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# Humans Can Discriminate More than 1 Trillion Olfactory Stimuli

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# Humans Can Discriminate More than 1 Trillion Olfactory Stimuli

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**Humans can discriminate several million different colors and almost half a million different tones, but the number of discriminable olfactory stimuli remains unknown. The lay and scientific literature typically claims that humans can discriminate 10,000 odors, but this number has never been empirically validated. We determined the resolution of the human sense of smell by testing the capacity of humans to discriminate odor mixtures with varying numbers of shared components. On the basis of the results of psychophysical testing, we calculated that humans can discriminate at least 1 trillion olfactory stimuli. This is far more than previous estimates of distinguishable olfactory stimuli. It demonstrates that the human olfactory system, with its hundreds of different olfactory receptors, far outperforms the other senses in the number of physically different stimuli it can discriminate.**

To determine how many stimuli can be discriminated, one must know the range and resolution of the sensory system. Color stimuli vary in wavelength and intensity. Tones vary in frequency and loudness. We can therefore determine the resolution of these modalities along those axes and then calculate the number of discriminable tones and colors from the range and resolution. Humans can detect light with a wavelength between 390 and 700 nm and tones in the frequency range between 20 and 20,000 Hz. Working within this range, researchers carried out psychophysical experiments with color or tone discrimination tasks in order to estimate the average resolution of the visual and auditory systems. From these experiments, they estimated that humans can distinguish between 2.3 million and 7.5 million colors (*1*, *2*) and ~340,000 tones (*3*). In the olfactory system, it is more difficult to estimate the range and resolution because the dimensions and physical boundaries of the olfactory stimulus space are not known. Further, olfactory stimuli are typically mixtures of odor molecules that differ in their components. Therefore, the strategies used for other sensory modalities cannot be applied to the human olfactory system. In the absence of a straightforward empirical approach, theoretical considerations have been used to estimate the number of discriminable olfactory stimuli. An influential study from 1927 posited four elementary odor sensations with sufficient resolution along those four dimensions to allow humans to rate each elementary sensation on a nine-point scale (*4*). The number of discriminable olfactory sensations was therefore estimated to be $9^4$ or 6561 (*4*). This number was later rounded up to 10,000 and is widely cited in lay and scientific publications (*5*–*7*). Although this number was initially calculated to reflect how many olfactory stimuli humans can discriminate, it has also sometimes been used as the number of different odor molecules that exist, or the number of odor molecules that humans can detect. We carried out mixture discrimination testing to determine a lower limit of the number of olfactory stimuli that humans can discriminate.

Natural olfactory stimuli are almost always mixtures of large numbers of diverse components at different ratios. The characteristic scent of a rose, for example, is produced by a mixture of 275 components (*8*), although typically, only a small percentage of components contribute to the perceived smell. We reduced the complexity by investigating only mixtures of 10, 20, or 30 components drawn from a collection of 128 odorous molecules (table S1). These 128 molecules were previously intensity-matched by Sobel and co-workers, which enabled us to produce mixtures in which each component contributes equally to the overall smell of the mix-

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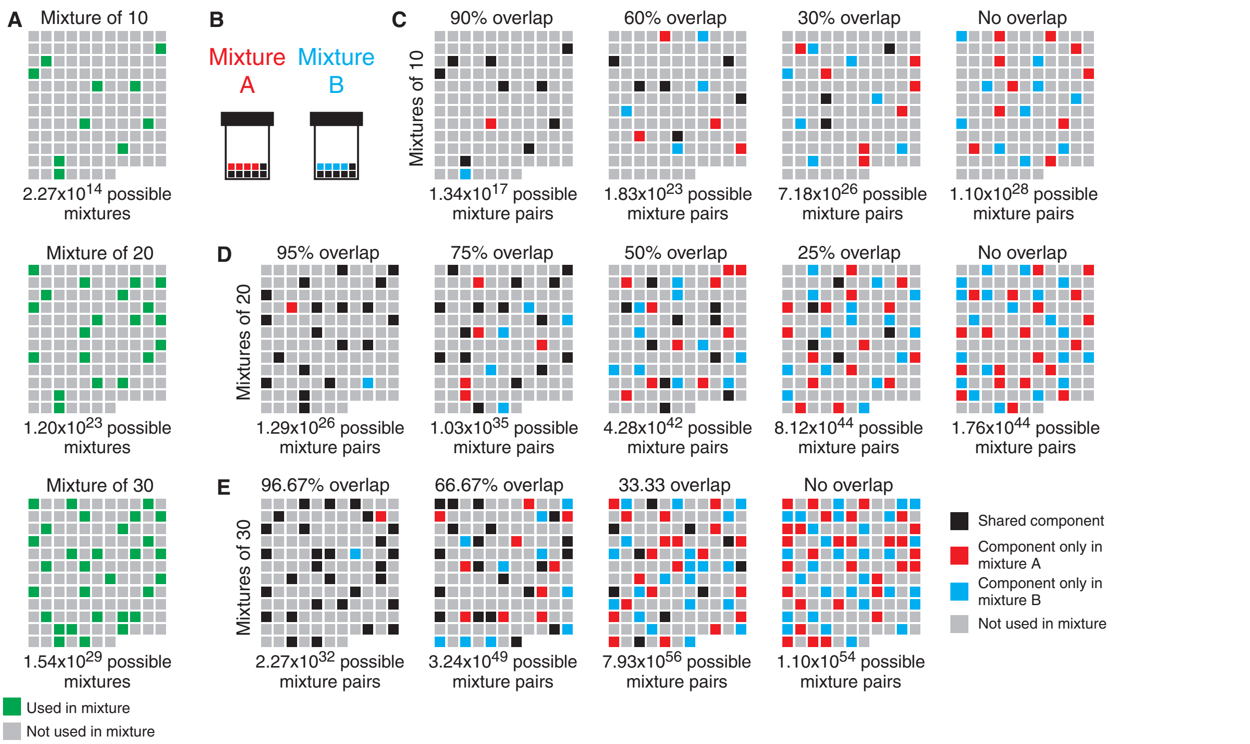


**Fig. 1. Odor mixtures used to test the resolution of the human olfactory system.** (**A**) Illustration of sample mixtures with exactly 10, 20, or 30 components (green squares) picked from a collection of 128 odorous molecules (gray squares) and the number of possible mixtures of each type. (**B**) Example of one mixture pair. (**C** to **E**) Schematics of each of the 13 types of odor pairs used for discrimination tests, along with the total number of possible mixture pairs of each type.

ture (9). The 128 molecules cover much of the perceptual and physicochemical diversity of odorous molecules (10–12) because the collection contains most of a collection of 86 odorous molecules that were selected to be well distributed in both perceptual and physicochemical stimulus space (9).

To generate each mixture, we combined these components together at equal ratios. The 128 components can be combined into $2.27 \times 10^{14}$ different mixtures of exactly 10, $1.20 \times 10^{23}$ different mixtures of exactly 20, and $1.54 \times 10^{29}$ different mixtures of exactly 30 (Fig. 1A). The most salient difference between two mixtures with the same number of components is the percentage of components in which they differ. We therefore performed psychophysical testing to determine the resolution of the human olfactory system along this axis. We asked by what percentage two mixtures must differ on average so that they can be discriminated by the average human nose. This percentage difference in components is the resolution of the olfactory system.

Subjects performed forced-choice discrimination tests to determine the discriminability of pairs of mixtures (referred to here as "mixture A" and "mixture B") that varied in the percentage of shared components (Fig. 1B). In double-blind experiments, subjects were presented with three odor vials, two of which contained the same mixture, whereas the third contained a different mixture. The testing procedure was computerized by using a custom-written application in which subjects were instructed to identify the odd odor vial on the basis of odor quality. Each subject completed the same 264 discrimination tests. The order of the tests was randomized. For each of 13 types of stimulus pairs (Figs. 1, C to E, and 2A), 20 different stimuli pairs were tested, for a total of 260 mixture discrimination tests. In addition, four control discrimination tests comprising individual odor molecules were interleaved across the mixture discrimination tests so as to measure general olfactory acuity and subject compliance. Because we wished to ensure that discrimination was based on odor quality differences and not small intensity differences, one of the three stimuli in a test was diluted in propylene glycol at a 1:2 ratio, the other at a 1:4 ratio, and the third was not diluted. The dilutions were assigned to the stimuli at random. The components and dilutions of all stimuli used in this study are given in table S2.

Twenty-eight subjects completed the study, but two were excluded from the analysis because they failed to correctly identify the odd odor in at least three of the four control tests. Data from 26 subjects [17 female; median age 30 (range of 20 to 48); 14 Caucasian, 5 African-American, 5 Asian, 2 Other; 4 Hispanic] are included in the analysis presented here.

Pairs of mixtures are more difficult to distinguish the more they overlap. At least half of the tested subjects could discriminate mixture pairs that overlapped by less than 75% of their components. Some could also discriminate mixture pairs that overlapped by 75 and 90%, but none could discriminate mixture pairs with more than 90% overlap (Fig. 2B). In this evaluation, the results of 20 mixture pairs of a certain type (for example, mixtures of 20 components that overlap by 75%) are pooled. Specific mixture interactions that are known to occur in odor mixtures, such as synergy and masking, are averaged out. To assess whether this biased our results, we also analyzed the results for each individual mixture pair, averaged across the 26 subjects (Fig. 2C). The results of this analysis were very similar. Of the 260 pairs of mixtures that were tested for discriminability, subjects performed above chance level for 227. For 148 of those, 14 or more of the 26 subjects (54%) chose the correct vial, resulting in a statistically significant difference from chance (Fig. 2C).

The resolution (or difference limen) of the visual and auditory system is defined as the difference in frequency between two stimuli that is required for reliable discrimination. In the olfactory system, resolution can be defined as the highest percentage overlap in components between two mixtures at which those mixtures can be distinguished. The resolution of the olfactory system is not uniform across the olfactory stimulus space. For example, half of the mixtures of 20 components with 50% overlap could be discriminated, whereas the other half were indiscriminable (Fig. 2C, middle). Nonuniform resolution across stimulus spaces is also found in other sensory systems. In hearing, for example, frequency resolution is much better at low than at high frequencies (3). In vision, wavelength discrimination is best near 560 nm, at which a difference in wavelength of 0.2 nm can be discriminated under optimal conditions (13).

We extrapolated functions that relate the percentage mixture overlap to mixture discriminability from our data. The function that relates the percentage mixture overlap ($x$) with the percentage of subjects that can discriminate the mixtures ($y$) is $y = -0.81x + 91.45$ (Fig. 3A). The function that relates the percentage mixture overlap ($x$) with the percentage of discriminable pairs ($y$) is $y = -0.77x + 94.22$ (Fig. 3B). According to these formulae, most subjects can discriminate mixture pairs that overlap by less than 51.17%. Most pairs that overlap by less than 57.43% can be discriminated.

To calculate a lower limit of how many discriminable mixtures there are, the number of possible mixtures and the difference between two mixtures that renders them indistinguishable have to be known. There are $2.27 \times 10^{14}$ possible mixtures of exactly 10 (out of 128), $1.20 \times 10^{23}$ possible mixtures of exactly 20, and $1.54 \times 10^{29}$ possible mixtures of exactly 30. Using the numbers from our data, a lower limit of how many discriminable mixtures there are can be calculated. Mathematically, this

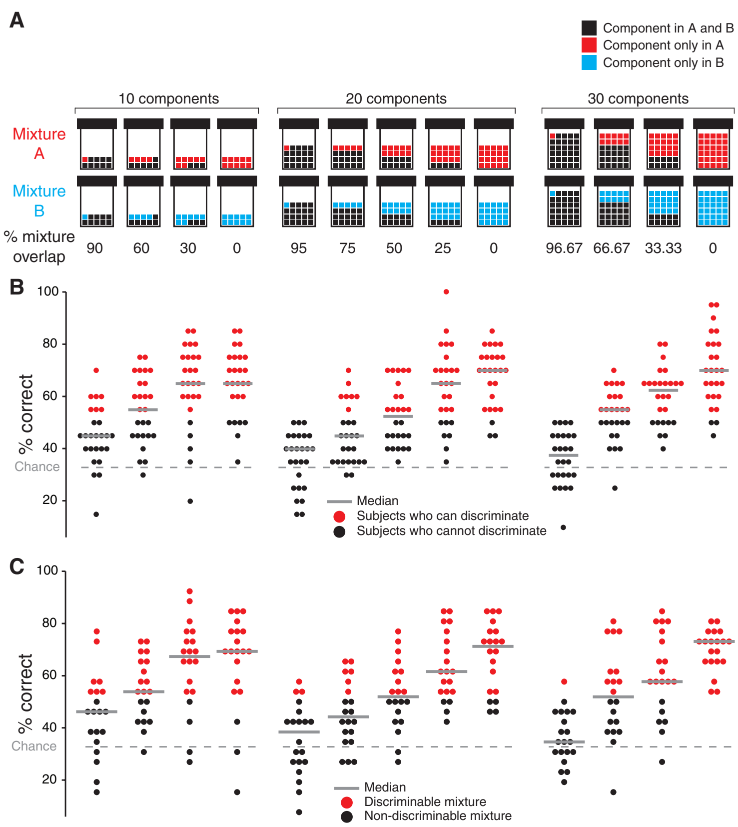


**Fig. 2. An empirical investigation of the resolution of the human olfactory system. (A)** Schematic of the discrimination tests carried out for mixtures of 10, 20, or 30 odorous molecules. **(B and C)** Results of discrimination tests with 26 subjects asked to discriminate mixtures of 10 (left), 20 (middle), or 30 (right) components with decreasing overlap from left to right. The dotted line represents the chance detection level (33.3%). For (B), dots represent performance of individual subjects across 20 mixture pairs. For (C), dots represent average performance of all 26 subjects for a given mixture pair. Statistically significant discriminability (red dots) was assessed with a $\chi^2$ test; $P < 0.05$.

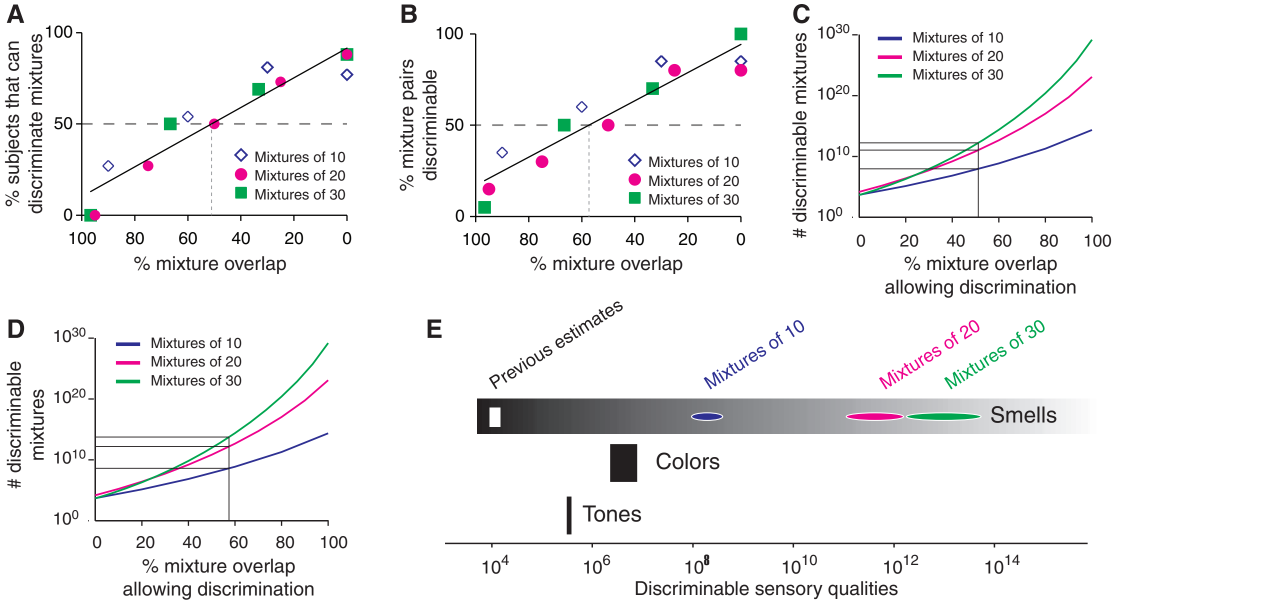


**Fig. 3. The number of discriminable olfactory stimuli.** (**A**) Discrimination capacity of subjects according to percentage of mixture overlap. (**B**) Discriminability of mixture pairs according to percentage of mixture overlap. (**C**) Extrapolation of the number of discriminable mixtures derived from (A). (**D**) Extrapolation of the number of discriminable mixtures derived from (B). (**E**) Summary of discriminable sensory stimuli across sensory modalities. Data are curated from the following sources: smells (previous estimates) (*5*–*7*), tones (*3*), and colors (*1*, *2*).

presents a coding problem that can be formulated in information theory as a problem of packing spheres in multidimensional space (*14*). The solution to this problem (details are available in the supplementary materials, materials and methods) shows that a resolution of 51.17% overlap results in $9.37 \times 10^7$ distinguishable mixtures of exactly 10, $1.12 \times 10^{11}$ mixtures of exactly 20, and $1.72 \times 10^{12}$ mixtures of exactly 30 (Fig. 3C). A resolution of 57.43% overlap results in $4.01 \times 10^8$, $1.55 \times 10^{12}$, and $5.58 \times 10^{13}$ discriminable mixtures, respectively (Fig. 3D).

Mixtures that overlap by less than 51.17% can be discriminated by the majority of subjects, which means that humans can, on average, discriminate more than 1 trillion mixtures of 30 components. However, there are large differences between subjects. The number of discriminable mixtures with 30 components in one subject of this study is $1.03 \times 10^{28}$, whereas it is only $7.84 \times 10^7$ in another subject (fig. S1).

One can calculate the number of mixtures that can be discriminated by either using the discrimination capacity of subjects or by the discriminability of stimulus pairs. Depending on what criteria are used, our results show that humans can discriminate $1.72 \times 10^{12}$ or $5.58 \times 10^{13}$ mixtures of 30 components out of the collection of 128 odorous molecules. $1.72 \times 10^{12}$ may seem like an astonishingly large number. However, there are $1.54 \times 10^{29}$ possible mixtures of 30 from the 128 components used here. Therefore, if there are $1.72 \times 10^{12}$ discriminable stimuli, this means that for each mixture tested there will be $8.95 \times 10^{16}$ other mixtures that cannot be discriminated from it.

Our results show that there are several orders of magnitude more discriminable olfactory stimuli than colors (*1*, *2*) or tones (*3*) (Fig. 3E). Colors are spatially arranged to create a large number of visual objects that are the building blocks of visual experiences, and tones can be combined to form a large number of chords that form auditory objects. The number of visual and auditory objects is much larger than the number of colors and tones, but it is unknown how many of these objects humans can discriminate. However, the difference between the number of discriminable olfactory stimuli and colors or tones is even larger if one considers that the number of discernible tones and colors includes stimuli that differ in loudness or brightness. We focused here only on stimulus quality and ruled out intensity-based discrimination. Thus, our estimate of $1.72 \times 10^{12}$ is a conservative one yet is still several orders of magnitude higher than previous estimates of the number of discriminable olfactory stimuli (*5*–*7*). The actual number of distinguishable olfactory stimuli is likely to be even higher than $1.72 \times 10^{12}$ for three reasons. First, it is currently not known how many odorous molecules there are or how many of them can be discriminated from the others. However, there are considerably more possible odorous molecules than the 128 different components that we used. Second, components can be combined in mixtures of more than 30 components. Third, even mixtures with the same components can be distinguished if the components are mixed at different ratios (*15*). Our results therefore establish only a lower limit of the number of discriminable olfactory stimuli. Although this lower limit of greater than 1 trillion is several orders of magnitude more than distinguishable colors or tones, it is presumably dramatically lower than the actual number of discriminable olfactory stimuli.

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### Supplementary Materials

www.sciencemag.org/content/343/6177/1370/suppl/DC1
Materials and Methods
Fig. S1
Tables S1 and S2

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