Report

Current Biology

The perception of odor pleasantness is shared across cultures

Highlights

- Culture plays a minimal role in the perception of odor pleasantness
- Individuals within cultures vary as to which odors they find pleasant
- Odor pleasantness can be predicted by the physicochemical properties of molecules
- Human olfactory perception is strongly constrained by universal principles

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In brief

Arshamian et al. compare 10 diverse cultures, including hunter-gatherers and horticulturalists, for their perception of odor pleasantness. Contrary to expectations, they find that culture is not a major predictor of odor pleasantness. Instead, there is substantial global consistency, which can be predicted by the physicochemical properties of molecules.

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Report

The perception of odor pleasantness is shared across cultures

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SUMMARY

Humans share sensory systems with a common anatomical blueprint, but individual sensory experience nevertheless varies. In olfaction, it is not known to what degree sensory perception, particularly the perception of odor pleasantness, is founded on universal principles,[1–5] dictated by culture,[6–13] or merely a matter of personal taste.[6,8–10,12,14] To address this, we asked 225 individuals from 9 diverse nonwestern cultures—hunter-gatherer to urban dwelling—to rank the monomolecular odorants from most to least pleasant. Contrary to expectations, culture explained only 6% of the variance in pleasantness rankings, whereas individual variability or personal taste explained 54%. Importantly, there was substantial global consistency, with molecular identity explaining 41% of the variance in odor pleasantness rankings. Critically, these universal rankings were predicted by the physicochemical properties of out-of-sample molecules and out-of-sample pleasantness ratings given by a tenth group of western urban participants. Taken together, this shows human olfactory perception is strongly constrained by universal principles.

RESULTS

In 1878, Margaret Wolfe Hungerford wrote, "Beauty is in the eye of the beholder," suggesting what one person finds beautiful, another may not. Consistent with this, we now know that facial preferences vary across individuals.[15] Importantly, however, they are also strongly shaped by culture[16] and may even have components that are universal.[15] Similar to beauty, the perception of odor pleasantness or valence—the principal dimension by which odors are categorized[1,17–20]—is said to vary across cultures.[6–13] For example, fermented herring is a greatly appreciated delicacy in Sweden, but it also emits a smell described as the "most repulsive in the world."[21] In addition, people also display individual variability in food preference, even within families.[6,8–10,12,14] At the same time, more recent studies of urban western participants demonstrate that valence can be objectively predicted from an odorant's chemical structure,[1–5] despite the fact that universal odor preferences have been disputed historically. It is unclear how to reconcile these perspectives: is odor preference culturally relative, driven by individual preferences, or universally constrained by molecular structure?

In order to address this question, it is necessary to assess all three factors simultaneously, but this has never been done with a diverse sample of cultures. Studies that have used an experimental approach to study the impact of molecular structure on odor preference tend to sample people with similar urban lifestyles and experiences—i.e., literate, educated, and technologically savvy individuals who partake of a common global fragrance and flavor industry[1–5] (although see Haddad et al.[2] and Majid et al.[22]). This provides only a weak and narrow test of the possible role of culture. To quantify the role that culture may play in odor preference, it is necessary to study diverse cultures, including those of small-scale societies that vary in their subsistence style and geography and where people are minimally influenced by global odor experiences, while at the same time measuring individual variability and the chemical structure of odorants.

Here, we assess the unique contribution of each of these factors by experimentally testing nine diverse communities.

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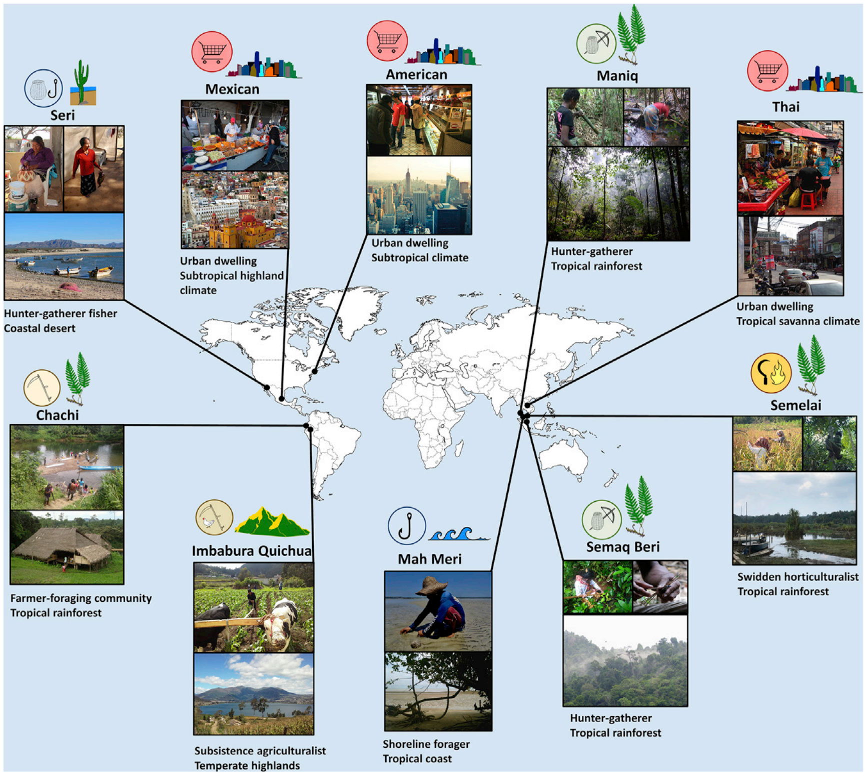

Figure 1. Cross-cultural sample

Odor preference rankings were collected from nine culturally and geographically diverse populations. These included the three hunter-gatherer groups, Seri from a coastal desert and Maniq and Semaq Beri from tropical rainforest, one shoreline forager, Mah Meri, from a tropical coast; one swidden-horticulturalist, Semelai, from tropical rainforest; one farmer-foraging community, Chachi, from tropical rainforest; one subsistence agriculturalist community, Imbabura Quichua, from temperate highlands; and two urban dwellers from industrial and postindustrial communities of bustling urban settings, Mexican and Thai. The data from these nine communities were then related to available data from a large dataset on odor preference collected from urban dwellers from the USA (New York City).

Critically, seven of these groups belonged to small-scale societies—including hunter-gatherers, horticulturalists, and subsistence agriculturalists—with a more traditional lifestyle and who do not experience the same chemical ecology as western and nonwestern urbanites (Figure 1; STAR Methods).

Odorants were selected based on a previous study with post-industrial urban dwellers from the United States (New York City) who rated the pleasantness of 476 diverse molecules.[23] We selected ten of these odorants such that the mean ratings would span the valence dimension from unpleasant to pleasant (for more details, see STAR Methods). Participants from nine communities were, with the help of a network of fieldworkers, presented with ten pen-like odor-dispensing devices,[24] each containing a unique odorant. A rank-order paradigm was chosen to assess odor pleasantness because not all groups had numeracy and use of scales and ratings is not the norm in these communities. The pens were randomly ordered and placed in a line in front of the subject. The participant first smelled all the odors in front of them and then ordered the pens from most pleasant to most unpleasant (from their left to right).

If odor valence is learned from exposure to cultural traditions, then societies should differ in their rankings of perceived odor pleasantness, with a diverse set of rank orders across cultures. If, however, odor valence is a matter of individual preference, there should be large within group variation. Finally, if perceived odor pleasantness is universal, then all groups should rank odors in the same way. Using the within-culture mean ranking for each odorant, we found that odor valence rankings correlated strongly and positively across all cultures (Figure 2; $r = 0.82 \pm 0.18$), supporting the idea that culture has a relatively small influence overall on odor pleasantness. Pleasantness rankings were also correlated for both the most pleasant and most unpleasant odorants (Figures S1A–S1D) and for their ranking consistency across individuals and cultures (Figures S1E and S1F).

We next conducted a two-way ANOVA using odorant identity and cultural grouping to determine the observed ranks for each individual + odorant pair. The first factor was "odorant identity." The second factor of specific cultures has no net effect because all individuals must give the same ten ranks, but the interaction between these factors, odorant × cultural grouping, we call "culture" since only this term establishes whether odor rankings vary across groups. The remaining variance not accounted for by these factors and their interaction we term "individual," which represents some combination of individual preference (not mediated by culture and odorant) and perceptual or task-related noise. The explained variance η^2 for each of these factors was used as the primary analysis measure (Table S1). We found culture only explained 6% of the variance, whereas 54% was due to individual variability (Figure 3; see Table S1 for details of statistical analysis and Figure S2A for the partition between individual preference and perceptual noise). Critically, odorant identity explained 41% of variance in rankings.

As a positive control, we simulated a case where culture drives odor preference by shuffling odorant labels in a manner that was consistent for each member within a culture but varied across cultures. Under these conditions, 41% of the variance was explained by culture, with the rest explained by individual variability. This positive control demonstrates that our method is sensitive enough to measure cultural variability should it exist. As a negative control for a possible effect of culture, we next shuffled individuals between cultures. Under these conditions, culture explained only 2% of the variance, not much smaller than the value observed in the unshuffled data (Figure 3). The analogous Bayesian model comparisons reached the same conclusions (Figures S1G and S1H). Consistent with only a small contribution for culture, direct assessment of interindividual ranking similarity using Kendall's

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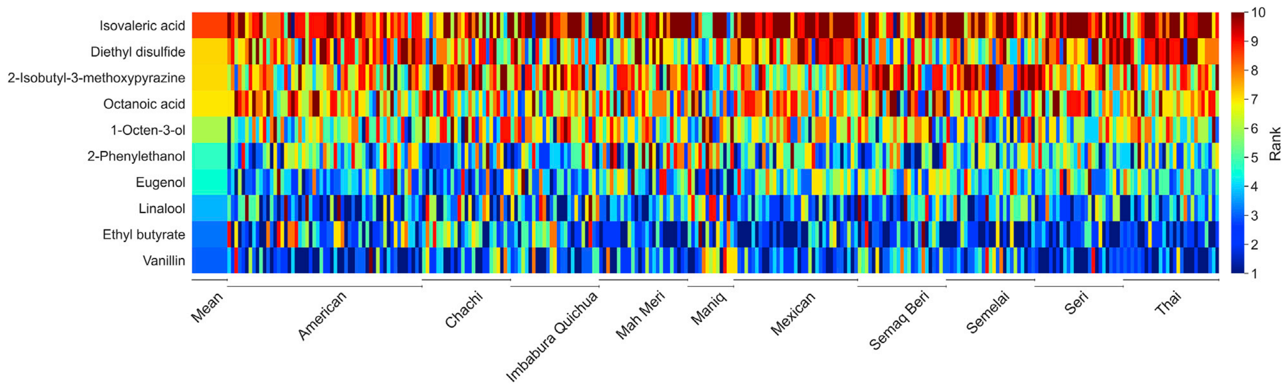

Figure 2. Pleasantness rankings across individuals and cultures

Between n = 16 and n = 55, individuals from each culture assessed each of 10 odorants. Nine cultures ranked the odorants in order from most (1, blue) to least (10, red) pleasant, whereas the Americans (specifically US Americans residing in New York City metropolitan area; data from Keller and Vosshall[23]) used numerical ratings, converted into ranks here. Each color patch represents the integer ranking that one individual (from the culture indicated at the bottom) gave to one odorant (indicated on the left). The broad column on the far left represents the average ranking for each odorant across all individuals. See Table S2 for more information about the odors, Figure S1 for in-depth analysis odor pleasantness ranking, and Figure S3 for the relationship between odor pleasantness and odor intensity.

τ showed the mean rank similarity for pairs of individuals within the same culture (τ = 0.32 ± 0.14) was only slightly higher than for pairs of individuals in different cultures (τ = 0.28 ± 0.11). In addition, a follow-up intensity ranking task showed that pleasantness ranking was not explained by the perceived intensity of odorants (Figure S3).

Perhaps, there is another shared factor that could explain odor pleasantness preferences. We considered two such factors: (1) subsistence type—hunter-gatherer (Semaq Beri, Maniq, Seri), subsistence horticulturalist (Semelai, Chachi, Quichuan, Mah Meri), and (post-)industrial urban dwelling (US American, Mexican, Thai)—and (2) continent—North American (US American, Mexican, Seri), South American (Chachi, Quichuan), and Asian (Semaq Beri, Maniq, Semelai, Mah Meri, Thai). We recalculated the ANOVA in Figure 3 to ask whether a factor corresponding to either subsistence or continent explained more variance than specific cultures (as identified in STAR Methods). We did not observe increase in variance explained; in fact, variance decreased (culture, η^2 = 0.056; subsistence, η^2 = 0.015; continent, η^2 = 0.021). Next, we used the same subsistence and continent groupings of individual cultures to ask if either explained the (small) differences in odor preferences between cultures better than random groupings. Specifically, we asked if a clustering metric, compactness (measured by the distance of cultures to cluster centers), was lower for either of these groupings than random groupings. We found weak evidence for continent as an organizing force (more compact than 96% of random clusterings) and less for subsistence (more compact than 77%). These analyses suggest that cultural preferences for odors are in large part locally determined. Taken together with the previous analyses, we find only a weak contribution of culture to odor pleasantness rankings.

If odor valence is largely universal, then it should be possible to predict it directly. Specifically, if physicochemical properties of odorants are the primary determinant of universality, the mean rank order from each culture should be predictable by a model trained using valence assessments made by a single culture. To do this, we used the remaining 466 odorants from the original American dataset—excluding our 10 test odorants—to build a model that uses molecular structure to predict pleasantness. Specifically, we used the best-performing model from the DREAM Olfaction challenge,[3] which applies the random forest algorithm to predict pleasantness ratings based on several thousand physicochemical features computed from each molecule's structure. We converted these predicted ratings into ranks for the 10 test odorants. We then computed the rank order similarity between all pairs of individuals (including the model) using Kendall's τ. For each and every culture, the within-culture mean rank order was more highly correlated with predictions from the model (on the test 10 odorants) than with any random participant from the same culture (Figure 4). In other words, a universal model trained on responses of western urbanites to an independent set of odorants was at least as good a predictor of the culturally and ecologically diverse field data that we collected as data from the same culture and same set of odorants.

DISCUSSION

Our results demonstrate the perception of odor pleasantness is largely independent of cultural factors, such as subsistence style and ecology, and can be predicted from physicochemical properties of odorants. Critically, across cultures, the perceived relative pleasantness of odorants seems to be equally robust—our effects are not driven by the peculiarities of one or two odorants (Figures S1A–S1F) or limited by the sample size of participants (Figure S2D). This is striking and is contrary to what would have been predicted from a cultural relativity perspective.[6–13]

Although it is widely accepted that valence is the principal perceptual axis of olfaction,[1,17–20] there has also been wide support for the idea that most aspects of olfactory perception are highly malleable and mainly learned[6–10,12,13,25–28] and importantly have little to do with an odorant's physicochemical properties.[29] Odor pleasantness is demonstrably plastic and

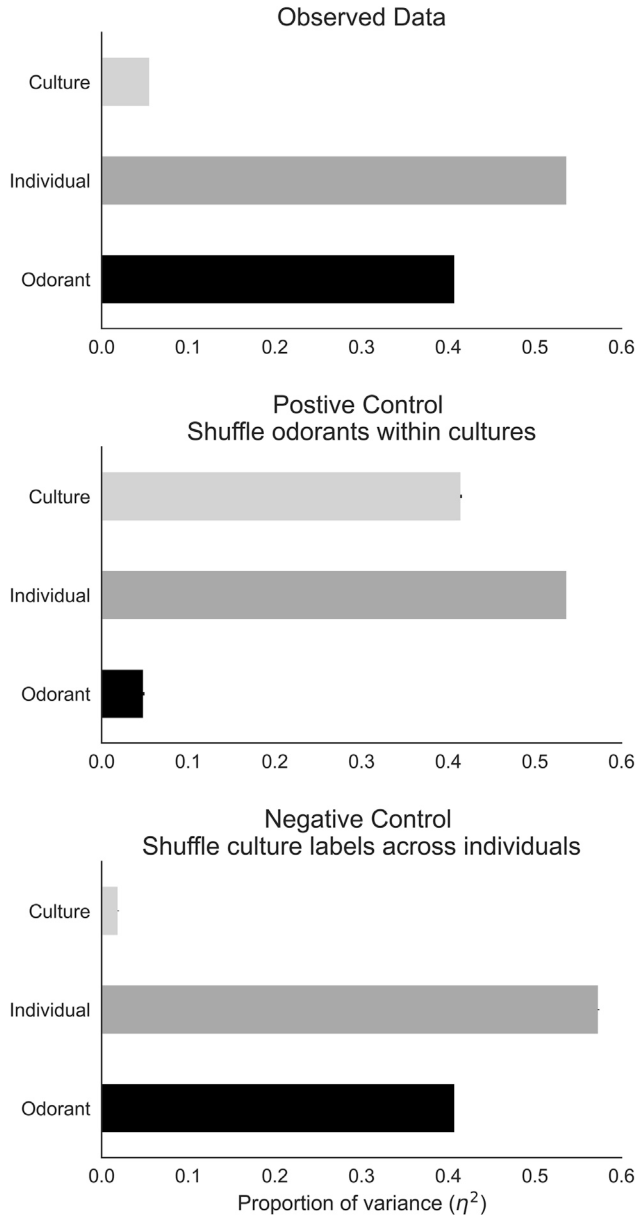

Figure 3. Proportion variance explained by factors determining odor pleasantness

(A) Culture (6%) plays a negligible role in explaining variance in the observed odor pleasantness rankings, whereas individual variability (54%) and odorant identity (41%) explain more.

(B) Positive control: odorant ranks were shuffled so that individuals within the same culture received a common shuffle, but individuals across cultures received different shuffles, simulating a "strong culturally determined odor pleasantness" scenario; this demonstrates that if the data did have a strong cultural component, it could have been detected with this method.

(C) Negative control: culture labels were shuffled across individuals. This removes culture-specific information in each individual's set of ranks, yet the contributions of each culture closely resemble the observed data. Bayesian analyses can be found in Figure S1, with further information in Figure S2 and Table S1.

modulated by factors such as early exposure[30,31] and context,[32–37] but our data clearly show the broader context of culture has little impact on the relative pleasantness of odors to one another, accounting for only 6% of the variance. By contrast, it has been estimated that up to 50% of the variance in judgments of facial attractiveness may be driven by culture.[38] Our data do not, however, adjudicate between learned versus innate explanations of odor pleasantness perception. Global regularities in odor perception could indicate common and shared experiences across all human groups. Infant data from diverse cultural contexts could adjudicate between these possibilities, although even here there are challenges since the fetus is already being enculturated into a specific chemical environment.[39]

Although showing only a limited role of culture, the perception of odor pleasantness seems, to a large degree, to be in the eye of the beholder across cultures. Although some of these differences in individual preferences across cultures could potentially be explained by differences in the reliability of the instrument at different locations and perceptual noise (see also Figure S2A), it is clear that personal preference, to a large degree, also shapes perception of odor pleasantness. Our findings are in line with what has been reported for judgments of attractive faces, where around 40% of the variance has been attributed to individual preferences.[38] In contrast, we do not observe large differences in rank variability across odorants, where differences do emerge as they appear at the individual but not at the cultural level (Figure S1).

To conclude, our data demonstrate that personal preference and physicochemical odorant structure—rather than culture—seem to be the primary predictors of the pleasantness of most odors. The latter is also reflected in the fact that odor valence is shared across a wide range of species, possibly due to processes at the receptor level that may shape valence for monomolecular odorants as well as complex mixtures.[4,40–43] Critically, we show there is a universal bedrock of olfactory perception shared among all people.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2022.02.062.

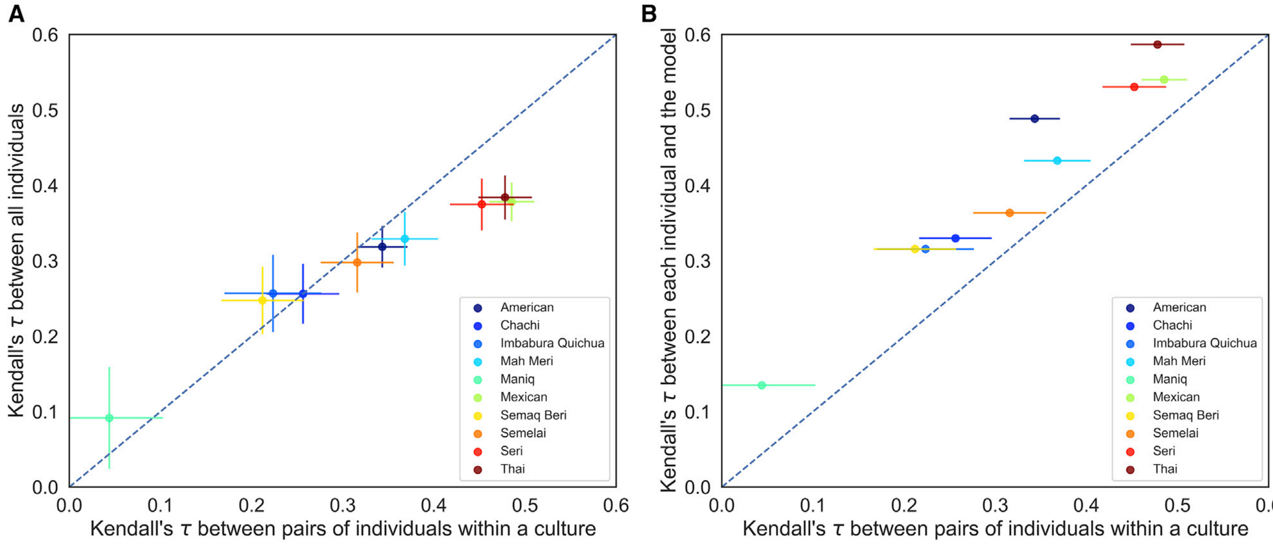

Figure 4. A universal model for odor pleasantness explains individual odor preferences

(A) The correlation of odor pleasantness rankings (Kendall's τ) between each individual and other individuals from their culture (x axis) is similar to the correlation between each individual and the entire population studied here (error bars are SEM for each group). The hunter-gatherer Maniq showed the lowest correlation to other groups and to each other, with no cultural consensus. Critically, the Maniq do not demonstrate a systematic alternative cultural odor preference but merely high levels of individual variation. A control task showed that this was not because they misunderstood the ranking task (Figure S4).

(B) Rankings predicted by a computational model trained on perceived pleasantness ratings for out-of-sample odorants were more correlated with individual rankings for the odorants used here than other individuals from the same culture (error bars are SEM).

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AUTHOR CONTRIBUTIONS

A.A., J.N.L., J.D.M., and A.M. designed research; N.K., E.W., S.F., C.O., and G.G.R. performed research; A.A., R.C.G., and J.D.M. analyzed data; and A.A., R.C.G., J.D.M., and A.M. wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
The datasets containing all data from all experiments are available on GitHub at http://github.com/rgerkin/shared-pleasantness	N/A	http://github.com/rgerkin/shared-pleasantness
Experimental models: Organisms/strains		
Human adults	Recruited locally	N/A
Software and algorithms		
The codes to generate all analysis are available on http://github.com/rgerkin/shared-pleasantness.	N/A	http://github.com/rgerkin/shared-pleasantness.

RESOURCE AVAILABILITY

Lead contact
Further information and requests should be directed to and will be fulfilled by the Lead Contact Asifa Majid, asifa.majid@psy.ox.ac.uk.

Materials availability
Picture stimuli for the protocol validation task will be shared upon request.

Data and code availability
All data and code are publicly available on GitHub at http://github.com/rgerkin/shared-pleasantness.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Subjects: Culture and Participant Sample
Our sample consisted of data from 10 communities with diverse modes of subsistence living in varied environments (Figure 1); see Figure S2D for participant sample size considerations. The data were collected and treated according to the ethical guidelines of the American Psychological Association, and the protocol was approved by the Ethics Assessment Committee at Radboud University. Informed consent was obtained in writing or orally as appropriate to each community. We briefly describe each community in turn.

Semaq Beri

The hunter-gatherer Semaq Beri live in the northeast of the Malay Peninsula. Traditionally they moved about the tropical rainforests in small bands of eight to ten families, making temporary camps of lean-to shelters, hunting and fishing, and foraging for the many kinds of wild tubers and seasonal fruits. They have become increasingly sedentized since the establishment of resettlement villages in the mid-1970s. The participants in this study live in a village of around 300 people, and maintain a forest-based subsistence mode. They speak the Semaq Beri language which belongs to the Austroasiatic language family. The total Semaq Beri population is approximately 2,300. Sample: There were 25 subjects (13 female and 12 male, M_{age} = 33.3 years, *SD* = 14.3 years) a number that is equivalent to approximately 1% of the total Semaq Beri population.

Maniq

The Maniq inhabit a mountainous region in the interior of isthmian Thailand. The area is covered by tropical evergreen forest. Maniq subsistence is hunting, gathering, and exchange of forest products for food. The Maniq population is around 300 with the size of a residential group varying day-to-day, usually close to 25-35. The group lives in temporary camps in the rainforest with minimal material possessions. Maniq is the main and first language, although everyone can understand and speak Southern Thai (with varying degrees of proficiency). Only a handful (<5) of Maniq have received basic schooling and most are illiterate. Sample: There were 16 subjects (8 female and 8 male, M_{age} = 33.4 years, *SD* = 12.5 years) a number that is equivalent to approximately 5% of the total Maniq population. Three participants were removed from the main analyses because of failure in the protocol validation task.

Seri

The Seri are a traditionally hunter-gatherer-fisher, semi-nomadic people, but since the mid-20th century are more sedentary. They take part in small-scale fishing operations, small ecotourism enterprises, sell permits to hunt on their land, work as hunting guides and benefit from the sale of arts and crafts, especially baskets made of desert limberbush. Seri live in 2 small villages in northwestern Mexico, along the coast of the Gulf of California in the Sonoran Desert. Their traditional homeland includes the biggest island in Mexico, Tiburon Island. The population size is between 900 and 1,000. The Seri people speak the Seri language. The participants in this study were from the village El Desemboque de los Seris, Sonora. Sample: There were 25 subjects (19 female and 6 male, M_{age} = 39.3 years, SD = 16.4 years) a number that is equivalent to approximately 2.5% of the total Seri population.

Semelai

The Semelai reside in the southwest of the Malay Peninsula in an area of lowland tropical rainforest. Traditionally they dwelt in small family groups scattered throughout the forest, growing rice in swiddens, fishing and hunting, and collecting forest products like rattan and resin for trade. Today the Semelai live primarily in resettlement villages of a few hundred people, and most are small-holder rubber tappers. They continue to fish and hunt. The Semelai speak the Austroasiatic language Semelai. Their total population is around 5,000. Sample: There were 25 subjects (13 female and 12 male, M_{age} = 38.3 years, SD = 13.8 years) a number that is equivalent to approximately 0.5% of the total population.

Mah Meri

The Mah Meri reside on the southwest coast of the Malay Peninsula in a rural landscape that has been dominated by rubber and palm oil plantations since the early 1900s. Traditionally the Mah Meri engaged in shoreline foraging along the mangrove-lined coast, hunting in the forest, and growing rice and other subsistence crops around their homesteads. Resettlement villages of several hundred people were founded in the mid-20th century. Cash-cropping was introduced, first coffee then palm oil, but the scarcity of land has long caused people to seek external employment, while others fish, or forage the shoreline. They speak Mah Meri, an Austroasiatic language. There are around 3,500 Mah Meri people. Sample: There were 25 subjects (13 female and 12 male, M_{age} = 39.4 years, SD = 15.7 years) a number that is equivalent to approximately 0.7% of the total Mah Meri population.

Imbabura Quichua

Imbabura Quichua people live in agricultural communities, planting crops like corn and potatoes, but are also famous for their long historical tradition of weaving which has developed into an important handcraft industry. Like the other Highland Quichua people of Ecuador, they speak a local variety of the Ecuadorian Highland Quichua language descended from the Quichua language introduced by the Incas from modern Peru. While many Imbabura Quichua people maintain a traditional rural lifestyle, eat local food, and speak mainly Quichua, others are connected to the national and overseas economies through trade, travel, and the tourism industry, and are bilingual in Spanish; both types of participants were included in the study, conducted in a semi-rural, semi-urban area. Sample: There were 25 subjects (14 female and 11 male, M_{age} = 43 years, SD = 15.7 years) a number that is equivalent to approximately 0.04% of the total Imbabura Quichua population of approximately 60,000.

Chachi

Traditionally the Chachi lived in isolated homesteads but today they live in small communities along the Cayapas river and its tributaries. Their lifestyle is mainly based on subsistence agriculture, with plantain as the basic staple, in addition to fishing and hunting. They also plant cash crops like cacao and engage in other activities like basketwork and logging, and use income to purchase outside supplies such as white rice, which has become an important staple in recent years. Their language is called Cha'palaa, from the Barbacoan language family. Participants are from a remote rural area where local people maintain a relatively traditional and autonomous lifestyle in which Cha'palaa is the dominant language and Spanish is used by a minority who have some experience outside the community. Sample: There were 25 subjects (13 female and 12 male, M_{age} = 44.6 years, SD = 14.9 years) a number that is equivalent to approximately 0.25% of the total Chachi population of about 10,000.

Mexican

Mexico is a country with a population of 126 million. Mexico is considered to be ethnically diverse. Group residence varies considerably with large cities having many millions whereas small towns can have populations in the thousands or less. Our sample of subjects came from Mexico City which has a population of approximately 8.9 million people. The majority of participants of the study were university employees (e.g., office workers). All subjects had access to all modern technologies (e.g., internet and television). The subjects were tested in Mexican Spanish. Sample: There were 35 subjects (19 female and 16 male, M_{age} =39.8 years, SD = 15.5 years) a number that is equivalent to approximately 0.0004% of the total Mexico City population.

Thai

Thailand has a population of almost 70 million with a mixture of ethnic groups. The data for this study was collected on the campus of the University of Ubon Ratchathani in Northeastern Thailand. The city of Ubon Ratchathani is a capital and an urban center of the province Ubon Ratchathani with 1.87 million inhabitants. Sample: The participants were from Ubon University and included university students and university employees (instructors, guards, cooks, shopkeepers). All subjects had access to all modern technologies (e.g., internet, television, etc.). The subjects were tested in Thai. There were 27 subjects (16 female and 11 males, M_{age} = 30 years, SD = 14.2 years) a number that is equivalent to approximately 0.0014% of the total of Ubon Ratchathani province.

Americans

The USA has a population of 328 million. Group residence varies considerably with large cities having many millions whereas small towns can have populations in the thousands. Our sample of subjects came from New York City, a racially and ethnically diverse city, which has a population of approximately 8.4 million people. Sample: There were 55 subjects (33 female and 22 male, M_{age} = 34.6 years, SD = 9.5 years) a number that is equivalent to approximately 0.00065% of the total New York City population.

METHOD DETAILS

Materials

Stimuli were presented in Sniffin' Sticks (Burghardt, Wedel, Germany) permeated with the odor diluted in mineral oil. The ten odors, all from Sigma-Aldrich, used the DREAM Olfaction Prediction Challenge dilution series (1): Isovaleric acid (CAS 503-74-2; 1/100,000 volume/volume), Diethyl disulfide (CAS 110-81-6; 1/1000), Octanoic acid (CAS 124-07-2; 1/1000), 2-Isobutyl-3-methoxypyrazine (CAS 24683-00-9; 1/1000), 1-Octen-3-ol (CAS 3391-86-4; 1/1000), 2-Phenylethanol (CAS 60-12-8; 1/1000), Ethyl butyrate (CAS 105-54-4; 1/1000), Eugenol (CAS 97-53-0; 1/1000), Linalool (CAS 78-70-6; 1/1000), and Vanillin (CAS 121-33-5; 1/10). See Figures S2B and S2C and Table S2 for additional details about odor selection and odor descriptors.

Experimental design

Our main experimental protocol was a pleasantness rank order task. As a control, we also conducted an intensity rank order task (Figure S3). For the Maniq we also conducted a protocol validation task using pictorial stimuli (see Figure S4).

Pleasantness rank order task

The odorants were randomly ordered on a holder so they made a line facing the subject. The subjects were told in their native language (i.e., Spanish, Seri, Imbabura Quichua, Cha'palaa, Thai, Maniq, Semelai, Semaq Beri, Mah Meri) to initially smell all the odorants in front of them (briefly and one at a time), and after smelling all odors to order them from the most pleasant to the most unpleasant (their left-to-right). The experimenter made sure that subjects did not smell an odor more than 2-3 seconds and that there was an interstimulus interval of 20 seconds between odor presentations. After subjects had smelled all odors on first encounter, they could freely re-sample the odors again while ranking them. To verify that subjects had understood the task correctly the experimenter asked them to point to the most pleasant and unpleasant odor after they finished the rank order task.

Intensity rank order task

Data collection was in two waves. In the first wave, data was collected from the Maniq, Seri, Mexican and Thai. We suspected some odorants were vulnerable to the humid weather conditions in the Maniq site, one of the first to be tested, although we were not able to measure this objectively at the time. In a second wave of data collection, we collected data for judgements of odor intensity. The same participants from five of the nine groups (Chachi, Imbabura Quichua, Semelai, Semaq Beri, Mah Meri) that participated in the odor pleasantness rank order task also ranked odors by intensity using the same paradigm. The subjects were told in their native language that the task was first to smell all the odors in front of them (briefly and one at a time) and then to order them from the strongest to the weakest (their left-to-right). As before, the experimenter made sure subjects did not smell the odor more than 2-3 seconds and that there was an interstimulus interval of 20 seconds between odor presentations. Before the start of the intensity rank ordering of the odors, the subjects undertook a control task to ensure they understood they had to order odors according to intensity and not odor pleasantness. In this control task, four different concentrations of the same odorant (i.e., 1-octen-3-ol in paraffin oil) were presented to the subject in steps of: 1/10,000,000 (basically blank); 1/100; 1/10; and 100% 1-octen-3-ol. To minimize adaptation effects, subjects first compared the two weakest concentrations, then the two strongest concentrations, then the second strongest and second weakest. Finally, they ordered odors from the strongest to the weakest (their left-to-right).

QUANTIFICATION AND STATISTICAL ANALYSIS

Further analysis details are provided in the supplemental information. Code and data are available on GitHub at http://github.com/rgerkin/shared-pleasantness. Values reported in the main text are mean ± standard deviation. Correlations are reported using Pearson's correlation (for means across groups) or Kendall's τ (for comparisons between individuals). The predictive model closely resembled that used by one of the authors (R.C.G.) previously in the DREAM Olfaction challenge.[17] Specifically, several thousand chemoinformatic features were generated programmatically for each molecule, and a random forest algorithm was used to predict pleasantness ratings (from a one hundred point scale on the DREAM Olfaction challenge dataset[3]). Only those molecules not used in the current manuscript were included in the training set, and the ratings for those molecules in the DREAM Olfaction challenge[3] were the prediction targets. This model was then used to predict the pleasantness ratings for the ten molecules used in the current manuscript; these predicted ratings were then rank ordered for analysis. The 10 selected odorants were well-distributed in physicochemical space (see Figure 2C for the Uniform Manifold Approximation and Projection (UMAP) plot of Mordred[44] physicochemical features and Principal Components Analysis (PCA) of the same features. We also resampled 10,000 random sets of 10 odorants and compared the actual set of odorants to these random sets of ten. The actual set had a lower Kulback-Leibler divergence with the full set of DREAM odorants (i.e., better represented the full probability distribution of pleasantness ratings) than 78.4% of random sets; the variance of pleasantness ratings in the actual set was higher than in 99.8% of random sets; and the actual set was more evenly spaced (variance of rating intervals) than 100% of random sets.

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Supplemental Information

The perception of odor pleasantness is shared across cultures

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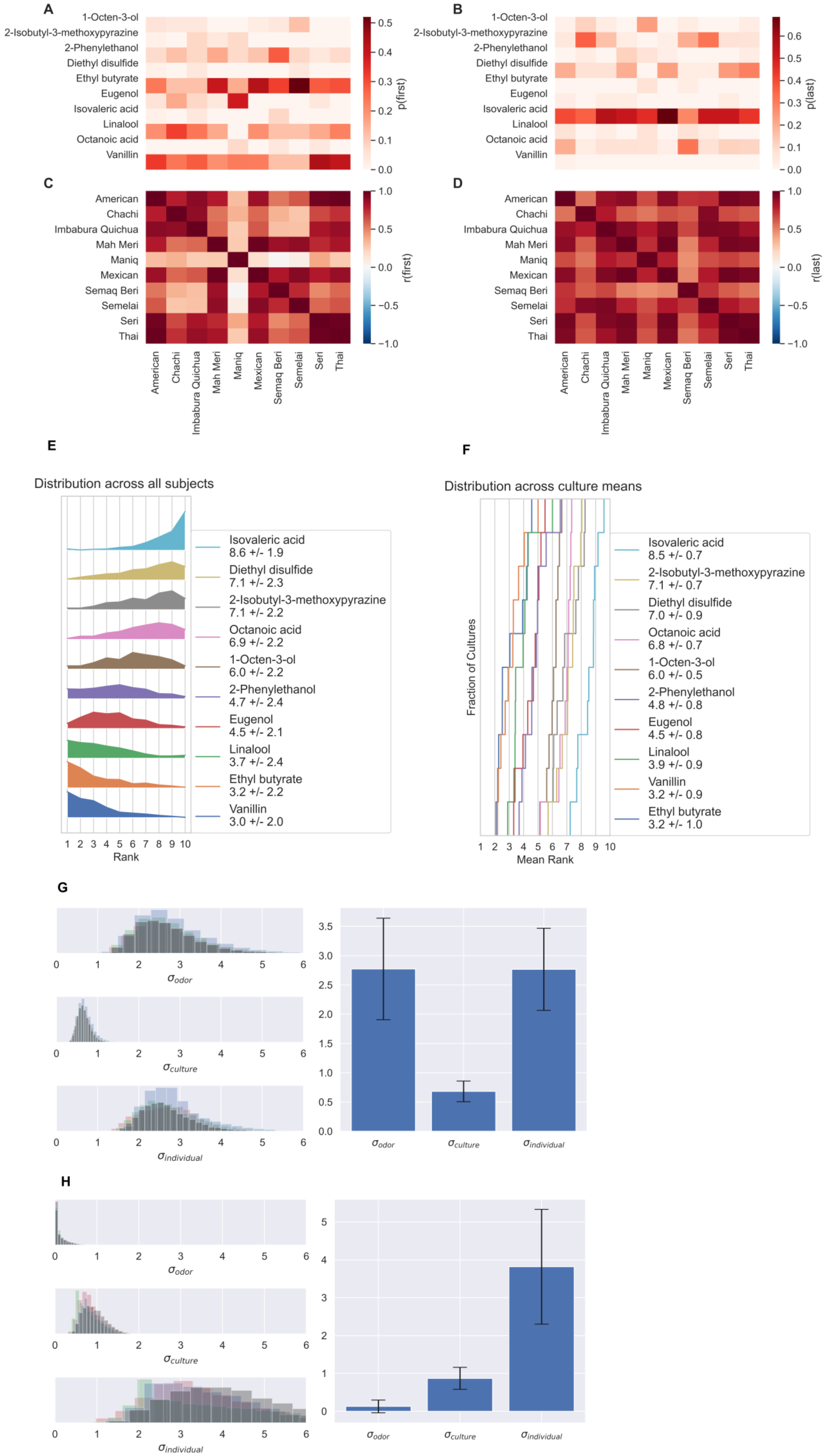
A
B
C
D
E
F
G
H
1-Octen-3-ol
2-Isobutyl-3-methoxypyrazine
2-Phenylethanol
Diethyl disulfide
Ethyl butyrate
Eugenol
Isovaleric acid
Linalool
Octanoic acid
Vanillin
p(first)
p(last)
r(first)
r(last)
American
Chachi
Imbabura Quichua
Mah Meri
Maniq
Mexican
Semaq Beri
Semelai
Seri
Thai
Distribution across all subjects
Isovaleric acid 8.6 +/- 1.9
Diethyl disulfide 7.1 +/- 2.3
2-Isobutyl-3-methoxypyrazine 7.1 +/- 2.2
Octanoic acid 6.9 +/- 2.2
1-Octen-3-ol 6.0 +/- 2.2
2-Phenylethanol 4.7 +/- 2.4
Eugenol 4.5 +/- 2.1
Linalool 3.7 +/- 2.4
Ethyl butyrate 3.2 +/- 2.2
Vanillin 3.0 +/- 2.0
Rank
Distribution across culture means
Fraction of Cultures
Isovaleric acid 8.5 +/- 0.7
2-Isobutyl-3-methoxypyrazine 7.1 +/- 0.7
Diethyl disulfide 7.0 +/- 0.9
Octanoic acid 6.8 +/- 0.7
1-Octen-3-ol 6.0 +/- 0.5
2-Phenylethanol 4.8 +/- 0.8
Eugenol 4.5 +/- 0.8
Linalool 3.9 +/- 0.9
Vanillin 3.2 +/- 0.9
Ethyl butyrate 3.2 +/- 1.0
Mean Rank
σ_{odor}
$\sigma_{culture}$
$\sigma_{individual}$

Figure S1. Results of odor ranking experiment, related to Figures 2 and 3.
Pleasantness rankings are correlated for the most pleasant and the most unpleasant odorants. (A) Fraction of individuals within each culture that ranked a given odorant as the most pleasant of the 10. (B) Same as A, but for the least pleasant odorant. (C) Correlation matrix computed from panel A; this shows the correlation between cultures in the number of individuals that rated each odorant as most pleasant. (D) Same as C, but showing a correlation matrix computed from B, for least pleasant odorants. (E) Distribution of ranks across individuals for each odorant. Mean +/- standard deviation (*M* +/- *SD*) of ranks for each odorant across individuals shown in legend. (F) Same as E, but first computing mean ranks across individuals within each culture; *M* +/- *SD* of 10 cultures. A cumulative histogram is used to illustrate the similarity in variances (represented roughly by the horizontal spread of the cumulant line for each odorant) across odorants; each odorant's cumulative histogram thus contains exactly one vertical segment for each of the 10 cultures. We examined ranking of odorants across individuals and cultures in order to establish whether some odorants showed more consistency. That is, we ask whether results are driven by consistency (across individuals and cultures) only in the most and least pleasant odorants or whether there is a broader pattern. All odorants showed comparable variance across individuals (SD = 1.9–2.4), though variance did differ across odors according to Levene's test (W =4.6, p = 4e-6); across cultures we detected no differences in variance (W = 0.891, p = 0.536). Furthermore, removing the 2 most and 2 least pleasant odorants from the sample and re-analyzing the data using ANOVA (Figure 3, main text) showed the effect of culture decreased from 6% to 5%. This shows results are not driven by agreement only in the most and least pleasant odorants, but by a broader pattern of agreement across odors. To further contextualize our results, in the DREAM dataset [S1], the mean standard deviation in pleasantness across individuals, averaged across all odorants, was 24.25 using a 100-point scale. This was not equally distributed across odorants, though this is in part due to the fact that odors at the edge of the scale can only vary in one direction. To facilitate a better comparison to that dataset, we identified odorants of comparable intensity, sampled random sets of 10, and ranked the explicit pleasantness ratings each subject gave those 10 odorants, then asked how variable ranks were across subjects. We did this 10,000 times, giving us an estimate of the low and high end of rank variability for random sets of 10 odorants. The average rank standard deviation was similar to the current data: DREAM average lowest *SD* (of 10 odorants) = 1.9; highest *SD* (of 10) = 2.7; mean *SD* = 2.4. Our data: lowest *SD* = 1.9; highest *SD* = 2.4; mean *SD* = 2.2. (G) A Plackett-Luce model (also known as exploded logit model or rank-ordered logit model) was constructed to perform full Bayesian inference on the rank data. In this hierarchical model, variance is partitioned between nested groups: individual, culture, and odorant identity. The left-hand panel shows the marginal posterior distribution for the parameters associated with this variance. Each sampling chain (semi-independent estimate of the posterior distribution) is shown in a different color, but all estimates converge to roughly the same distribution. The right-hand panel shows the mean and standard deviation of these posterior distributions. (H) Same as G but using a control in which we shuffled odorant labels in a manner that was consistent for each member of a culture but varied across cultures. This destroys any universal structure to odor preference.

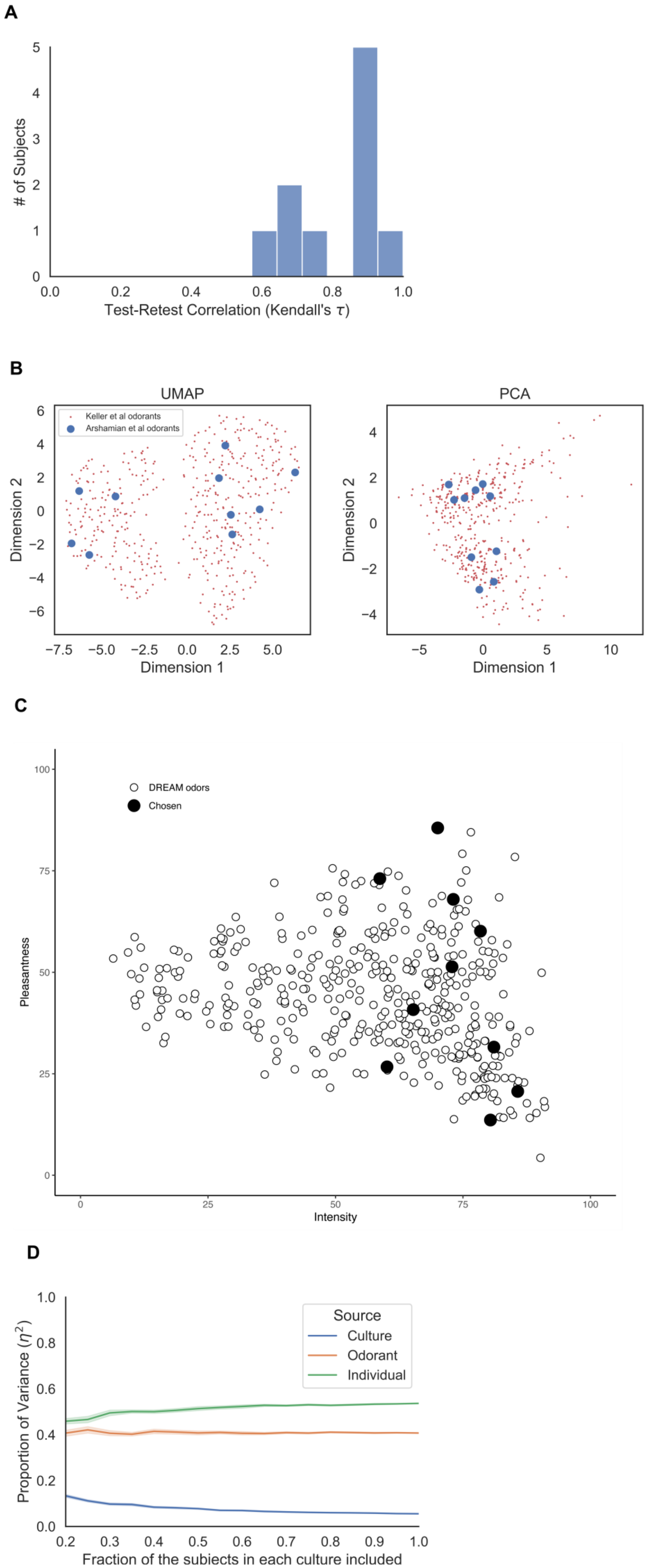
A
# of Subjects
Test-Retest Correlation (Kendall's τ)
B
UMAP
Keller et al odorants
Arshamian et al odorants
Dimension 2
Dimension 1
PCA
Dimension 2
Dimension 1
C
DREAM odors
Chosen
Pleasantness
Intensity
D
Source
Culture
Odorant
Individual
Proportion of Variance (η^2)
Fraction of the subjects in each culture included

Figure S2. Results of odor ranking experiment, related to Figure 3 and Star Methods.
(A) From our primary data collection, we are not able to disentangle the contributions of inherent individual differences in odor pleasantness versus perceptual or task-related noise. To disentangle this further, we ran a separate study where we tested the same participants twice on the ranking task described in Star Methods. To estimate the number of participants required, we first conducted a power analysis by simulation which showed that for a hypothetical rank correlation (Kendalls' τ) of 0.8, we would be powered to estimate τ with a standard error < 0.03 with 10 subjects. Based on this, we tested 10 participants (7 female and 3 male, M_{age} = 28.1 years, *SD* = 6.5 years) from Philadelphia, USA. We were unable to implement the study in our original fieldsites due to COVID related travel restrictions. All participants performed the rank order task, one day apart. The observed correlation (Kendall's τ) between the two days is shown in Figure S4, τ = 0.81 +/- 0.13 (median = 0.87), a high value ($-1 < \tau < 1$), indicating most individual variance in this setting was due to preferences of the individual rather than unexplained random variation. Since a laboratory is a controlled setting, this is likely to be an upper bound on intra-individual rank correlation and estimates may be lower under field conditions. We used this upper bound to create synthetic replicates of the original worldwide dataset, such that the computed τ across replicates matched that observed in the laboratory setting. Finally, we developed a simple generative linear model from four additive, independent variance terms (universal, culture, individual, noise) and asked for what values of these terms we obtain data that best resembles the real data (using a post-hoc analysis of variance). The % variance explained using the best-performing generative model closely resembled the estimates obtained using the original ANOVA (Figure 3), but now with a distinction between "individual" and "noise". Variance explained by the individual was 45.3 +/- 2.4 %, whereas noise variance was only 7.4 +/- 4.3%. Thus, the variance explained by individual preference in the original model (Figure 3) is still large, and not due primarily to perceptual or task noise. (B) All odorants from the DREAM dataset [S1] (red) and the subset selected for the current study (blue). (Left) Uniform Manifold Approximation and Projection (UMAP) plot of Mordred [S2] physicochemical features; (Right) Principal Components Analysis (PCA) of the same features. The 10 selected odorants are well-distributed in physicochemical space. (C) Comparison of current odorant sample to DREAM dataset [S1]. Average intensity ratings (across subjects) are plotted on the x-axis and average pleasantness ratings on the y-axis. Open circles represent all odorants at the higher of two tested concentrations of the DREAM dataset, and the 10 odorants chosen for the current study are filled circles. (D) The same analysis shown in Figure 3 using progressively larger subsets of the original data. For each fraction from 0.2 to 1, we drew 25 random subsets of that fraction of participants (rounded to the nearest integer) from each culture, used that as our source data, and repeated the ANOVA. Beyond ~½ of the subject pool, we did not observe any meaningful change in results.

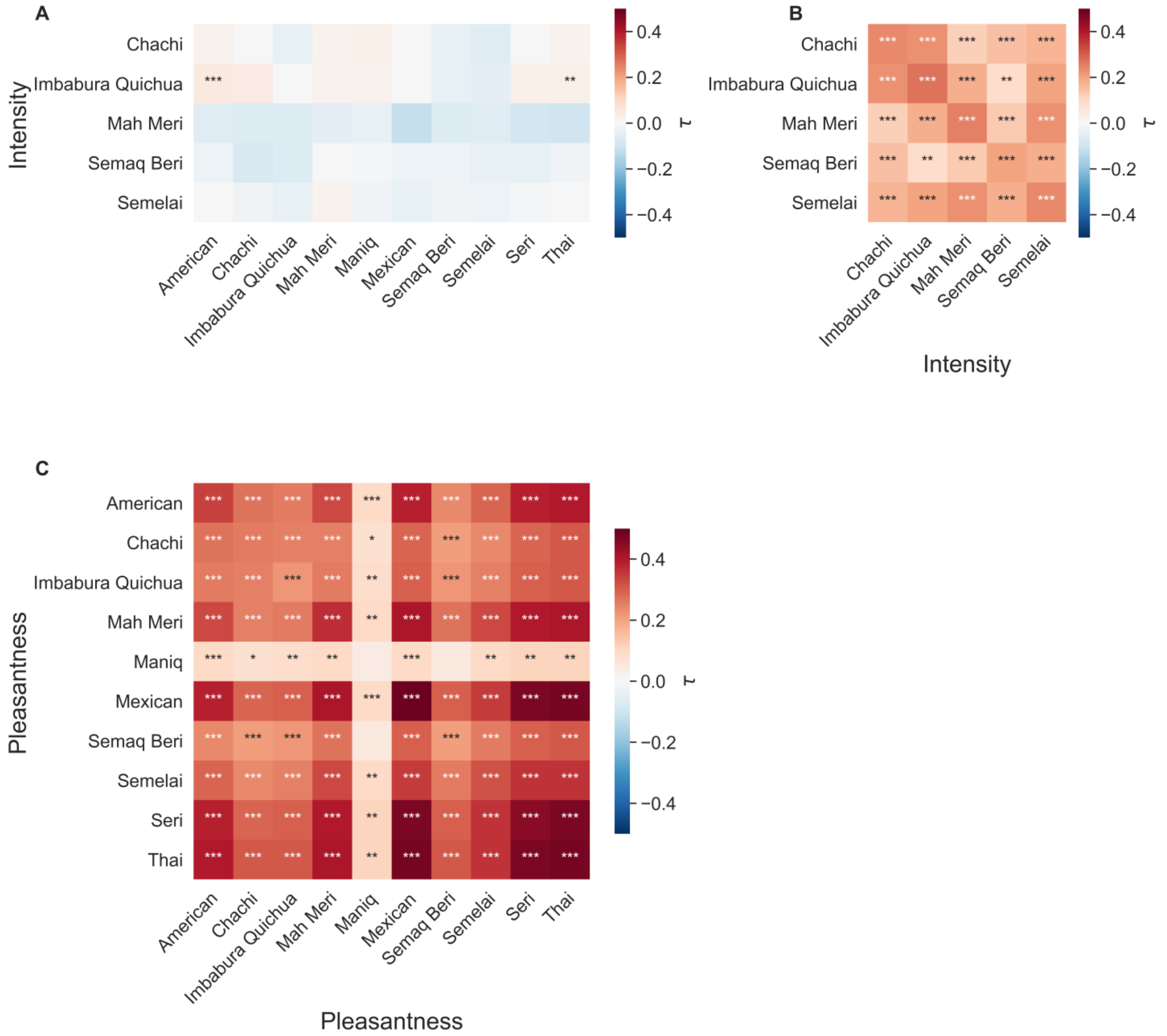

Figure S3. Results of intensity ranking experiment, related to Star Methods and Figure 2. (A) Rank correlations (Kendall's τ) between individuals of ranked pleasantness of the 10 test odorants (x-axis) and ranked intensity of the same 10 odorants (y-axis) were computed, and mean τ reported for pairs of individuals within and across cultures. Correlations were consistently near zero and not significant. Note, intensity data was collected in only some cultures, but from the same set of individuals as pleasantness data. (B) The correlation between individuals for intensity alone was significantly positive, suggesting a "universal intensity" factor that is independent of pleasantness. (C) The correlation between individuals for pleasantness alone is positive and significantly greater than observed for intensity. In all panels, comparisons between individuals and themselves were excluded. All rank correlations are annotated with statistical significance according to a binomial test, comparing the fraction of pairs of individuals that had $\tau > 0$ against the null hypothesis of fraction ½, and applying Bonferroni correction for multiple comparisons. *$p < 0.01$; ** $p <$ 1e-4; *** $p <$ 1e-10.

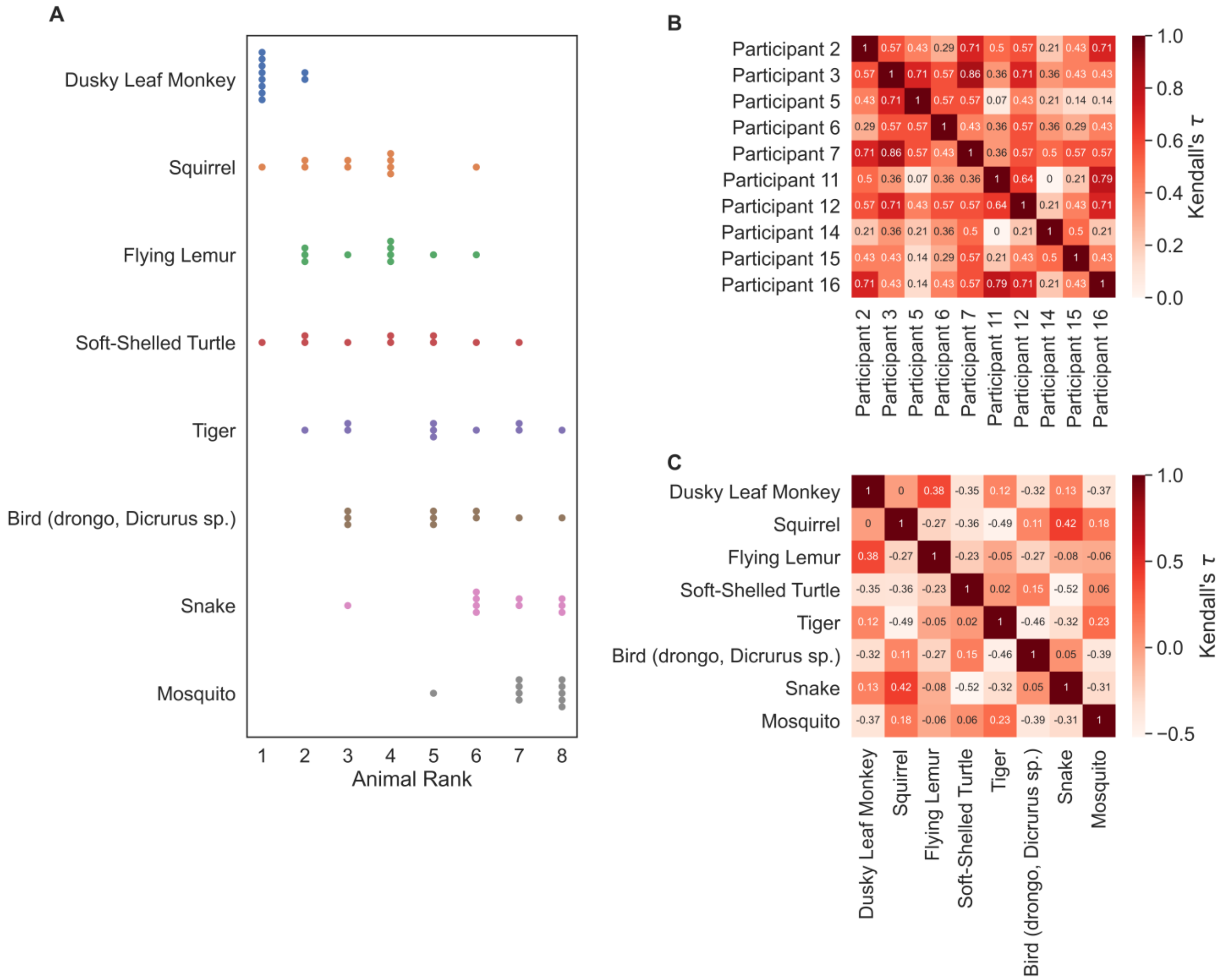

Figure S4. Results of protocol validation for Maniq, related to Star Methods.
As the Maniq are not accustomed to formal testing, we included a control task to confirm they could rank stimuli. We asked a subset of the same Maniq participants to rank order a set of 8 photographs of animals according to their hedonic value from most pleasant to most unpleasant (left-to-right). We were able to test ten of the original 16 Maniq participants who participated in the odor pleasantness ranking task with this protocol. Animals were chosen so they varied in hedonic value, established according to long-term ethnographic fieldwork by author EW. Maniq participants were able to rank items in an ordinal fashion. (A) Each dot is the ranking given by one subject for one animal. (B) Rank correlation (Kendall's τ between participants). (C) Rank correlation between animals.

Source	SS	DF	MS	F	p-unc	n2
Odorant	9403.903	9.0	1044.878	227.827	2.470e-323	0.408
Culture x Odorant	1282.366	81.0	15.832	3.452	3.729e-22	0.056
Residual	12382.965	2700.0	4.586	NaN	NaN	0.537

Table S1: ANOVA table for original data, related to Figure 3.
We conducted a two-way analysis of variance (ANOVA) using odorant identity and culture to determine observed ranks for each individual/odorant pair, as described in the main text. The dependent variable is each integer corresponding to the ranking of one odorant by one individual. The first factor "Odorant" represents the identity of odorants, i.e., one of 10 categorical values. The second factor is the identity of the culture, also one of 10 categorical values. Each individual only ranked odorants once (in the main experiment), so there are no additional factors/levels. Importantly, the culture factor has no net effect by itself (because all individuals must give the same ten ranks, so within each culture all ranks will be used an equal number of times), and is not considered further. "Culture" exerts its effect through the interaction between the two main factors, so it is this interaction we label "Culture" in all analysis based on ANOVA. As our controls in Figure 3 show, had there been a rank order preference shared within but not across each culture, this interaction term would have explained a substantial portion of the variance; thus, this effect was in principle identifiable. Because the residual component of the variance can be explained only by some combination of individual preferences and noise, we label it "Individual". We conducted alternative analyses to handle the non-independence of ranks in Figure S1G-H, and conducted an additional experiment to disambiguate individual preferences and noise in Figure S2A.

PubChem ID	IUPAC Name	Common or trivial name	Quality descriptors	Example of natural sources containing the odorant
10430	3-Methylbutanoic acid	Isovaleric acid	cheese, ripe fatty, sour stinky feet, sweaty, dairy, rancid, fermented, fruity note	human sweat, rancid plant and animal-based fats
8077	Diethyl disulfide	N/A	gassy ripe onion, greasy garlic	garlic, lychee, durian
379	Octanoic acid	Caprylic acid	fatty, waxy, rancid, oily, vegetable, cheesy	coconut oil, mammalian milk
32594	2-Isobutyl-3-methoxypyrazine	Galbazine	green pea, green bell-pepper, galbanum, natural, nutty, roasted	peanuts, grape, baked potato
18827	1-Octen-3-ol	Mushroom alcohol	mushroom, earthy green, oily fungal, raw chicken	one of the most abundant volatile organic compounds produced by fungi
6054	2-Phenylethan-1-ol	Phenethyl alcohol	sweet, floral, rose, fresh and bready with a rose and honey nuance	many different types of fresh fruits (e.g., tomato) and flowers (e.g. rose), olive oil
7762	Ethyl butanoate	Ethyl butyrate	fruity, juicy fruit, pineapple, cognac Fruity, sweet, tutti frutti, apple, fresh and lifting, ethereal	many different types of fresh fruits (strawberry, melon, Spondias *mombin L,* dalieb fruit) as well as ripe fruit (banana, nectarines, kiwi)
3314	2-Methoxy-4-(prop-2-en-1-yl)phenol	Eugenol	sweet, spicy, clove like, woody, with phenolic savory ham and bacon notes and cinnamon and allspice nuances	clove, betel pepper, cinnamon, tulsi, bay leaf, turmeric, nutmeg, thyme
6549	3,7-Dimethylocta-1,6-dien-3-ol	Linalool	citrus, orange, floral, sweet, rose, woody, green, blueberry, terpy, waxy	one of the most common single compounds in floral scents (>50% of all families investigated); also, present in many fruits (e.g., lemon, grapefruit, tangerine, grape, blueberry, apple)
1183	4-Hydroxy-3-methoxybenzaldehyde	Vanillin	vanilla, vanillin, sweet, creamy, spicy, phenolic and milky	with two known exceptions, it is exclusively present in orchids of the genus Vanilla**.**

Table S2: Odorants, their descriptors, and potential natural sources, related to Star Methods. This table provides further information about each odorant with their chemical and common names, odor quality descriptors in English, and potential natural sources which have been extracted from The Good Scents Company (www.thegoodscentscompany.com). This web resource aggregates chemical and usage information about odors and flavors from several databases (e.g., PubMed, EINECS, FEMA).

Supplemental References

S1. Keller, A., Gerkin, R.C., Guan, Y., Dhurandhar, A., Turu, G., Szalai, B., Mainland, J.D., Ihara, Y., Yu, C.W., Wolfinger, R., et al. (2017). Predicting human olfactory perception from chemical features of odor molecules. Science 355, 820–826.

S2. Moriwaki, H., Tian, Y.-S., Kawashita, N., and Takagi, T. (2018). Mordred: A molecular descriptor calculator. J Cheminform 10, 4.