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Analysis and Synthesis in Olfaction

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ABSTRACT: Natural environments contain numerous volatile compounds emanating from a large number of sources, and the survival of many animals depends on their ability to segregate odors of interest within complex odorous scenes. In a recent paper, we described how the ability of mice to detect odors within mixtures depends on the chemical structure and neural representation of the target and background odorants.

Odorous objects vary greatly in the number of volatile compounds of which they are composed, yet all are perceived as single objects, and human subjects cannot tell whether a smell is elicited by a single odorant or by a mixture.[1] This inability to perceive the complexity of an odor is the basis for the widely held view that olfaction is a synthetic sense in which mixtures of odorants are perceived as a whole at the expense of the perception of individual components. Further support for this view comes from experiments showing that human subjects cannot detect a target odorant when it is embedded in a mixture of just a few background odorants.[2] However, while synthesis may play a crucial role in object recognition, segregating odors of interest from complex backgrounds is crucial for the survival of many macrosmatic species. In a recent paper, we described the results of a behavioral test of olfactory figure-ground segregation in mice.[3] Mice were trained on a Go−No-Go task in which they were presented with pseudorandom mixtures of up to 14 components and were required to report the detection of target odorants by licking a water spout that was positioned in front of their mouth (Figure 1A). We found that mice were highly capable of performing the task and responded correctly in ∼90% of the trials with accuracy gradually decreasing as the number of mixture components increased (Figure 1B).

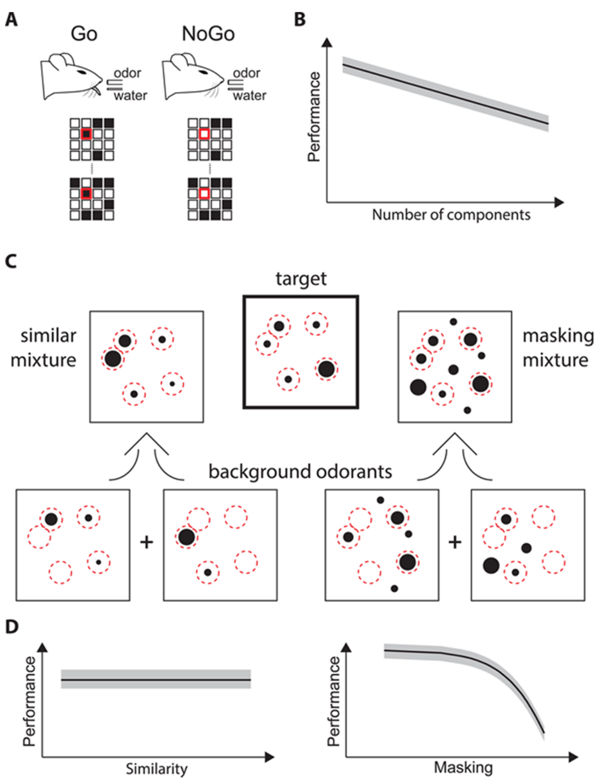

Figure 1. Olfactory figure-ground segregation in mice. (A) Mice were presented with random mixtures chosen from a pool of 16 odorants and were trained to report the presence of a specific target odorant (red square) by licking a water spout. Each odor was either on (filled squares) or off (empty squares) in each trial resulting in almost 50000 possible mixtures. (B) Behavioral performance degraded as the number of background odorants increased. (C) A cartoon depicting two parameters that describe relationships between the target and the background representations by olfactory bulb glomeruli. Background odorants may combine to activate glomerular patterns that are similar to the target pattern (left) or may mask the target by overactivating glomeruli that represent it (right). Black circles are activated glomeruli with the size of the circle denoting the level of activation. Red dashed circles show glomeruli activated by the target odorant. (D) Behavioral performance is insensitive to the similarity between target and background glomerular responses (left), but drops as the masking of the target pattern increases (right).

Our goal was to provide a description of the relationship between the composition of the figure and background and the difficulty of segregation. In the visual and auditory systems, difficulty of segregation is related to the similarity between features of the figure and the background. One would find a red circle in a blue background with higher fidelity and speed compared with a red circle in a magenta or pink background. A more general description that relates behavioral performance to parameters of the figure and background is typically provided by plotting a psychometric curve in which the behavioral performance is plotted against the stimulus parameter of interest (in this case, the difference in wavelength between the figure and background). However, there is no agreed metric for describing chemical compounds, and therefore olfactory stimuli are not easily parametrized.

We adopted two different approaches to overcome this limitation. First, we analyzed the dependence of target detection on the number of background odorants containing the same

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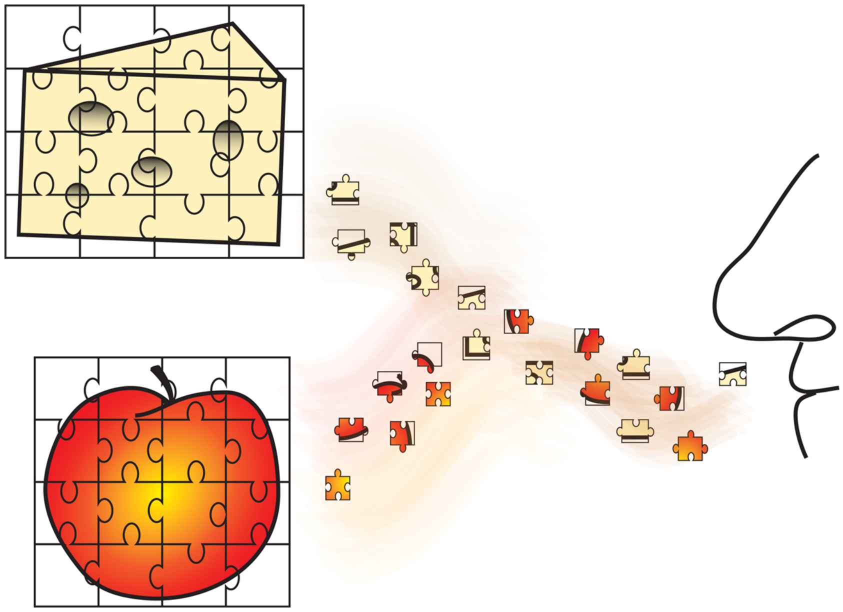

Figure 2. Synthesis and analysis in olfactory scene segmentation. The cheese and the apple are each composed of multiple odorants (symbolized by puzzle pieces). Segmentation of this scene requires synthetic abilities to combine the pieces from a common puzzle and, at the same time, analytic abilities to segregate between the two puzzles.

functional group as the target (tiglic acid). While this is not a quantification of chemical similarity, it provides some insight into the relationship between segregation difficulty and chemical composition. We found that performance was inversely correlated with the number of background odorants that shared the target's functional group but was insensitive to other background odorants, indicating that a common functional group is accompanied by stronger masking of the target.

The second approach was to base our analysis on the representation of odorant identity by olfactory receptors rather than on physicochemical features. These representations provided a well-defined metric for comparing odorants. To this end, we turned to optical imaging and recorded odorant responses of olfactory bulb glomeruli (each representing a single receptor type) in mice expressing the genetically encoded Ca^{2+} indicator GCaMP3 in all olfactory receptor neurons. Each odor was then described as a response vector in olfactory glomerular space allowing us to test how behavioral performance correlated with mathematically defined relationships between the representations of the target and background. We found that behavioral performance was best explained by the amount of overlap between the representations of the target and background odorants (Figure 1c,d).

From these experiments, we concluded that (1) the mouse olfactory system has a strong analytic ability and can detect odors of interest against rich backgrounds, (2) the difficulty of figure-ground segregation is related to the chemical similarity between the figure and background components, and (3) the difficulty of segregation is related to the amount of overlap in the representations of the figure and background components by olfactory receptor neurons.

So how do we reconcile the view of olfaction as a synthetic sense with our conclusion that olfaction has analytic abilities? Is olfaction a synthetic sense or is it analytic? We would argue that olfaction, like other senses, is both analytic and synthetic. It is synthetic for the purpose of perceiving multiodorant objects and analytic to segregate these objects from background smells. This is not different from vision and audition. When in an orchestral concert, we can easily segregate the sounds of the horns from the sounds of the strings. However, both the horns and the strings are identified by combinations of frequencies that need to be grouped to synthesize the percept of an auditory object. Similarly, in the presence of multiple odorous objects, the olfactory system identifies the objects by their unique combinations of volatile compounds and, at the same time, segregates among these objects (Figure 2).

The difference between sensory systems is not in their label of synthetic versus analytic; it is a difference in the sensory cues that are used to perform analysis and synthesis and the boundaries of stimulus complexity with which it can deal. For instance, both the visual and the auditory systems may use the location of a stimulus in space to guide synthesis and segregation. Two stimuli at the same (or nearby) location probably originate from the same object. While spatial information most probably contributes very little to olfactory scene analysis, coordinated fluctuations in time may be used as a signal for grouping components.[4] An experience-dependent learning process in which the statistics of odorous scenes and the behavioral relevance of specific components is inferred may be a fundamental determinant of olfactory scene analysis.[5] If certain components always appear together and signify an object of interest, they most probably will elicit a holistic percept. However, if individual components (or submixtures) carry information that is useful for the animal, these components will be perceived analytically. Future behavioral experiments that combine requirements for both analytic and synthetic perception will be necessary to elucidate the determinants of synthesis and analysis in olfaction.

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Notes

The authors declare no competing financial interest.

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