



ELSEVIER

# Smelling in multiple dimensions

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Smell is perhaps the most subjective of the human senses, making odors difficult to measure and define. In everyday language, in the philosophy of aesthetics, and in the lab, this low opinion of odors means that smells are often characterized simply along an axis of good or bad. Odors and the ways they are perceived, however, are varied and incredibly complex, requiring an understanding of chemistry, neuroscience, aesthetics, and social science. Science and art that engage the sense of smell have the potential to expand our understanding of how biology and chemistry interact.

## Addresses

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## Introduction: molecular aesthetics

We take an average of 24,000 breaths per day, each inhalation swirling countless molecules over our olfactory receptors to give us a smelly glimpse of the chemical world. The human nose can detect and distinguish between thousands of different smells, from the complex combinations encountered in nature to the pure molecules synthesized in the lab. Despite the importance of odors in daily experience and the fact that humans have a surprisingly keen sense of smell, humans have a remarkably low opinion of the nose, neglecting to cultivate and educate the sense of smell while zealously deodorizing the world.

Smell has also been intellectually neglected by ancient philosophers and modern art critics alike, with odors and perfumes excluded from the realm of beauty and aesthetics by Plato and their art status still debated today. While, according to Plato ‘beauty is the pleasant which comes through the senses of hearing and sight,’ the pleasures of smells are subjective, sensuous, volatile, and evanescent, unworthy of serious study [1•]. Today it is widely believed that odor is among the lower, less evolved senses, unable to convey the moral or intellectual

aspects of beauty the way that hearing and vision can. Distaste for the subjectively sensual leads both philosophers and scientists to ignore the multidimensional complexity of the sense of smell, judging smells primarily along a simplistic axis of ‘good’ vs. ‘bad.’ People without training in perfumery typically describe smells based on the objects that produce them—‘smells like strawberries’ or ‘smells like rotten eggs’—qualified with language of attraction or disgust, good or (usually) bad: ‘fetid, foul, stink, stench, rancid, vile, revolting, nauseating, sickening’ [2]. The nose can detect when something is delicious or rotten, only the eyes and ears can identify something beautiful or interesting.

Likewise, the subjectivity of olfaction means that the human nose cannot be trusted as a scientific instrument. Whereas the earliest chemists relied on their senses—on sight, smell, and taste—to understand chemical reactions, the formalization of the science of chemistry in the 18th century involved the development of precise instruments to objectively measure and quantify chemical phenomena. Scientists used these machines to standardize scientific observation, relegating the human senses and the difficult-to-quantify smell of chemicals to the privacy of the lab, inadmissible in scientific communication [3]. The difficulty of scientifically measuring odors continues to be a challenge in the science of olfaction today, where statistical methods and chemical analysis are used to understand how the nose responds to smells and how the brain decides if they are good or bad [4••].

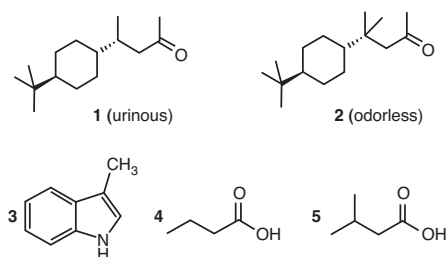
These analytical approaches provide a powerful way to understand odors, but much of the study of olfaction shows that even the simplest judgments of odor quality are highly context-dependent, changing and shifting depending on molecular, biological, emotional, and social contexts. Perhaps there is an esthetic aspect to this complexity as well. Some chemists, including the Nobel prize winner Roald Hoffmann, judge the molecular beauty of a chemical based on the visual simplicity and harmony of its shape, or on an intellectual appreciation of its function, natural or designed [5]. For the chemical biologist, the often context-dependent interactions of a molecule with biological systems are fascinating, powerful, and potentially even beautiful. How molecules interact with the olfactory system is a complex process transforming chemical signals into neural impulses and conscious perceptions [6], governed by the physics and chemistry of the molecules, the genetics and structure of the olfactory receptors, the neural architecture of the pathways that interpret smells, as well as the psychological, social, and cultural context of molecules and odors.

This brief review highlights some of the challenges inherent in objectifying smells, from the chemical and biological to the linguistic, social, and emotional aspects of odor, as well as methods from science and art to overcome these challenges. Science and art that encourage engagement with the multi-faceted complexity of odor perceptions can change the way that we smell the world.

### The context-dependence of good smells

What makes a molecule smell good or bad? In the first century BCE, Lucretius developed one of the first comprehensive theories of odor, hypothesizing that pleasant smells consisted of smooth, rounded atoms, while unpleasant smells were produced by spiky, irritating atoms [4<sup>••</sup>]. Two thousand years later, theories of olfaction still connect good and bad smells to the physical characteristics of molecules, through statistical correlations between human subjects' odor descriptions and molecular size or chemical functional groups [7]. The limited vocabulary available to the untrained nose translates to odor descriptions primarily related to pleasantness, leading researchers to hypothesize that the hedonic axis of good vs. bad is the primary and evolutionarily hardwired pathway of our olfactory cortex, structurally determined [8] and computationally accessible for the training of electronic noses [9].

These correlations, however, do not hold in all circumstances, particularly when we look beyond one-dimensional descriptors. Challenges to the hedonic axis emerge from molecular, linguistic, and experiential areas, adding valuable complexity to the understanding of olfaction. While there has been limited success in correlating structure to odor, often very similar chemical structures can smell extremely different, while very different structures can smell very similar. For example, molecule **1** smells ruinous (ostensibly bad) while the almost identical **2** is odorless [10<sup>•</sup>]. Small changes to structure or the addition of functional groups in different molecular backbones can also significantly alter the smell of a molecule in a manner that cannot be predicted by current structure-odor models.



Beyond this unpredictability, objective analysis and classification of odors based on their chemical structures is made difficult by olfaction's sensitivity to concentration,

experiential context, and social or emotional factors [4<sup>••</sup>]. Skatole (**3**, from the Greek root *σκατο* – meaning 'dung'), for example, is an indole with a strong fecal odor at high concentrations, but it is often used in perfumery at a much lower concentration where it has a pleasing floral scent. Odors presented in different sequences or combinations are also perceived differently. This is particularly the case when odors are ambiguous, such as dihydromyrcenol, which has both a citrus and a wood-like character [11].

Despite the salience of pleasantness in odor descriptions [12], there is evidence that smell, though hard-wired partly, is flexible, learnable, and highly context-dependent [13<sup>•</sup>]. Molecules do not always smell the same, good or bad, and people can learn to tolerate and even enjoy many 'bad' smells in different situations and environments. The ability to learn to identify smells shows that the challenge lies often in a lack of education and vocabulary rather than a lack of olfactory receptors or neural pathways.

Flavorists and perfumers are trained to match smells to words and types, consistently performing better on tests of odor identification than the untrained, and consistently less likely to classify odors based simply on hedonic qualities [14]. Semantic analysis of odor descriptions provided by perfumers or constrained to similarity to reference odors exposes other salient factors, including 'freshness' or 'femininity/masculinity' rather than hedonic qualities [15].

These data from perfumers show that cultural and linguistic factors play a large role in our understanding of odors. Having the vocabulary to describe the characteristics of odors beyond good and bad allows for a more multifaceted smell experience. The anthropology of odor also shows that disregard for smells is not a universal of human cognition, but is influenced strongly by culture and language. Analysis of odor descriptions in Maniq, a language spoken by only 240–300 people living in hunter-gatherer societies in southern Thailand, identifies many more words for odor qualities and a deep appreciation for the world of olfaction [16]. In order to address the olfactory gap in many languages, co-author Sissel Tolaas, an artist and odor researcher, has developed a novel language for odor descriptions based on an analysis of words used to describe odors in several languages in many countries around the world. Nasalo provides an unprecedented level of detail in describing odors, giving words to many odors that may go unnoticed (Table 1). An expanded vocabulary for talking about smell opens up many more dimensions for olfaction.

Beyond the structural aspects of language and culture that influence the cognition of smells, social and emotional factors play a large and often fine-grained role in odor

**Table 1**

**A sample of words in the Nasalo language to describe odors. Nasalo was invented by Sissel Tolaas as an international language consisting of words to communicate smells and smell impressions. People are asked to describe the same smell in one word in their native language. These words are then analyzed and compared to create the Nasalo word**

Word	Definition
afiisook	bad fish
beetwe	wet concrete
cikin	perfume that smell ok but are somehow displace
cassca	sweat mixed with metal of cars
casspo	sweat in connection with sport
dusbi	dusty brick
fre	wet and rainy street after a sunny day
goohish	young dog
giispa	paper money
gjluu	etherealizing, glorifying
hiin	magic
isjfe	fresh cut grass
jamp	apple pie
kankalay	smells that penetrate the air
letdir	muddy football
muk	tobacco
ossee	rosebush
passlo	ardent, burning, fervent, passionate
puqsa	mold, mushrooms
skunka	metallic, mouse, fish, snake, coins, humid earth
shooth	McDonald's
tarkee	train
urbcas	dry pollution of cars
xk'aja	fermented

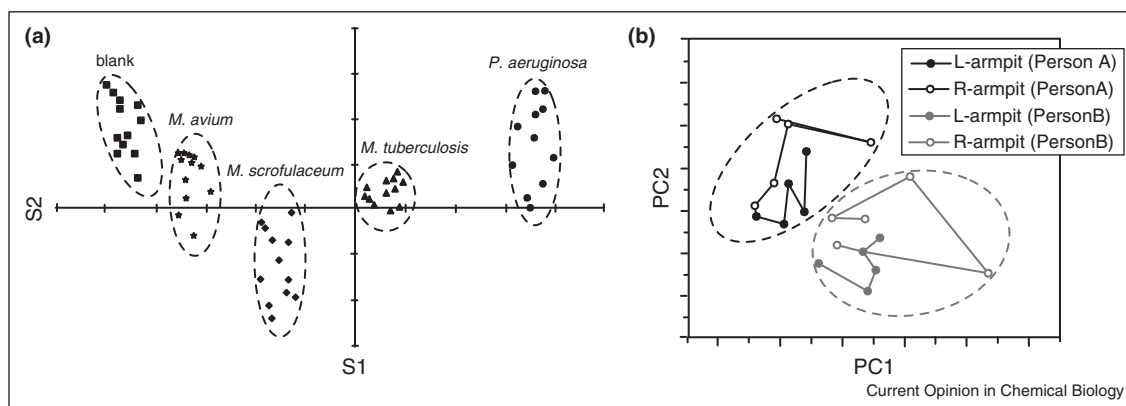
perception. The same molecules can smell different depending on the emotions or taboos associated with the smell and its source. For example, the smell of the same odor molecules—a mixture of butyric (4) and isovaleric acid (5) often found in cheeses—generates very different descriptions and emotional responses depending on whether the subject has been told that it comes from Parmesan cheese or vomit [17]. Isovaleric acid provides the flavor notes for Swiss cheese [18] and human

body odor [19], praised on the one hand and aggressively covered up on the other hand (or armpit). The variability in smell profiles and perceptions shows that judgments of good and bad are hardly universal. Contextualizing the information from the senses and from scientific instruments is crucial to understanding the perception of odors—how biology and chemistry interact.

### Methods for olfactory objectivity

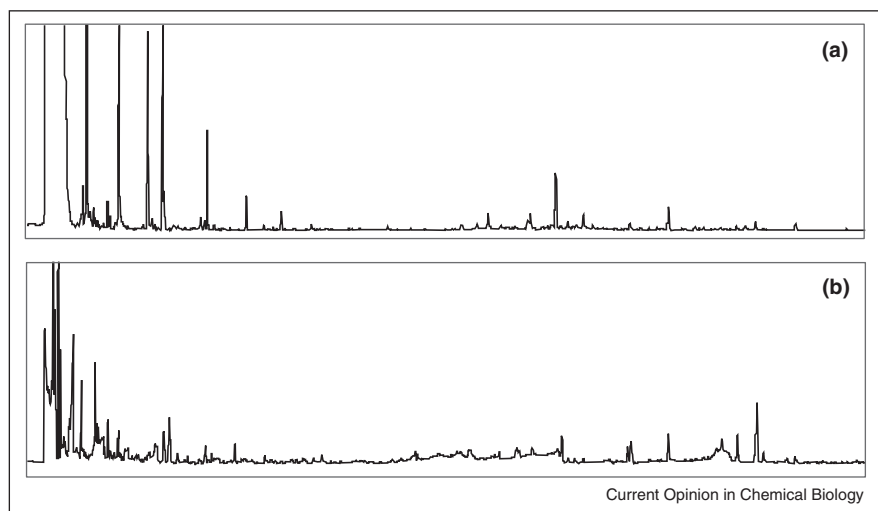
Given the challenges involved in classifying odors, statistical methods are often used to define and identify odor profiles. Principal component analysis (PCA) is a method for simplifying complex datasets by identifying the primary factors that explain the variance in the data. Such methods can isolate factors from the semantic descriptions of odors [20] or from odor data collected with mechanical rather than biological means, such as gas chromatography–mass spectrometry (GC–MS) headspace analysis or electronic nose-based ‘machine olfaction’ [21]. PCA can be used to cluster complex datasets captured from multidimensional chemical profiles. It allows researchers to distinguish between the odors of individual microbial species [22] (Figure 1a) as well as the body odors of individual humans [23] (Figure 1b). These simplified maps of odor characteristics can then be used to predict the identity of an unknown volatile molecule with higher confidence than an untrained human nose.

These mathematical and mechanical approaches seek to remove human subjectivity and emotion from the classification of odors, to combine an individual's senses into a statistically powerful cohort, or to remove the human nose altogether. These tools can help researchers to better understand the complex chemical world and the complex neurological world of odor perception [6], but are they enough to fully define multidimensional olfactory space? The experience of olfactory art and more subjective methods suggests otherwise.

**Figure 1**

Statistical analysis of electronic nose data can distinguish (a) between cultures of different clinically important bacterial species [22] and (b) between the body odor of two healthy people [23].

Figure 2



Headspace analysis of the smell of 1976 Penfolds Grange Hermitage wine **(a)** in a glass and **(b)** in the mouth of the artist Sissel Tolaas. These traces were used as the basis of a resynthesis of the odor.

Figure 3



Co-author Sissel Tolaas in her lab. Her artistic process involves the precise mixing of volatile molecules to recreate natural odors, based on headspace analysis and information from her own nose. Photograph by Alexandra Daisy Ginsberg, reproduced with permission.



Figure 4



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The cheeses produced by bacteria isolated from the human body. Photograph by Alexandra Daisy Ginsberg, reproduced with permission.

Analytical methods like headspace technology can give a detailed picture of the chemical composition of an odor, but using that data to reverse engineer smells does not always reproduce the 'real thing.' Tolaas's work on capturing and recreating odors uses a mix of approaches and apparatus, including both headspace analysis and the human nose. Her recent piece, St(62) + [PGh(76) × Rp(100)],<sup>10</sup> analyzed the odor of a bottle of 1976 Penfolds Grange Hermitage wine both in the glass and in her own mouth using headspace analysis (Figure 2) and expert human assessment (Figure 3).

Reconstituting the odor from constituent molecules based on the chromatograph resulted in a strikingly different odor than when the smell was produced from descriptions provided by humans. Where the human-verified smell was warm and familiar, giving the smeller a feeling of drinking an excellent wine, the headspace analysis yielded an odor that was sharp and chemical, a change in the resolution of the smell that is difficult to define. This difference is important for artists and perfumers, the nascent science of the digital transmission of

smell [9,24,25], as well as for our understanding of the composition and perception of odors.

### Olfactory art: bodies and cheese

Olfactory art can improve the understanding of smells, not just by improving vocabulary or exposing the gaps in olfactory technology, but by pushing discussion of odors beyond a one-dimensional understanding of the volatile world [1•]. Smell art draws from chemistry and neuroscience, using many of the same tools to construct and structure smells. Tolerance to and preference for smells depends on our exposure to odors and the situations within which we experience them. By re-encountering 'bad' smells in different contexts, both scientific and artistic, we can learn to smell along different dimensions and discover what can be interesting and beautiful about odors.

Collaborative work that brings together artists and scientists has a long history, promoting critical exploration of science, as well as the esthetic dimensions of scientific practice [26•,27,28]. The authors' collaboration through Synthetic Aesthetics [<http://www.syntheticaesthetics.org>]

connected our individual interests and experience with odors and biology, starting with an exploration of the ‘bad’ odors of the human body and the ‘good’ odors of cheese.

Body odors have recently played a large role in smell art [1•], particularly Tolaas’ exploration of the odors produced when people face their fears in ‘The FEAR of Smell — The Smell of FEAR’ (MIT, 2006). The odors of the body, of sweat and other excretions, have long been objects of disgust, crucial to how humans negotiate with the biology of the body and with microbes [2]. This makes them fascinating subjects for olfactory art as well as microbial ecology. The characteristic odors of the human body are produced in collaboration with the diverse microbial species that live in and on the body. The skin is home to many hundreds of types of bacteria [29], nurtured in the warm and moist environment of the body’s folds and fed by the skin’s oily secretions. Breaking down these products leads to the range of odors that the body produces, from the hair on our head to the space between our toes.

Body odors are aggressively deodorized, but there is growing support for their importance in nonverbal human communication [30], in mate choice [31], and in medicine. Body odors have long been important in medical diagnosis; changes to the metabolism from disease—either inborn, acquired, or infectious—can lead to changes in body odor that can be detected by a physician, a trained animal [32], or more recently, an electronic sensor array [33]. An awareness and familiarity with body odors and those of the body’s microbial symbionts can help to maintain human health.

Like skin, cheeses are aged in warm and moist environments, where complex biofilms made up of several bacterial and fungal species interact to break down the milk fats and proteins to produce cheese flavors. The association of cheesy smells and body odor extends beyond the butyric (4) and isovaleric acid (5) of Parmesan cheese and vomit. Limburger cheese with its strong foot-like odor is home to many strains similar to those found in the crevices between toes, a strong enough association to fool species of mosquitoes that target the feet and ankles [34].

To highlight the connections between human bodies and food and to foreground the microbial symbionts of skin, we produced a series of cheeses with bacteria captured from our own bodies (Figure 4). Each cheese had a unique odor, capturing some of the diversity between different people and between different parts of the body. With odors ranging from floral and yogurty to rotting and putrid, these cheeses challenged our ability to categorize and compartmentalize smells. If isovaleric acid smells good in cheese and bad on the body, what happens when the cheese microbes come from the body? In re-contextualizing our microbes and our food,

we find that good and bad are not enough to describe these smells, that disgust is a matter of circumstances as well as odor [2,35].

## Conclusions

Detecting and responding to the chemical environment is a defining characteristic of life, but the human sense of smell is often considered vestigial, a relic of mammalian ancestors who got around on all fours, noses to the ground [2]. However, in exploring olfaction through chemistry and neuroscience as well as art and aesthetics, we see that smells provide a rich opportunity for understanding how our biology interacts with the chemical world.

Tolerance and disgust of odors in different contexts mirrors the contradictions between hyper-sterilization and the growing understanding of the importance of bacteria to human health. As we gain a more nuanced understanding of the microbes that are a crucial part of the body, we tolerate and accept microbes into our lives, no longer simply ‘germs’ but complex organisms that strengthen our bodies and our environments through ecosystem bonds. Likewise, a deeper understanding of odors and olfaction allows us to tolerate smells, to value their importance and their power, and to smell their nuanced and subjective beauty.

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