specific odor is very difficult [39, 100]. These and other benefits and drawbacks to digitizing chemical senses are described at greater length by Spence et al. [93].

4.5 A Rose By Any Other Name: Existing Olfactations

Even before our coining of the term "olfactation" in this paper, the practice of encoding information in scents has manifested in numerous contexts. The use of odors in VR environments to increase the user's sense of presence is as old as VR itself, dating back to *Sensorama*, the very first VR implementation, patented in 1962 [41]. Outside of the realm of virtual reality, there are numerous real-world examples of designs and methods that use odor to detect or convey crucial information, and we are not the first to suggest that olfaction could be used as a means to augment information visualization [99]. Of the real-world examples relying on smell alone to convey information, the most widespread and widely-known application is likely as a safety mechanism; for example, mercaptan gas, which smells of sulfur, is added to natural gas piped into homes and other buildings to warn those inside if there is a gas leak [66]. Firefighters are trained to use smell on the job to detect the burning of different types of materials to assess the dangers of the scene of a fire [53]. To give less ubiquitous examples of non-visual olfactation displays to convey information about risk, one system uses a buzzing sound and a peppermint scent to alert drivers that they are at risk of falling asleep at the wheel [37]; another system (as mentioned in Section 4.2) diffuses of the scent of mint to represent a rising market, lemon to represent a falling one [53].

More recent examples of information olfactation without corresponding visual interface include *inScent* [25] and Dmitrenko's unnamed prototype [24] for driver notifications using specific fragrances. inScent is a mobile olfactory display, in the form of a necklace, which is evaluated in their user study as a means to alert the wearer when they have a message, remind them of calendar events, notify them of the occurrence of an event (they use the example of a package being delivered), and give them a sense of time passing [25]. Another olfactation display warns the user that they are wasting energy resources [70], and yet another uses scented modeling clay to communicate trends in abstract sculptures [48]. Dmitrenko et al. [24] conduct two user studies in which they explore the mapping of specific scents to convey information about whether the driver of a vehicle should slow down, refill their gas tank, or be aware that they are passing by a point of interest; they find that users are capable of establishing a mental map of semantic messages encoded into specific odors [24].

A meta-analysis of the state of the art in chemical display systems by Spence et al. [93] argues that mixed reality systems, including VR, are the most commercially viable environments for digital scent. In the domain of VR research, early work by Keller et al. [54] was among the first to explore the application of an olfactory display for analytical tasks, specifically in the field of medicine, by implementing a system to detect odors and proposing that an olfactory display be used to increase presence by surgeons who are unable to be on site for the surgery, but who are able to advise remotely. While not strictly analytical in nature, Rizzo et al. [85] and Chen [14] focus on the therapeutic application of olfactory feedback for patients with post-traumatic stress disorder, arguing that the increased sense of presence from olfactory feedback may improve the user's experience and task-oriented outcomes in VR. In general, however, studies that combine visual and olfactory displays for the express purpose of conveying information are not common. To the best of our knowledge, this is the first study that combines visualization, olfactory display, the representation of data for analysis, and a model for the design space thereof.

5 Information Olfactation Design Space

In visualization, a *mark* is a unit of conveyance: A point, line, or area, for example [73]. A visual channel represents the dimensions along which a mark may be parameterized: Position, area/size, shape, hue, color value, and so on, along with temporal transitions of all of the above (motion, for example, meaning a change in position; or growth, meaning a change in size) [73]. Visual spatial substrates are the medium of conveyance–the space in which visual elements exist, the structure thereof, and the mapping of features of the data to be visualized to that space [10].

The olfactory equivalents of marks, channels, and substrates are not entirely straightforward. Foundational cognitive psychology studies investigating the atomic variables of olfaction, for example, do not themselves distinguish between modes and units of conveyance [71, 72]. To mirror the traditions in visualization, this section outlines the design space of information olfactation in terms of its primitives.

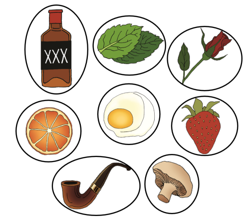
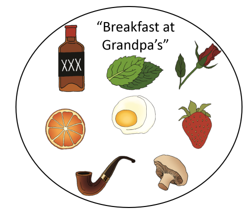
5.1 Olfactory Marks

Olfactory marks are the base elements of the olfactory display for information olfactation. Where visual marks are internally consistent spatial primitives—points, lines, areas, and volumes [73]—we have identified three olfactory marks (Table 2) that must be thought of as existing in two different domains. The first domain is chemo-associative; the chemical composition of odors displayed to the user may be linked to real-world objects as *smell glyphs* based on the fragrance classification model of olfaction (Section 2.2), or it may be a *molecular bouquet* more closely aligned with the chemical topography model (Section 2.1)–a complex cocktail of odor molecules that is either completely fabricated or is simply a mixture of enough glyphs that it becomes difficult to distinguish between them. The second domain is a spatiotemporal one: The air is a vehicle for transporting odor molecules, but it also conveys information about the odor source that is fundamentally inseparable from the chemical composition of molecules it carries. Our proposal of airburst as a mark is based on a more holistic look at the sense of smell as cross-modal (Sections 3.4 and 3.5) and anatomy-dependent (Section 3.2).

5.1.1 Smell Glyphs and Fragrance Classes

Given real-world objects with distinct "natural" odors (e.g., oranges, pine, lavender, and so on), any odor representation of such an object may be considered a *smell glyph*. These glyphs act as an olfactory mark, mapping fragrances to discrete information features. Smell glyphs can be grouped into categorical *fragrance classes* using empirical work clustering together odors by perceived similarity. We base our categorical clusters (Table 1) on empirical and theoretical work by Castro et al. [11] breaking odors into eight discrete groupings (which they refrain from naming, so we take the liberty here): citrus, acerbic-synthetic, leafy, floral, fruity-non-citrus, woody, spicy-smoky-nutty, and heavy-rotten. In this way, distinct fragrances corresponding to real-world smells (oranges, pine, lavender, and so on) may act as a broad (class) or narrow (glyph) olfactory counterpart to visual glyphs.

Table 2: Summary of olfactory marks.

Mark	Description	Example
Smell Glyphs	Odor signatures linked to specific real-world objects may be considered "smell glyphs." These glyphs are clustered into "fragrance classes" of similar scent groups defined by Castro et al. [11]	
Molecular Bouquets	Individual smell glyphs are perceived most strongly upon the user's initial exposure. Continuous exposure to many smell glyphs may result in the user perceiving the stimuli—much as they would a single perfume—as a single bouquet.	
Airburst	The air plays the dual role of a *unit* of conveyance for olfactory information, as well as that of the *medium* of conveyance–i.e., a substrate [10]). The user can control their "sniff cycle," but the olfactation designer can control the intervals of odorant diffusion, among other characteristics of the air.	

5.1.2 Molecular Bouquet

Consider the example given in Section 3.1 in which the scent of motor oil in an orange grove is presented as being more likely to contribute to the formation of an odor-associated memory than the smell of oranges alone. While the smell of motor oil alone *may* be enough to elicit the memory of the event of exposure to these stimuli, the argument might be made that the combination of motor oil and all of the other odors in the air at the time—say, oranges, grass, dirt, and bark—is even more likely to do so. The person exposed to this cocktail of fragrances, rather than picking out the distinct scent glyphs, might simply remember it as being *the smell of the orchard*.

The chemical topography model of perception treats olfaction as a chemo-reception process determined by the differential binding affinities of constituent molecules to the olfactory receptors. While the human nose can effectively detect fragrance classes, it becomes difficult to recognize individual constituents when more than a few individual fragrances are bundled together [53]. Complex combinations of odor molecules may present an opportunity, however, in creating a unique fingerprint for embedding nuanced information views in the user's head. Once imprinted, the unique bouquet may facilitate improved conceptual recall of the information in the view once emitted again, with or without the visualization present.

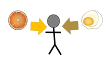
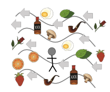
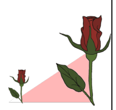
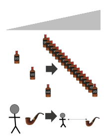
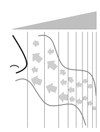
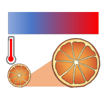
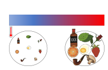
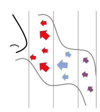
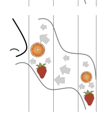
5.1.3 Airburst

Olfaction is how we detect volatile molecules in the air around us. Because of this volatility, there is no olfactory equivalent to a static image. We argue that, with the exception of the direct electro-stimulation of olfactory sensor neurons, divorcing the air carrying odor stimuli from the basic units of conveyance of that stimuli (i.e., considering it to fall strictly into the domain of "substrate") does not reflect the way human beings experience smell. If the "sniff cycle" is a unit of olfaction [55, 97], then we propose an *airburst* as a temporal unit of olfactation: In Table 2, we visually represent airbursts as the individual cross-sections of a directed stream of air that is flowing toward the user–the sections of air falling between the vertical lines dividing the figure.

5.2 Olfactory Channels

Like the visual channels, which control features of visual marks, olfactory channels are characteristics of the olfactory marks which can be adjusted depending on values in the data. In this section, we present five olfactory channels (Table 3): Direction, saturation, frequency, air flow rate, and air quality (or, climate).

Table 3: Summary of olfactory channels.

Channel	Description	Glyph	Bouquet	Burst
Direction	Air burst origin position simulating object location			
Saturation	Odor molecules in the air, by volume			—
Air Flow Rate	The rate and pressure of air flowing at the user			
Air Quality	Temperature, humidity, and other features of the air			
Temporal Pattern [Meta]	The sequence composition of odor views			

5.2.1 Direction (or, Origin Position)

The bilateral anatomy of the nose is a reflection of the underused ability in humans to detect the direction of odors and track them to their perceived origin [32, 81]. By taking advantage of the stereo nature of the nose, the olfactory interface designer can create the impression that objects in the space around them are emitting an odor from a point of origin relative to the user's own position. This could be used to direct user's head to positions in three dimensional space where they are best situated to interact with information encoded for any of their senses.

5.2.2 Saturation (or, Chemo-Intensity)

A solution is a liquid mixture in which the minor component—a solute—is uniformly distributed within the major component–the solvent, often water, for example. The *saturation* of a solution is defined as a measure of the amount of solute—the minor component in a solution, such as an aromatic essential oil—dissolved in the solution . We define the concentration of an aromatic solution in terms of volume fraction which may be expressed as volume of solute divided by the volume of the solution. Early studies in experimental psychology have indicated that people experience distinct perception of three intensity levels (three levels of dilution) of odorants [30].

5.2.3 Air Flow Rate (or, Kinetic Intensity)

Several early empirical studies on the subject of factors influencing olfaction has indicated that the rate of flow of the air saturated with odorous molecules heavily influenced the experience of the participant [72, 94]. A positive change in the flow rate is associated with a positive change in the detection of the olfactory stimuli [56, 71]. To propose an untested hypothesis for future research, it is possible that air flow rate may, by virtue of the cross-modality of olfactory perception, act as an indicator of distance between the user and the source of the odor: In a "natural" setting, an odor may be carried farther by a strong wind. Thus, if the odor molecule saturation remains constant, an increase in the flow rate may be perceived by the user as a greater distance between their nose and the source of the odor. The rate of air flow should be considered an olfactory channel with respect not only to the ability of the user to detect a scent, but also a channel with a potential direct relationship with the user's perception of the space around them.

5.2.4 Air Quality (or, Climate)

Thermoception—the sense of perceiving temperature—is dependent on thermoreceptors found on the skin of the human body, including on the epithelium lining the nasal cavity. A thermoreceptor is a non-specialized sense receptor; specifically, it is the receptive portion of a sensory neuron that codes absolute and relative changes in temperature. Olfaction of distinct odors at different temperatures can convey different information, and (at least in some species of animals), higher temperatures tend to improve odor molecule detection [84]. Humidity, barometric pressure, and CO_2 concentration have also been shown to affect olfactory perception [60, 64]. Temperature, humidity, and other non-olfactory qualities of the air carrying the odor may be considered an auxiliary channel in information olfactation.

5.2.5 Temporal Pattern (or, Scent Animation)

Perception of stimulus often involves a two stage process within the human nervous system: An analytical categorization of stimulus into similar features or patterns (spots of light, frequencies of sound), and a configuration process that determines the perception (the sight of a house, the voice of a human) [102]. We propose the temporal pattern of a mark (or collection thereof) as an olfactory *meta-channel*: The olfactory equivalent of mark animation (channel change over time) created by moderating sequences of "frames" in an olfactory "view." The *temporal pattern* of an olfactory view is the set of interval frequencies and durations of diffused odor and auxiliary stimuli (e.g., temperature), and the transitions performed to modify them over time.

5.3 Substrates of Olfactation

As with information visualization, the substrates of information olfactation are spatial in nature. The chemo-topographic mapping of the world around the user constructed via olfactory perception is implicitly a spatial one. We use it to gather information about the place we are situated in and the events that have occurred or will occur in them (rain, for example [50]), as well as to detect and locate objects in that space (consider the first reaction a person may have to a foul smell in their car or house, for example).

While we do not claim to have an exhaustive list of all possible substrates for the purpose of designing the olfactory interface, we do propose a few general approaches to mapping data to spatial substrates.

5.3.1 Dimensionality

We have thus far discussed our olfactory marks in the context of its conceptual dimensions—the dimensions of the data—as if smell glyphs represent a single dimension, and molecular bouquet represents a multitude of dimensions. For the purposes of the user's experience, the reverse is true: A bouquet may contain the mapping of many individual variables as smell glyphs, but when taken as an ambient part of the environment, it is itself perceived as only one dimension. As part of our passive sniff cycle, we unconsciously reduce all dimensions down to one [97]—until we need to locate a single odor by engaging in directional active sniffing [91]. This is where spatial substrates (and spatial dimensionality) become most relevant.

In our 2D implementation, we create a spatially one-dimensional olfactation corresponding to a two dimensional visualization. In our VR implementation, we use air flow direction and the position and orientation of the user relative to an object in a VR environment to, for lack of a better word, *spoof* the user into perceiving a spatially three-dimensional olfactory substrate. However, the substrate of an olfactation need not be exclusively spatially one- or three-dimensional. In *Smelling Screen*, Matsukura et al. [68] implement a two-dimensional spatial mapping featuring olfactory signals localized to within different regions of an LCD screen. By blowing olfactory molecules from four corners of a monitor, they were able to create smell regions on the screen. Similarly, in *Smellmap*, McLean [69] projects a cartographic map of Amsterdam onto a 2D plane of regions coated with 11 custom fragrances based on smells described in a spatial survey.

5.3.2 Structures

As with information visualization [10], information olfactation is at its core the mapping of features and entries in the data to be olfactated to its olfactory structures. *Olfactory structures* are the olfactory representations of spatial substrates, temporal encodings, olfactory marks, and the features thereof to be controlled by the olfactory channels. In the VR example described in section 7.1, we map our olfactation to the same spatial substrate as our visualization. In our 2D examples, we chose a *single* spatial dimension, which does not match the 2D visualization. These decisions, chosen for the simplicity of illustrating our model, are not proscriptive: We encourage future researchers in the visualization community to use olfactation, and to explore and evaluate a variety of mappings.

5.3.3 Airburst Revisited (as a substrate)

We have argued that the air, which is necessary as a medium of conveyance for olfactory stimuli (again, excepting direct electrostimulation), may be viewed as an olfactory mark–divided into segments of arbitrary length as a unit of olfactation. With that said, an airburst cannot be removed from temporal encoding: The number of units of an airburst containing the odorant (frequency) and auxiliary stimuli (temperature, humidity, etc) and the rate at which they are connecting with the user (flow rate) are measures of time. Likewise, the spatial nature of the airburst cannot be ignored: Excluding electrostimulation and nose-to-the-ground scent tracking, the direction that the air is flowing onto the user is a determinant of the sense of spatial encoding. Even in our prototype's one-dimensional mode, the user experienced the flow of air from a direction in front of them, albeit a stationary one. The airburst is not *only* a vehicle for transporting odor molecules, but a vehicle it is nonetheless.

6 VISCENT IMPLEMENTATION

Our infrastructure consists of a visual-olfactory display system, a VR headset, a display unit and a workstation. The olfactory display system is controlled by interactions with the visual display system. The system allows switching between scents, altering the temperature of the air carrying the scents, changing the burst frequency of the scents and the direction of air flowing at the user.

6.1 Olfactation System Overview

Our implementation includes a multi-scent olfactory display system that can be converted between supporting visualizations in a two-dimensional view, and those in a VR environment. Apart from delivering aromatic scents, the 2D visualization mode is equipped with air temperature variation based on user interaction. For the sake of reproducibility, we based our desktop olfactory display around the principles described in Herrera et al. [42], with simplicity and cost in mind, although we have extended it to meet the requirements of our model of olfactation by using ultrasonic diffusers allowing the user to select different smell glyphs, and by using a solenoid-controlled airflow through a Peltier module to alter the temperature of the airburst. The visualization in VR mode incorporates a head-mounted display (HMD) augmented with an array of ultrasonic diffusers with bi-directional airflow output for directional tracking. This gives the user the impression that a three-dimensional olfactory spatial mapping exists around them. In all implementations, we have set burst frequency to intervals of nine seconds ON (aromatic atomization activated), nine seconds OFF (aromatic atomization deactivated) in order to avoid habituation.

6.2 Olfactory Display System

The olfactory display system consists of six ultrasonic atomizers attached to essence oil cartridges. Upon actuation, a piezo-electric disk vibrates at an ultrasonic frequency, atomizing the aromatic solution. This is released out in the form a mist. The cartridges sit on a table top display unit for the 2D visualization mode whereas the VR visualization mode holds tiny cartridge pods attached on to a HMD. The table top olfactory display unit employs a diffusing fan that blends the odorous mist with air producing a diffused flow directed at the user. It also employs a peltier based air heating system to produce a stream of thermally controlled (heated up) air. An air compressor feeds pressurized air into the peltier based heating system to produce a warm air jet venting alongside the diffusing fan. This table-top display houses the control unit, employing an Arduino Mega 2560 (based on ATmega2560 microcontroller) that controls and activates each of the systems. The VR visualization mode employs a bi-directional air stream output, attached to either sides of the HMD. This bi-directional air stream runs on the pressurized air delivered by the compressor. All the pneumatic channels are controlled through electromagnetic solenoid valves.

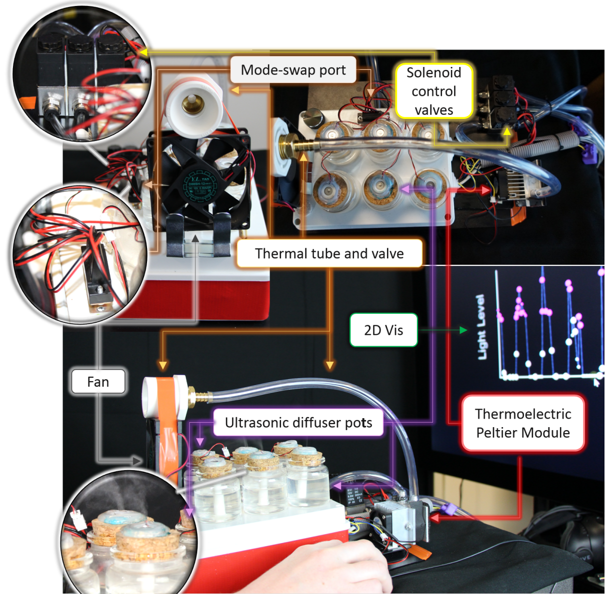


Fig. 2: viScent and the 2D display: magnified view of each of the primary components on the prototype depicting the ultrasonic atomizers, diffusing fan, pneumatic solenoid valves, Peltier-based thermoelectric heating system and the accompanying 2D visualization.

6.3 Visual Interface and Interaction

Research implementing network graph visualizations for immersive, collaborative analytics has found a task speed and movement balance advantage from using HMDs over those using CAVEs, while CAVEs have an advantage in communication between users [16]. Because our implementation was not collaborative, we use this as the basis for our decision to use a HMD over a CAVE. In the 3D VR environment, grabbing a node with a controller triggers the diffusion of odor. In the 2D network graph view, clicking a node acts as the diffusion trigger. In the 2D line and point chart, clicking a point diffuses odor and may switch the thermal air flow on or off. The visual interface was designed in Unity, allowing for easy integration between the Arduino control and objects in the view.

7 EXAMPLES

As stated in Section 1, we are proposing information olfactation largely as a supplement, rather than a replacement, for information visualization, and so our examples all include basic visual components. Our examples include 2-dimensional and 3-dimensional force-directed network graph layouts [26], both of which used the SNAP Bitcoin dataset [61], and a 2-dimensional line and point chart using multivariate building air quality time series data [95]. Rather than presenting our examples as a standard, we use them as a call to action:

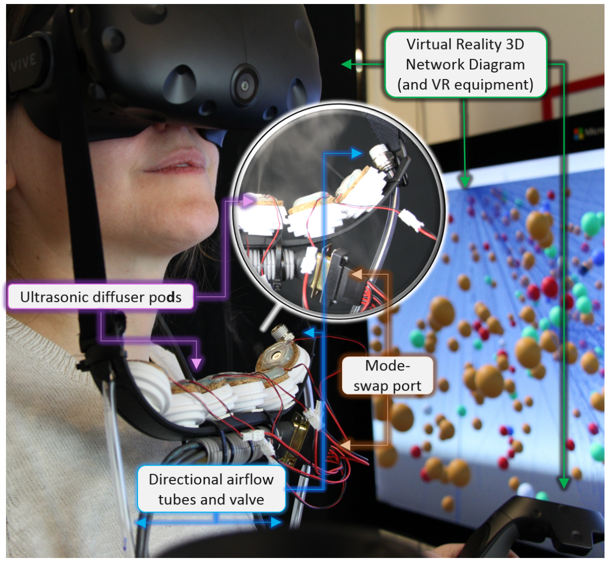


Fig. 3: viScent and VR: a magnified view of ultrasonic atomization in play and bi-directional air stream nozzles for creating an olfactory spatial mapping.

Our mapping of data to visual and olfactory marks and channels is not proscriptive, but a proof of concept to be improved upon.

7.1 VR 3D Network Graph

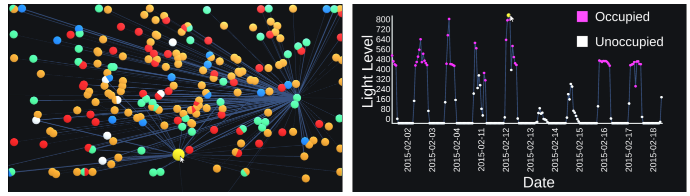
In light of recent work arguing that immersive environments are the most practical means for introducing taste and olfactory displays [93], and the formation of the domain of immersive analytics [13], we have opted to present one example in VR using the viScent HMD. While there are other papers that offer more sophisticated implementations of information visualization in VR environments [15, 104], the purpose of our application was to act as a simple example of a data structure with a well-explored spatial encoding where olfactation could augment the user's analytical performance. In this example, we used visual channels and olfactory marks to complement each other: Each node represents an entity, its color and smell glyph are determined by its average transaction rating profile (binned into six quantiles, corresponding to our number of smell glyphs), and each link represents a Bitcoin transaction between two entities in the SNAP dataset [61].

7.2 2D Network Graph

To isolate the ways that the user's experience of olfactory stimuli differ in a three dimensional workspace relative to a traditional, two-dimensional one, one of our two visual examples is the two-dimensional sibling of our VR network graph, using the same dataset and the more traditional 2D force-directed network layout. In both our 3D and 2D network visualizations, we chose the arbitrary pairing of pear-black, lemon-orange, leather-red, coconut-white, lavender-blue, and peppermint-green in order of quantile (low to high) to represent our nodes in smell-color combinations. Unlike the 3D view, nodes in the 2D network were not only mapped to smell glyphs, but also to air burst temperature, which was not mapped to a corresponding visual channel: Entities who mostly transacted during the weekend were cool, and those who transacted mainly during the week were hot.

7.3 2D Line and Points

While the purpose of this paper is not to explore the entire domain of information visualization with respect to the areas that olfactation may play a supportive role, we did want to include a multidimensional dataset other than the network graph data used for our VR visualization. We selected building air quality data recorded over the span of several days because features related to attributes of the air seemed an appropriate fit for the purpose of an implementation in which air itself is a display structure [95].



(a) Force-directed network graph layout. (b) Line and point chart.

Fig. 4: Traditional 2D visualizations controlling an olfactory display.

In this example, we used glyphs to represent a variable that was not represented visually: CO_2 levels. As with our network example, we binned the observations into six groups (the number of smell glyphs we built into our prototype) based on the quantile they fell into for the variable mapped to smell glyphs (CO_2 level). We mapped temperature to the actual temperature in the building, although our prototype only allowed for a high/low switch (temperatures in the upper half of the distribution were encoded as hot; the lower half was encoded as cool).

8 Discussion

Information olfactation is a model for extending the user's immersion in visual exploration of information, supplementing visualization with multi- and cross-modal feedback that takes advantage of users' sense of smell based on the researchers' mappings between data and olfactory structure. Olfaction is a more subtle sense than vision: We process odor far more heavily than imagery before it even reaches our brain, which then proceeds to attempt to suppress conscious awareness of the odor until a cycle of active sniffing is voluntarily initiated. With that said, it presents clear benefits in terms of information recall, ability to affect the user's mood and emotions, feature signaling where clear vision is impossible or visual attention must be relegated elsewhere, and in augmenting the immersion of the user.

8.1 Limitation: Not Everyone can Smell

Anosmia, the inability to detect fragrances, is a symptom associated with a wide variety of causal factors. These include conditions affecting the brain, like meningitis or Parkinson's disease, congenital conditions such as Kallmann syndrome, lasting damage of the mucosa or olfactory receptor neurons (often caused by compounds that pass through the nasal passage like cigarette smoke or nasal sprays [2, 96]), and inflammation or short-term sinus congestion and blockage associated with temporary conditions like influenza or the common cold.

Another potentially limiting phenomena, known as odor fatigue, olfactory adaption, or affective habituation, is the loss in distinctive perception of an odor due to prolonged exposure. While there is evidence that 9-second intervals of a given fragrance (punctuated by an absence thereof) prevent habituation [79], this is still an under-explored topic.

On the other hand, not everyone can see. The use of a different sensory modality such as smell has a particular advantage for visually impaired users, who are partially or completely excluded from using traditional visualization. For users with no vision, a display system that takes greater advantage of the other senses may augment the experience of working with data in creating successful perceptual pathways through sensory substitution and sensory augmentation. It is also worth noting that, in some instances (e.g., loss of smell due to infection), anosmia can be combated through training [18].

8.2 Scents and Sensibility

While our approach in this paper is in many ways mirroring the field of information visualization, we want to emphasize that we are not in any way proposing that the topic of information olfactation will eventually supersede infovis. There is a reason why visualization is such a powerful information communication mechanism, and that is because our visual system is our most important, highest-bandwidth, and most accurate sense. The sense of scent, as we have discussed at length in this paper, has only a fraction of the resolution, capacity, and flexibility as vision. In other words, even if we had wanted to, there is little practical outlook for creating data-rich applications where the olfactory display is the only display.

Rather, as our examples have already illustrated, we see information olfactation as a **complement** rather than as a replacement for information visualization, where scent can provide strong, recognizable, and even visceral responses to information displays. Our designs and findings in this paper have all focused on the use of olfactory marks, glyphs, and channels in support of the visual representations, or in support of situations where the user cannot look at, or cannot see the display. We continue to think that this will be the primary—and perhaps even the only—effective use of information olfactation in the future.

8.3 Anecdotes from our Examples

We found the use of both the 3D and 2D approaches we selected as examples to inform our sense of how our olfactory experience, not just our visual experience, might be affected by the change in spatial dimensionality and immersion in the visual environment, and also how our experience may be affected by the auxiliary channel of climate and air direction. We were validated in gaining a sense that the perception of air directionality aided in our ability to locate selected nodes in the VR 3D network. The cross-modality of olfaction also seemed to affect our experience: Being able to see which odors were being diffused in 2D made it easier for us to perceive differences between scents.

While we have avoided making any recommendations for design thus far, one feature that we omitted from our example cases has inspired one obvious suggestion for future studies: As with visual structures, olfactory structures must make explicit the mapping between variables in the data and their olfactory encodings. In its present state, this mapping was not made explicit during use in our examples, which we found to have a detrimental influence on our ability to discriminate between glyphs. In fact, for the examples given in Section 7, our visual and olfactory encodings of the data were not carefully selected.

The purpose of these examples was not to design orthogonal and exhaustive olfactory implementations of canonical visualization techniques. Rather, we included them to explore interesting point designs in the space defined by our paper. More rigorous and structured exploration is left for future work. It may, therefore, be considered a challenge: Do better, we dare you!

9 Conclusion and Future Work

In this paper, we have introduced the design space of *Information Olfactation*, its marks, channels, and substrates, along with a high-level task taxonomy for design, as a supplement to information visualization and immersive as well as ubiquitous analytics. As a proof of concept, we have extended our theory to application in viScent, our implementation of most of the olfactory marks and channels for analysis outlined in our model of information olfactation. In the future, we will extend our implementation to explore the marks, channels, and substrates described in the design space of olfactation. Beyond our prototype, a clear general direction for future work is in domain application and user studies of visual-olfactory implementations. Further refinement of olfactation techniques and their incorporation into visual-olfactory systems based on findings from user studies is another, longer-term opportunity for picking low-hanging research fruit.

One measure that is common in the literature surrounding olfaction, but not included in our model of information olfactation, is that of *hedonic scale*. The work by Obrist et al. [78] (noted in Section 3 for their introduction of categories of user experience in olfactory interfaces) and a later study extending it by Dmitrenko et al. [23], are heavily influenced by readings on hedonic measures. The perceived pleasantness of an odor is a fairly subjective one [22], but there is some evidence from studies using scent to augment the experience of driving automobiles that "good" smells improve user task performance relative to exposure to unpleasant or no specific olfactory stimuli [24, 83]. While this makes it an inappropriate olfactory channel analogous to the aesthetic merit of visual composition, it also, like visual aesthetic, should be taken into consideration when designing the olfactory interface; design recommendations around this metric therefore *would* be appropriate for future studies.

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