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Making Scents

Aromatic Output for HCI

By Joseph "Jofish" Kaye
Culturally Embedded Computing
Cornell Information Science
jofish@cornell.edu

Smell is an underused sense in human-computer interaction (HCI). In our daily lives, smell tells us whether food is safe to eat, if a fire is breaking out in the next room, and, as evidence increasingly shows, if we find a potential mate attractive [8]. In HCI, however, smell is an almost entirely unexplored medium. There are reasons for this: technical difficulties in emitting scent on demand, chemical difficulties in creating accurate and pleasant scents, and issues of research focus and direction. However, it is now possible to purchase off-the-shelf, easily controllable hardware for aroma output, and incorporating scent into HCI is now comparatively simple.

The vast majority of work in HCI involves our senses of sight and hearing, with occasional forays into touch. Much of HCI has assumed a single user at his desk with a single screen, controlled by a single keyboard and mouse. The vision of ubiquitous computational power has led to a corresponding emergence of ambient and calm media: efforts exploring distributed input and output for distributed computing. Scent is an excellent medium for ambient or calm display; a scent can "move easily from the periphery of our attention, to the center, and back" [18]. Users rapidly acclimate to an ambient scent, but a change in aroma calls attention to itself. Although inappropriate for rapidly changing information, and limited in bandwidth, our sense of smell is well evolved, accurate, and valuable as an interface.

Why Smell Is Difficult

To understand the problems and opportunities of scent emission, it is necessary to understand the basics of how our sense of smell works.

Physiology and Chemistry of Smell

We have approximately a thousand different kinds of olfactory receptors in our nose, and it is thought that each can sense a single kind of chemical bond in a molecule [17]. It appears this is the fundamental mechanism of smell; for example, a carbon-nitrogen triple bond (C_N) vibrates at a characteristic frequency, which to us smells of bitter almond. We have about a thousand different kinds of receptors in our nose, each tuned to a different chemical bond [10].

Compare this to vision, in which we have only four different kinds of receptors-red, green, and blue cones plus rods. It's therefore comparatively easy to organize the full palette of colors into a three-dimensional space. Doing the same with smell would take a thousand-dimension space. This is the fundamental problem of producing arbitrary scents on demand.

The complexity of this problem is such that the science of smell has not even been successful in creating a rigorous, systematic, and reproducible classification scheme for smell. The difficulty is that we have no good abstract or higher-level categories, other than the smells themselves. What does mint taste like? Well...mint. Higher level categories, like "floral," merely indicate "this set of smells are found on flowers." Even that category has holes; many people find the scent of daisies unpleasant and would not describe it as floral if they were smelling it without seeing the flower itself in front of them. It's like trying to develop a system of color classifi-

Figure 1a. Solenoid-activated perfume bottles

cation by referring to red objects as "fire-engine colored" or green objects as "spinach-colored."

Human Olfactory Bandwidth

Previous work has attempted to explore the characterization of olfaction in terms of bitrate and bandwidth. Smell researchers refer to smell *quantity* and *quality* as the metrics in measuring bandwidth. Quantity refers to the number of levels of intensity it is possible to sense, and quality refers to the number of different smells it is possible to sense, not a measure of scent verisimilitude.

Quantity: How Much?

Engen and Pfaffman [5] looked at judgments of odor intensity and attempted to define the bandwidth of odor in terms of information theory. They used four simple scents, in which the scent is provided by a single pure molecule, and diluted the scents to varying degrees: For each set of diluted scents, subjects attempted to arrange the samples in order of intensity. The conclusion was that subjects could determine approximately 1.5 bits of information, or three categories, before accuracy rates dropped to chance.

However, the writers did not include zero as a bit; their figure of 1.5 bits was arrived at by observing that subjects could arrange three bottles containing successive dilutions of 100 percent, 50 percent, and 25 percent odorant in order successfully, and that accuracy decreased after that point; it was assumed that subjects could distinguish between 0 percent and 25 percent solutions of a scent. Counting that zero point, we would describe this result as meaning subjects could distinguish two bits or four categories of smell intensity. This can be thought as measuring the existence of a smell as being *none*, *weak*, *moderate*, or *strong*.

Furthermore, the levels of those intensities vary extensively, both across the population and across individuals; fluctuations in individuals studied over time have been shown to be as much as the variation in a population as a whole. In addition, we become acclimatized to scents around us rapidly. Studies have shown that partial, if not total, adaptation occurs in under a minute [10]. Therefore, it is important not to rely on scent intensity for any information display.

Quality: How Many Smells?

Engen and Pfaffman [6] also investigated the number of smells subjects could sense. Their results were that subjects could identify only 16 smells reliably, or four bits of information. However, there is clearly conflicting evidence that perfumers and flavorists can identify thousands of smells, and it seems not unreasonable that a comparatively untrained subject would recognize at least dozens.

More recent work has shown that significantly better results can be found when the scents tested are not pure single molecules, like those used by Engen and Pfaffman, but mixtures of molecules making up a smell—coffee, rather than amyl acetate, for example. However, it turns out that the primary problem with identifying different kinds of smells is naming.

For example, it is hard for subjects to remember a given smell that they have been told to label “fishy-goaty-oily”; when the experimenter suggests the name “leather,” there is a far higher recognition potential on subsequent exposures to the scent [10].

Smell Math

Whereas combining different scents to convey information is more useful than attempting to manipulate intensities, mixing aromas can have unpredictable effects. Many lemon-scented products contain citral, an equal mixture of neral and geranial, easily grasped as a unitary smell of “artificial lemon scent.” However, a mixture of rose and mint is easily distinguishable as two distinct aromas, and experts or even enthusiastic amateurs can distinguish dozens of different aromas in a wine. This is important to consider in choosing scents for information display. While it has been conjectured why various scents appear to combine when smelled together whereas others remain distinct, it is necessary to try a given combination to determine the effect.

Olfactory Bandwidth: Conclusions

The upshot of our abilities and limitations in olfactory bandwidth is that attempting to convey information through scent must rely on the *qualities*, not the *quantities*, of the scents. Intuition suggests that increasing the intensity of the stimulus increases the significance of the message: A very bright flashing light is more important than a dim flashing light; your car making a loud noise is more expensive than your car making a quieter noise. Our inability to sense levels of a scent, and variability in so doing, precludes this from being a meaningful metric in olfactory display. Information must be displayed by the presence or absence of a scent.

Creating Scents: Why Fake Smells Smell Fake

Because of the absence of a small group of smell primaries, any currently available system for computerized scent output will rely on having a small selection of already mixed scents that can be emitted on demand. The degree of precision required in mixing a scent precludes on-the-fly mixing with most current technologies, although this is potentially possible with the nanoliter control that inkjet-type systems could provide, or similar control as implemented in commercial mixing systems, such as that developed by Bush Boake Allen [15].

Figure 1b. Solenoid-activated perfume bottles

A Word on Electronic Noses

A variety of attempts have been made over the past 50 years to develop an electronic nose capable of detecting and recognizing smells. This article is not the place for an overview of these technologies, but in considering an output device it is important to consider the corresponding input. These devices use a set of polymers, each of which bond to varying degrees with different molecules, producing characteristic changes in electrical resistance. A variety of electronic noses are used in research and manufacturing. Artificial noses have not come close to the accuracy and versatility demonstrated by our noses, let alone those with more specialized olfactory apparatuses, such as dogs.

Technologies

Fundamentally, there are only a few methods to get scent into the air from a source. The control side is comparatively simple: The computer, be it a full-featured desktop machine or a simple embedded chip, sends a signal out through a serial or parallel port to a relay, which turns on the output device itself for a designated period of time.

To produce the greatest amount of scent diffused in the shortest period of time, one method is to spray the actual liquid scent into the air, in a manner similar to that of an airbrush, using a supply of compressed air to provide the impetus. This approach is currently in use in prototypes built by British Telecom, and was used in the inStink project at the MIT Media Lab. Although it is easy to build initially, control over output quantities requires careful calibration, and the apparatus, requiring an air compressor or source of bottled compressed air, is bulky and awkward.

It is also possible to use bottles of scent, similar to standard perfume bottles, with the head pressed down by either solenoids or a motor-controlled cam (see figures 1a and 1b). The advantage of these devices is that they provide a useful amount of scent in a short time. However, control over scent quantities is limited to multiples of the amount of scent sprayed out in a single press. It is possible to use either sealed aerosol scents, in which the propellant is provided with the scent, or pump-action sprays, which require a greater activating force, because the activating push must provide sufficient energy to propel the aroma into the air. Wall-mounted bathroom fragrancers frequently use this type of device.

For more accurate control, it is possible to use inkjet technologies to spray scents into the air. These technologies allow nanoliter control over quantities output; this has been the subject of research by the author with Hewlett-Packard and, extensively, by AromaJet (www.aromajet.com). However, inkjet-based systems require further research to provide practical systems for frequent use.

A different approach is to use heat to increase the evaporation constant of a scented oil or wax, contained in a pot or wick, which can then be wafted out to the user with a fan if desired. Without the fan, this is the approach used by TriSenx's Senx Sampler device, and by Osmooze's P@D. The AC2i Olfacom device uses a similar technique, except it uses polymer beads to encapsulate the scent, rather than a wax or wick.

Similarly, waxes can be made volatile enough to evaporate without the aid of heat, needing only a fan to waft the scent into the room; this is a technique used by devices made by companies such as Rubbermaid for wall-mounted bathroom fragrance diffusers. The low power requirement means they can be run off a single D-cell battery for several weeks, enabling their installation without additional wiring.

Another possibility for encapsulating scent is to use a scratch-and-sniff system, which uses a mechanical device to scratch the surface, thereby releasing scent. Again, this can be with or without the aid of a fan to aid diffusion into the room. Whereas this has been the theory behind several patents, and at least one startup (Israeli company ScentIT, acquired by Digiscents), currently no commercial devices on the market incorporate this technology.

When scenting larger spaces, it can be useful to incorporate a scent output device based on one of the foregoing into the air conditioning or ventilation system of the space to be scented. This is a method used by ScentAir, Aromasys, DaleAir, and others.

In summary, there are several technologies for emitting a scent under computer control; it is important for researchers interested in adding such devices to their projects to consider the quantity of scent they wish to emit, the duration of the output and project, and the number of users to whom the scent output will be directed.

Uses of Controlled Scent Output

To tell the story of the history of computerized scent output, I've separated the field into three categories: scent emitted in conjunction with other media, scent emitted for its own sake, and scent emitted to convey information other than the scent itself, or "olfactory display."

Scent to Accompany Other Media

Scented Films: In the 1950s, cinema owners were concerned about the increasing tendency of their clients to remain at home in front of the television, rather than visiting the cinema. There was a rush to create technologies to lure customers back to the cinema: 3-D glasses, vibrating seats, and, of course, scented films. The 1959 travelogue *Behind the Great Wall* was released in "Aromarama," a system that piped scents through the cinema's air-conditioning system. The next year, *Scent of Mystery*, starring Elizabeth Taylor, was released in "Smell-O-Vision"; clues to the identity of a murderer were given by aromas piped to each individual seat.

These efforts were not successful: *New York Times* film critic Bosley Crowther summed up popular opinion when he wrote "If there is anything of lasting value to be learned from Michael Todd's *Scent of Mystery* it is that motion pictures and synthetic smells do not mix" [4].

Scented Virtual Reality: Inventor Morton Heilig was inspired by the same impetus that resulted in Aromarama and Smell-O-Vision: to lure customers away from their televisions. He developed Sensorama, an immersive virtual reality (VR) motorbike ride, in a form factor resembling an arcade game. Heilig saw Sensorama as the future of cinema, an immersive experience, complete with nine different fans to simulate the wind blowing on the user's face, a vibrating seat to simulate driving over cobblestones, and the aromas of jasmine and hibiscus as the driver passed a flower garden, or the scent of baking pizza as one passed by an Italian restaurant in Brooklyn [12]. Sensorama never received the attention or funding necessary to scale up to commercial success, although Heilig continued to patent improvements over the next decade.

Another interesting example of the use of olfaction in virtual reality is the firefighter training work developed by John Cater at the Deep Immersion Virtual Environment Laboratory at the Southwest Research Institute. His team built a backpack-mounted firefighter training device, with microencapsulated scents delivered through the oxygen mask that is standard firefighter equipment. This provides very tight control over scent qualities and quantities: "Olfactory output is...completely proportional from a hint of odor to a stench that makes you want to rip the mask off..." [20].

Very few uses of smell in VR have reached the heights of Sensorama. Perhaps the current leader in the field is Digital Tech Frontier (www.dtf.net), which provides a variety of immersive VR setups that can include scent output for trade shows and custom demonstrations.

Scented Computers: Web Sites and Games: In November 1999, *Wired* magazine published an enthusiastic and widely read article extolling the potential of Digiscents' iSmell system [11]. The reporter was clearly impressed by the sequence of scented movie clips designed by Macromedia founder Marc Canter. Two clips for *The Wizard of Oz* involved the aroma of cedar as Dorothy and friends entered the forest and the scent of wood smoke as the Witch stirred her potion over a fire.

Digiscents pinned their hopes on scenting Web sites and games: the whiff of aromatic vodka as you visit the Skyy Web site, or the scent of gunpowder as you fragged an alien in Quake. Digiscents' strategy was to develop the software standard for computerized smell output and license it to hardware vendors. Plans were foiled when no hardware vendors ended up developing such a device, and Digiscents failed to produce its own solution or find a viable alternative on the market. Digiscents folded in April 2001.

Several other companies are now producing technologies in this space with more commercial success, including Olfacom, TriSenx, and aerome; all have equipment that may be of interest to the HCI researcher interested in scent output.

Scented Spaces: Controlled output of artificial scents has been used at museums such as the Bow Street Old Whiskey Distillery in Dublin, the Natural History Museum in London, and the Jorvik Viking Museum in York to provide appropriate ambience. Interestingly, evidence shows that smelling these scents again can help subjects remember information presented in the exhibits [1].

Various companies have experience providing systems aimed at scenting large spaces, and their expertise is valuable in large-scale scent-output installations. ScentAir and AromaSys both have extensive experience in commercial systems. There are also several examples of using aroma for artistic installations, such as Pletts Haque's *Reactive Spaces*, which uses scent and color to define areas within a space (www.p-h.org.uk/rs.html) or Alex Sandover's *Synesthesia*.

Scent for Its Own Sake: Other systems have focused on the controlled release of scent for its own sake, such as in kiosk applications for perfumes and for other notably scented products, such as wines and foods. Companies such as ScentAir, aerome, and Olfacom have built several such systems for a variety of clients. An alternative approach is Jenny Tillotson's work with wearable scent-output systems, which explores health, wellness, and emotional applications of scent output worn on the body [16] (see figure 2). Her most recent work, Scentient Beings, aided by aerome AG, releases different scents over the course of day. (www.smartsecondskin.com)

Summary: Research in computerized scent output for a variety of applications is significant, although it has been spread out across disciplines and industries. A major stumbling block has been the difficulty in purchasing systems for turnkey use; it will be interesting to watch research progress as such devices become readily available and affordable.

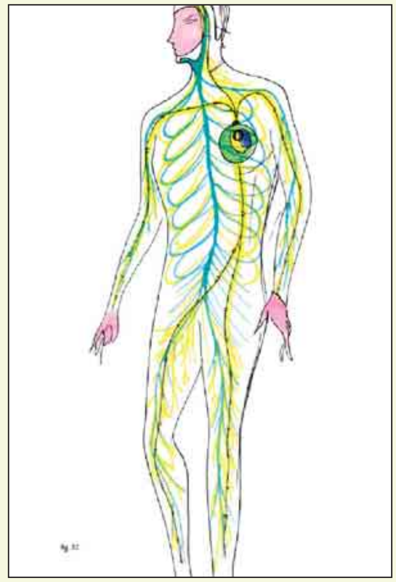

Figure 2. Wearable scent-output systems

Symbolic Olfactory Display

Imagine a computer system that could output scents as easily as our current systems output sound and video. Some users would no doubt be delighted to smell alien flesh burning as they fragged their way through the latest version of Quake. However, to develop a system useful for more extensive human-computer interaction, it is necessary to abstract the scents from their referents. For example, to use icons and windows and pointers, it is necessary to ignore the fact that they are made up of dots of red and green and blue. Similarly, an interesting situation arises if we allow the assignment of arbitrary values to scents: in an appointment book system, the aroma of roses could mean "pick your wife up from the station," and a whiff of orange greeting you in the morning could mean "relative's upcoming birthday-send a card today," if you so chose.

Scent As Abstract Information Display: Theory

The notion of using smell to display abstract information is comparatively novel. A scent is inherently linked to its origin or referent partly because of our systems of categorizing smells. However, in the manner of the development of earcons and auditory icons [2] it is possible to describe smicons and olfactory icons [9].

We can define an "olfactory icon" as a scent output to convey information—where the scent is environmental and semantically related to the information to be conveyed. For example, releasing the smell of gunpowder when a shotgun is fired in Quake would be an example of an olfactory icon. By comparison, a "smicon" is a scent used to convey information that has only an abstract relationship with the data it expresses. For example, the release of the scent of wintergreen each day at noon by an olfactory clock would be a smicon. (See [7, 9] for more details.)

Like any new medium, olfactory display has started by copying other media currently in existence. These examples show a number of uses of symbolic olfactory display but are far from exhaustive.

Incense Clocks: Japanese and Chinese cultures have a long tradition of using incense clocks. When lit at one point, the incense would burn steadily, marking time. A refinement introduced by the Japanese in the *koban-tokei* was to use differently scented incense tablets; tablets were placed in a regular order and would each burn for an hour at a time. Such clocks were used in Buddhist temples, and with a sniff the priest could tell the current time to the hour.

Scent: A more recent example of symbolic use of scent comes from Rob Strong and Bill Gaver's paper [14] describing three systems for minimal, expressive communication, *Feather, Scent, and Shaker*. *Scent* was a metal bowl containing essential oil that could be heated under digital control, releasing scent within. The authors proposed that heating could be activated by a homesick traveler, so that "a scent fills the home space to indicate the traveler's thoughts, lingering for a time before fading away."

inStink: inStink explores the application of scent to presence awareness and, loosely, to computer-supported cooperative work, by attempting to connect two spaces using scent. inStink attempted to display the activity in a kitchen in a remote space, such as another kitchen. In the kitchen, a rack of electronically tagged spice jars provides the input: the essential oil corresponding to the spice used is sprayed into the remote space. If the cook were preparing a curry, then the remote space might be scented with aromas of garam masala, cumin, and turmeric. Conversely, if the remote space smelled of cinnamon, nutmeg, and ginger, the chef might be making apple pie, or spice cake. The intent is not to provide a one-to-one mapping of input to output, which current technology is unable to achieve, but rather to leverage the abstraction between the spice scents and the recipe used to provide a sensation of connectedness and awareness [9].

Scent Reminder: Scent Reminder is an extension to Microsoft Outlook that enables users to set up smell alarms; if they need to pick up their children from school at 3:30 p.m., Scent Reminder can start to waft the aroma of baby powder across the room at 3:00 p.m. as a gentle reminder of the upcoming appointment [9] (see figure 3).

Dollars & Scents: Dollars & Scents used scent to display the classic ambient output: the state of the stock market. Mounted just inside the building entrance, visitors would smell mint if the Nasdaq was up more than half a percent and lemon if the market was down [9].

Honey I'm Home: Honey I'm Home is similar in essence to Strong and Gaver's Scent: a distant loved one can trigger it to emit a whiff of a single scent, "like blowing a kiss across the Internet" [9].

Building Scented HCI

HCI researchers interested in incorporating scent into their projects have several options open to them. Prices range

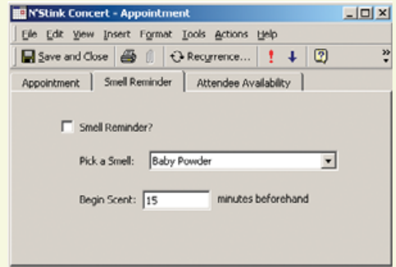

Figure 3. Microsoft Outlook's "Scent Reminder"

from $25,000 or more for a large-scale system suitable for scenting an auditorium or theme-park ride to $50 for a simple, serially controlled, single-scent, desktop device.

The first step is to decide on the parameters: What information should be displayed, what scents should be used to display it, and to how many users should the information be displayed.

The question of what information should be displayed is fundamental. Olfactory display is useful for slow-moving, medium-duration information-or information for which an aggregate representation is slow changing. For example, Dollars & Scents maps the volatile Nasdaq index but does so by tracking only if it is up or down. Remember that introducing another instance of the same scent into a space may not be perceived as a new event by users in the space.

In olfactory display, it is generally advisable to minimize the number of different scents used. It is more useful to build an initial system with one, two, or three scents and then work up if necessary than to start out with a dozen different aromas. Once again, it is not possible to rely on scent intensities to convey information; our sensitivity is too low, and there is too much variation across societies and across individuals to make that an option. Mixing two scents to convey information is often feasible, but researchers are advised to test scent combinations carefully to confirm that components are distinguishable [7, 9].

The choice of which hardware solution to use is determined most significantly by the number of simultaneous users, and to a lesser degree by the number of scents to be emitted. Researchers looking for a large-scale solution, suitable for scenting a large room, space, or entire building, should consider systems such as Aromasys', the ScentBlitz from ScentAir (www.scentair.com) or a DaleAir system (www.daleair.com). Typically, these systems are built for a single scent, although it is possible to buy systems that can deliver multiple scents.

On a smaller scale is a system suitable for a small group of users. For these, the researcher should explore the Olfacom system (www.olfacom.com) or the ScentPOP from ScentAir. Aerome (www.aerome.de) also has systems suitable for such displays, ranging from six- and 12-scent systems to their single-scent, environmentally aware, reusable ScentController.one.eco.

Providing scent for a single user can be tricky; scent inherently will diffuse to surrounding spaces—although this can be an advantage in applications such as ambient display. If a certain degree of diffusion is acceptable, a simple low-cost solution is to build a solenoid-controlled perfume bottle similar to the ones used in Dollars & Scents or Honey I'm Home [9]. There are also a number of commercial solutions, including serial- and USB-controlled solutions from Olfacom and Osmooze (www.osmooze.com). All of these provide a single scent per diffuser; as mentioned, aerome has six- and 12- scent products, and Trisenx (www.trisenx.com) claims a 20-scent personal scent diffuser should be available as this goes to press.

For projects requiring focused smell output to a single user, there are two options. Toroidal vortices of scent-smoke rings without the smoke provide a focused way to direct scent to an individual, particularly when combined with a nose-tracking system [19]. A similar system has been proposed commercially by Microscent (www.microscent.net). Alternatively, several systems have been prototyped that use a head-mounted "nose-phone" device [9]. However, for most applications it will be sufficient to use one of the unfocused systems described in the previous paragraph.

All of the aforementioned companies work closely with scent manufacturers to provide both a library of standard scents and custom scents for individual projects; this is unlikely to be a stumbling block for most uses of scent in HCI.

Conclusions

Computerized scent output has a great deal of potential. Like any other medium, it has certain affordances: It is suited for slow-moving, medium-duration data, rather than rapidly changing information unless presented in aggregate. Any system must rely on users' distinguishing different qualities, not quantities, of smells; it is also important to use scents that are unlikely to cause allergic reactions. Remember, too, that associations with smells vary by individual and culture; the scent of root beer is considered pleasant in the United States, whereas the same aroma is associated with a strong disinfectant in the United Kingdom.

There has been increasing interest in the use of ambient displays, particularly as a paradigm for user interaction in a world of ubiquitous or everyday computing, rather than a mode that assumes a single user with a single computer on a desk. Olfactory display is well suited to use in such an environment, and the current commercial offerings make prototyping and customized installations rapid and simple.

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