

# Learning from spiny lobsters about chemosensory coding of mixtures

Charles D. Derby\*

Department of Biology and Center for Neural Communication & Computation, Georgia State University, P. O. Box 4010, Atlanta, GA 30302-4010, USA

## Abstract

Studies of the peripheral olfactory system of the Caribbean spiny lobster *Panulirus argus* and related decapod crustaceans have helped us understand mechanisms of coding of mixtures, some of which are discussed in this review. Although the number of cells in the lobster's olfactory system is much lower than in vertebrate olfactory systems, it is a highly complex system. The receptor neurons (RNs) of this olfactory system are complex processors that cannot be categorized into discrete cell types, but rather have a diversity of response profiles. Each RN can have different types of receptor proteins, second messengers, and/or ion channels, which undoubtedly contributes to the functional diversity of these neurons and makes them complex peripheral integrators. The RNs probably encode information about the quality of mixtures as a distributed or population code, providing a basis for behavioral discrimination of natural food stimuli. Analysis of distributed codes for a series of blend ratios of binary mixtures reveals that the qualities of individual compounds are probably not lost when mixed. Such peripheral processing allows spiny lobsters to perceive complex odors as a set of elemental cues if the salience of the components is sufficiently high. © 2000 Elsevier Science Inc. All rights reserved.

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## 1. Introduction

The conceptual and technical approaches that have been used successfully by Erickson and others to study coding in the taste systems of mammals, which include characterizing tuning properties of cells, defining the information contained in assemblages of these cells, and comparing neural output with behavioral discrimination capabilities [22,23], are equally applicable for studying chemosensory systems of invertebrates. One of the goals of my and other laboratories has been to explore how the chemosensory systems of decapod crustaceans, such as lobsters, crabs, and crayfish, are functionally organized to allow these animals to solve problems related to finding food and mates. We can then compare their functional organization with that of other animals to decipher common principles of coding and specific adaptations to different environments.

In this article, I will review our current understanding of mechanisms of olfactory coding of mixtures based on studies of the peripheral olfactory system of the Caribbean spiny lobster *Panulirus argus*. First, I will describe the general organization of the crustacean olfactory system. Second, I will show that this system is composed of receptor neurons (RNs) that are complex peripheral processing units that represent a diversity of response profiles rather than belonging

to obvious cell types. Third, I will argue that a distributed or population code in their olfactory organ contains sufficient information to allow spiny lobsters to discriminate the quality of biologically relevant mixtures. Finally, I will show that spiny lobsters can process odor mixtures either as elements (i.e., a combination of the identifiable components) or as a configuration (i.e., a mixture-unique entity). Furthermore, this flexibility in mode of processing is possible because, as revealed by the distributed codes in the peripheral olfactory system, the qualities of individual compounds are not lost when the compounds are mixed to form a blend.

## 2. Crustaceans as models for studying olfactory coding

The chemosensory systems of aquatic crustaceans have been used successfully to study many aspects of chemosensory coding, from the molecular to behavioral levels [1,2,4,8,9,31,56,58]. One species that has been studied extensively is the Caribbean spiny lobster, *Panulirus argus*. Of particular interest has been its olfactory organ—the antennules, which are the first pair of antennae (Fig. 1).

Antennular chemical sensing is called “olfaction” in these aquatic animals on the basis of morphological and functional similarities with “olfactory” systems of other animals—antennae of insects and other arthropods, and the olfactory organ of vertebrates [3]. All of these “noses” contain modified ciliary cells that are bipolar, with apical processes (dendrites or cilia) containing the transduction machinery

\* Tel.: 404-651-3058; Fax: 404-651-2509

E-mail address: cderby@gsu.edu

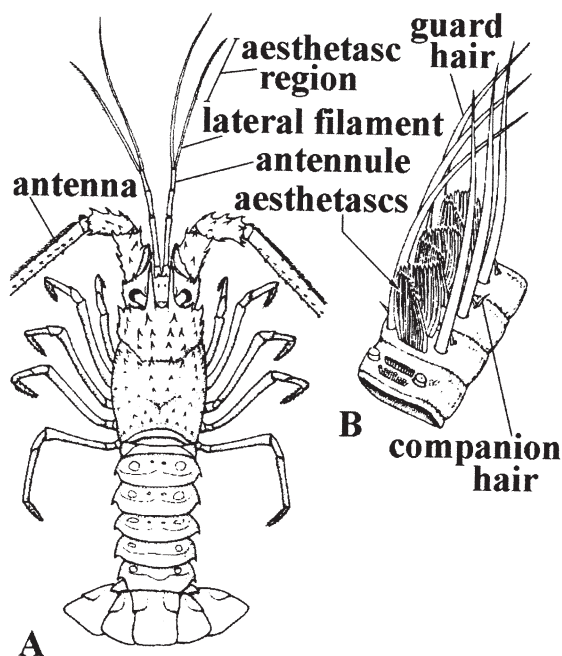


Fig. 1. Peripheral olfactory system of the spiny lobster *Panulirus argus*. (A) Spiny lobster with its first pair of antennae, called the antennules. (B) High-magnification view of the aesthetasc region of the lateral filament of the antennule. From [34].

made accessible to environmental chemicals, and axons that project to the CNS [1,5,34,46]. There are anatomical similarities in the first-order olfactory processing centers in the brains of crustaceans, insects, vertebrates, and other animals, all of which have their neuropil organized as glomeruli [1]. The long-held suggestion that this glomerular organization is a way of partitioning odor qualities in the CNS is supported by physiological and molecular studies of insects and vertebrates [6,27,36]. The “noses” of crustaceans are also similar to those of vertebrates in that they often contribute to chemically activated complex behaviors, such as courtship behavior [4,31] and food-searching behavior [4,42]. However, because the “noses” of lobsters function in aquatic environments, the chemicals that serve as stimuli tend to be fairly small water-soluble molecules such as amino acids, amines, nucleotides, and sometimes sugars and peptides [7]. Thus, the stimulatory chemicals for aquatic crustaceans are more similar to those detected by olfactory and taste systems of fish and taste systems of terrestrial vertebrates than the volatile compounds used by the olfactory systems of terrestrial vertebrates and arthropods.

There appear to be at least two antennular chemosensory pathways of decapod crustaceans: aesthetasc, and nonaesthetasc pathways (Fig. 1). The aesthetasc pathway refers to a specialized type of sensillum, the aesthetascs, each of which contains hundreds of chemosensory neurons but no mechanoreceptor neurons [34,35]. The aesthetasc chemoreceptor neurons are found only on the lateral flagellum of the biramous antennules. Their axons project to the olfactory lobes in the brain. In addition, nonaesthetasc chemoreceptor

neurons abound in the lateral and medial antennular flagella, although they are more poorly characterized. The nonaesthetasc chemosensory neurons apparently project together with mechanosensory neurons into the lateral antennular neuropil, which has a nonglomerular arrangement [47,48]. Because the aesthetascs are the most prominent type of chemosensory sensillum, they have been the focus of most studies of the antennule. The differences in the functional roles of these pathways are largely unexplored, but are currently being investigated [53].

### 3. A focus on olfactory processing of mixtures

A central question that we have addressed using the spiny lobster is: how is the peripheral olfactory pathway organized to extract information about the type or quality of chemical mixtures? Our focus has been on food mixtures because they represent natural stimuli [7]. Many sensory systems have special adaptations to process natural and complex stimuli. For example, complex feature detectors have been described in the auditory and visual systems [54,57]. We have taken this approach despite the complexities created by studying processing of complex stimuli such as mixtures. The stimuli that we have used in our studies of processing of mixtures include the following: (1) aqueous extracts of homogenized tissue of four prey of lobsters (crab, shrimp, mullet, and oyster extracts); (2) artificial mixtures of these four extracts (crab, shrimp, mullet, and oyster mixtures), which contain 29–35 compounds including amino acids, amines, nucleotides, nucleosides, and organic acids, at concentrations that they occur in the tissue extracts; and (3) mixtures of two to seven of the components of the artificial mixtures.

### 4. Beyond labeled lines: Antennular chemoreceptor neurons are complex peripheral processing units that do not fall into obvious “cell types”

A critical step in understanding how a peripheral chemosensory system processes mixtures is knowing how individual receptor cells respond to mixtures and their components. Although this has been acknowledged [19,33,37], the complexities created by it can be daunting. Nonetheless, what it tells us about the roles of RNs in the processing of natural stimuli is invaluable.

Single-unit extracellular recording of action potentials from the axons of antennular RNs is standard practice [14], and has allowed us to characterize chemosensory coding at the cellular and system levels. When a suite of single compounds found in natural food of lobsters (see the previous section for examples) is used to probe the specificity of RNs, narrowly tuned excitatory response spectra are commonly observed. A RN is usually excited much more by one compound (the “best compound”) than the next best compound. RNs with narrow excitatory tuning have been described for a variety of different odorants; notable examples

include taurine, L-glutamate, ammonium, AMP, or ATP [16,52]. Application of multivariate methods such as cluster analysis to such data sets has led to the identification of clusters of RNs, with members of a cluster sharing a characteristic “best compound” that differs from those of RNs belonging to other clusters [15].

Such observations can lead one to think that “cell types” exist in this system, possibly functioning as labeled lines for particularly important odorants. But other observations argue against the presence of functional cell types, especially for natural stimuli. First, single RNs of spiny lobsters can express more than one type of receptor molecule that mediates excitation, usually with one type being more prevalent than others on a given cell [10]. The less abundant receptor type on a cell varies. This is expressed physiologically by RNs with the same “best compound” having different second-best compounds [10,17], thus increasing diversity of responses. Second, odor-evoked inhibitory responses are common, as clearly shown by intracellular patch-clamp recordings [2,49]. Inhibitory responses can be difficult to identify from extracellular recordings of RNs, because the spontaneous spiking rate of these cells is often low [12]. Nonetheless, inhibitory responses are present, and must be included when defining the response spectrum of a cell. When this is done, it is apparent that cells that have a similar excitatory response spectrum can differ in their inhibitory response spectrum [12,32]. As an example, RNs with narrow excitatory response profiles for taurine can be inhibited by any of several other odorant compounds, and the intensity of the inhibition by a compound can differ across cells [32]. Because of this diversity in inhibition for cells excited by a given odor compound, “cell types” become less apparent when mixtures containing excitatory and inhibitory are tested in addition to single compounds. Third, the binding of an odorant to its receptor sites can be inhibited by other odorants, and in so doing affect the electrophysiological responses of RNs to that odorant [11,28]. In addition, odorants differentially inhibit binding of different receptor types. For example, betaine is much more effective at inhibiting binding of taurine or glutamate to their respective receptors than AMP binding to its receptors [28]. These latter two effects can contribute, along with other phenomena, to “mixture interactions,” which can be broadly defined as a response to a mixture that is not expected from the responses to the components of that mixture [37]. Because mixture interactions are not equally expressed in all RNs, it is perhaps not surprising that observing a broad diversity in response profiles of RNs, without identifying “cell types,” is most likely when mixtures are used as test stimuli. For example, when artificial mixtures of crab, shrimp, mullet, and oyster (CM, SM, MM, and OM, respectively) (see previous section for a description of these mixtures) are included as test stimuli in a characterization of response spectra, RNs cannot be sorted into “cell types” [30]. Rather, there is a continuum of response profiles, with the exact response profile being determined by many response features.

Thus, excitatory responses, inhibitory responses, and binding interactions all contribute to the response profiles of RNs. RNs that are all highly excited by the same odorant compound are not necessarily inhibited by the same compounds, are not necessarily slightly excited by the same compounds, do not have the same binding interactions, and do not show the same mixture interactions. Consequently, RNs do not fall into “types” when challenged with an array of natural complex stimuli.

A mechanistic explanation for this diversity of response profiles among members of a population of antennular RNs is that individual RNs can express a wide variety of molecules involved in olfactory transduction. For example, individual RNs may functionally express at least two types of receptor molecules [10], several types of G-proteins [40, 55], at least two second messengers (cAMP and IP3) [2], and a variety of ion channels involved in odor transduction [2]. A multiplicity of signaling cascades in single olfactory RNs has also been found in many other species including vertebrates [2,21,44]. Such properties allow each RN to provide unique contributions to the neural code for stimulus features.

In summary, RNs of spiny lobsters function as complex peripheral processing units. Individual RNs can have a diversity of receptor proteins, second messengers, and ion channels. The combination of these that occur in RNs defines the response profiles of the RNs. When challenged only with single compounds, the diversity of RNs is only partially characterized, and with such limited information one may be tempted to identify “cell types.” However, when RNs are probed with complex stimuli that mimic natural stimuli and with the components of these mixtures, it becomes apparent that there is a tremendous diversity in the response profiles of the RNs and that there are no “cell types.”

## 5. The lobster’s nose has a distributed code for the quality of mixtures

Knowing the central projection patterns of RNs of specified response properties would improve our understanding of how a population of RNs encodes mixture quality. Unfortunately, we do not currently know the projection patterns of functionally defined RNs into the glomerular neuropil of the olfactory lobes [47,48]. Thus, our analysis of peripheral coding has depended on evaluating the information in populations of recorded RNs whose spatial projections are unknown.

We have used many sets of chemical stimuli to test the idea that a distributed code, also called an across-fiber or across-neuron pattern code [22,23], is used by the antennule to encode odor quality. These stimulus sets include single compounds [17], complex artificial mixtures (CM, SM, MM, OM) [29], tissue extracts of crab, shrimp, mullet, and oyster [29], binary mixtures [12], and different blend ratios of binary mixtures [52]. In many of these studies we have

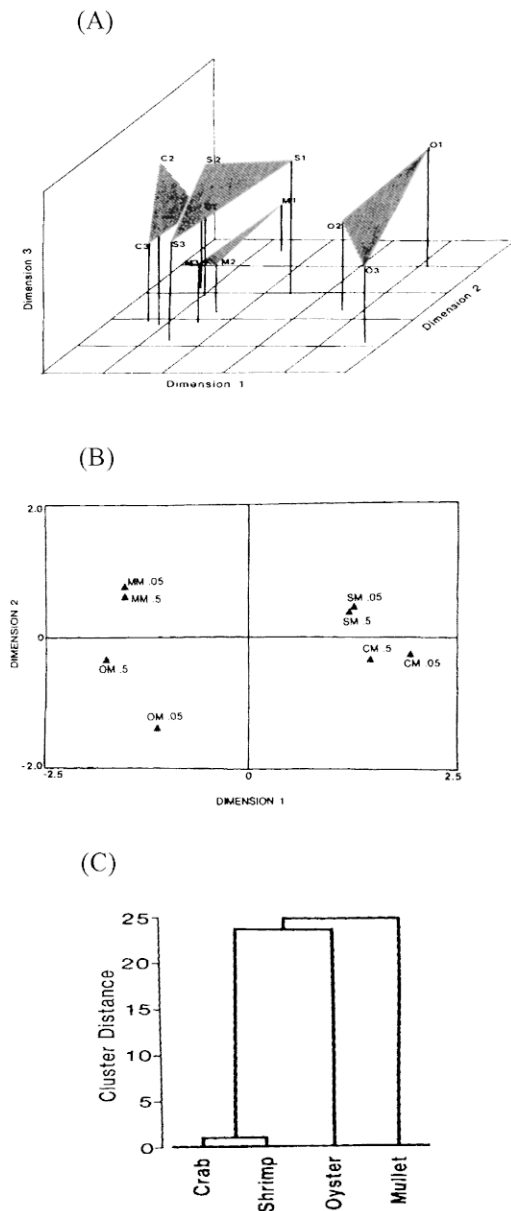


Fig. 2. Spiny lobsters use information in distributed neural codes to assess differences in stimulus quality of four complex food odors. The odors are crab, shrimp, oyster, and mullet mixtures (CM, SM, OM, and MM, respectively). (A) Relative similarities between mixtures according to distributed codes for a population of 30 RNs. The locations of the four mixtures, each at three concentrations (1, 2, 3, 5, 50, and 500  $\mu$ M, respectively), are shown in a three-dimensional space derived from multidimensional scaling. Each point represents the distributed code for one stimulus, and each shaded triangle represents the stimulus space for a two-log unit concentration range of each mixture. (B) Relative similarities between mixtures according to behaviors of discrimination. The locations of the four mixtures, each at two concentrations (50 and 500  $\mu$ M), are shown in a two-dimensional space derived from multidimensional scaling. This analysis is based on aversion values from four groups of animals, with members of each group being aversively conditioned to both concentrations of only one of the four mixtures. (C) Relative similarities in the compositions of the mixtures. This dendrogram represents the results of a cluster analysis, based on the relative amounts of the components of the mixtures. From [18].

tested different concentrations of each stimulus to evaluate the effect of stimulus intensity on the distributed code for stimulus quality.

We compared distributed codes for different stimuli using the conceptual and technical approaches established by Erickson and his colleagues. We recorded single-unit spiking activity from members of a set of RNs, measured similarities in the distributed code generated by various odor stimuli using metrics such as vector-space analysis [20], chi-square values, and Pearson correlation coefficients, and then compared these distributed codes using multivariate techniques such as multidimensional scaling [23].

The results support the idea that distributed codes contain the information necessary for this chemosensory system to distinguish odor quality (Fig. 2A). For example, the distributed codes for the artificial mixtures CM, SM, MM, and OM are different from each other, and these differences are highly correlated with the differences in their compositions [29,30] (Fig. 2). CM and SM, which have the most similar compositions among these four mixtures, generate the most similar distributed codes. On the other hand, CM and OM evoke highly different distributed codes. Furthermore, changes in stimulus intensity by as much as two orders of magnitude have relatively little effect on the codes for stimulus quality.

Behavioral studies suggest that spiny lobsters use the information in the distributed codes in assessing stimulus quality [13,24–26]. Lobsters can be conditioned using aversion paradigms, as has been used to study chemosensation in other animals. Lobsters were conditioned to give an aversive response to one chemical stimulus, and then examined for response generalization to other stimuli. Results show that the greatest generalization is between CM and SM, and very little generalization occurs between either CM or SM and OM (Fig. 2B). Thus, spiny lobsters perceive as most similar those mixtures that have the most similar composition.

These behavioral results, taken together with the studies of distributed codes, lead to the conclusion that spiny lobsters can use sensory information available as distributed codes in their olfactory organ to discriminate the quality of natural, complex chemical stimuli. Future studies that define the central projection patterns of RNs into the glomerular olfactory neuropil will be important in characterizing in more detail how peripheral information about odor quality and intensity is encoded in the CNS.

## 6. Spiny lobsters can use either elemental or configural cues in discriminating the quality of a mixture because the qualities of individual compounds are not lost when the compounds are combined

In theory, an animal might perceive sensory cues either as a combination of its elements (elemental cues) or as a mixture-unique entity (configural cues) [41]. Which of the cues dominates perception can be influenced by the degree of salience of each [38,41,43,45,50,51]. We explored this

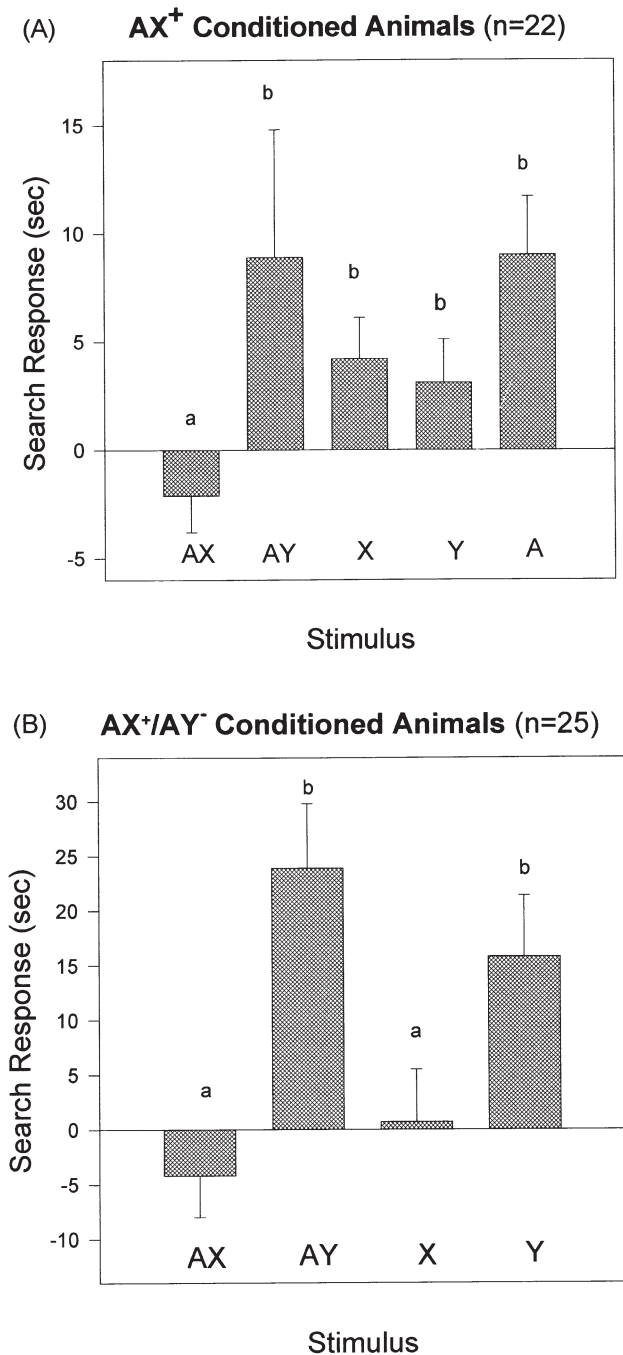


Fig. 3. Elemental and configural processing. (A) Generalization between the binary mixture AX and other odorants for animals conditioned to AX<sup>+</sup>, suggesting configural processing. (B) Generalization between the binary mixture AX and other odorants for animals conditioned to AX<sup>+</sup> and AY<sup>-</sup>, demonstrating elemental processing. AX<sup>+</sup> represents the conditioned stimulus that was forward paired with an unconditioned aversive stimulus, by first introducing AX<sup>+</sup> followed within 3 s by presentation of the aversive stimulus, which was a black plastic square mounted on a rod that was rapidly rushed toward the lobster until the lobster moved away. Odorant compounds were tested at doses that evoked search responses of equal magnitude in unconditioned animals. Values are means  $\pm$  SEM of control-corrected search responses,  $n$  = number of animals tested. For all animals, A = adenosine-5' monophosphate. For 11 animals in (A) and 12 animals in (B), X = betaine and Y = L-glutamate; for 11 animals in (A) and 13 animals in (B), X = L-glutamate and Y = betaine. Bars topped with different letters are significantly different by analysis of variance with repeated measures and SNK multiple range tests ( $p < 0.05$ ). From [39].

issue by using behavioral studies to examine whether spiny lobsters can discriminate and identify the components of odor mixtures that they would normally treat as unique entities, when the task demands [39].

Spiny lobsters can detect the individual components in binary mixtures, and must, therefore, be able to process the components of mixtures as independent elements [39], as shown in Fig. 3. Lobsters conditioned to avoid a binary mixture, AX, did not generalize from AX to the mixture's components, A or X, or to a binary mixture containing one novel component, AY. This suggests that configural cues may dominate elemental cues in this task. However, a different result occurred when lobsters were conditioned not only to avoid binary mixture AX, as in the previous paradigm, but also to continue responding to AY by presenting AY as unpaired with the aversive stimulus during the conditioning phase of the experiment (Fig. 3). Lobsters conditioned in this way generalized between AX and X and between AY and Y, unlike the lobsters conditioned only to AX. These results support the idea that changing the salience of a mixture's components by giving them different reinforcement contingencies changed the way that the mixtures were perceived. As a result of such conditioning, animals perceived the mixture's components as separate elements, and as a consequence, animals generalized between binary mixtures and their most salient or predictive components. Similar abilities to identify a mixture's components as elemental cues were seen for a five-component mixture. These results show that the salience of components of mixtures can affect how a mixture is processed, as has been shown in another arthropod, the honey bee [50].

This demonstration of elemental processing in spiny lobsters has implications for the way that odorant mixtures are processed by the peripheral olfactory system. It suggests that a mixture and its components should generate different distributed codes, but the mixture's distributed code should have features similar to both of its components. Furthermore, different blend ratios of a given binary mixture should generate distributed codes whose similarity to the distributed codes for their components is predictable from the blend ratio. That is, a blend ratio that is dominated by one component should produce a distributed code more similar to the code for the dominant component than for the minor component.

This hypothesis was tested by Stullet and Derby [52] in an analysis of the distributed codes for a set of olfactory RNs in response to different blend ratios of three binary mixtures and their individual components (Fig. 4). Seven different blend ratios of each binary mixture were used, from a 0.1/99.9 ratio to a 99.9/0.1 ratio, with all stimuli having a total concentration of 100  $\mu$ M. Blend ratios usually evoked distributed codes expected from their composition. The higher the relative concentration of one component in a mixture, the more similar was that mixture's distributed code compared to the dominant compo-

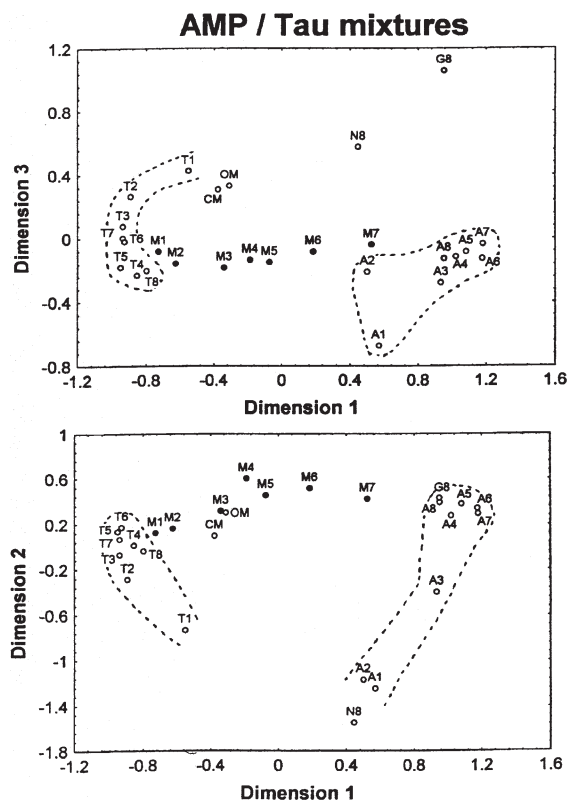


Fig. 4. Neural coding of different blend ratios of the binary mixture AMP + taurine and its components. Multidimensional scaling of similarities in the distributed codes for the responses of a population of 29 RNs to AMP (A), taurine (T), and the binary mixture AMP + taurine (M). For A and T, the numbers 1–8 represent concentrations of 0.1, 1, 10, 50, 90, 99, 99.9, and 100  $\mu$ M, respectively. For M, the numbers 1–7 represent blend ratios for A+T of 0.1/99.9, 1/99, 10/90, 50/50, 90/10, 99/1, and 99.9/0.1  $\mu$ M, respectively. Two two-dimensional plots are used to represent the three-dimensional solution to the analysis. The dashed lines have no statistical meaning but visually delimit distributed codes for all of the concentrations of each component. CM = crab mixture, OM = oyster mixture, G8 = L-glutamate, N8 = ammonium chloride, each at 100  $\mu$ M. From [52].

ment's distributed code (Fig. 4). These results suggest that for the distributed codes generated in the peripheral olfactory system, the qualities of individual compounds are maintained when the compounds are mixed to form blends. These findings provide a neural explanation of the ability of spiny lobsters to elementally process an odor mixture.

## 7. Summary and conclusions

The olfactory system of spiny lobsters and other decapod crustaceans has helped direct our understanding of how complex stimuli are encoded by peripheral sensory systems. These systems might be considered simpler than that of mammals, due to their having <1% of the receptor neurons of mammals. Yet they are still highly complex, in several respects. First, the complement of RNs is still huge, numbering ca. 600,000 in spiny lobsters, which confers on the animals considerable sensitivity and breadth of responsiveness [34,35]. Second, individual RNs can possess a diver-

sity of transduction pathways, including multiple types of receptors, second messengers, and ion channels [2,10]. Such diversity enables considerable peripheral integration of complex stimuli, even before synaptic integration in the CNS, and it influences the intensity of responses to mixtures. Finally, the perception of mixtures by lobsters can be influenced by the salience of the mixture's components, such that the components of a mixture can be perceived as either elemental or configural cues.

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## References

- [1] Ache BW. Phylogeny of smell and taste. In: Getchell TV, Doty RL, Bartoshuk LM, Snow JB Jr, editors. *Smell and Taste in Health and Disease*. New York: Raven Press, 1991. pp. 3–18.
- [2] Ache BW, Zhainazarov AB. Dual second-messenger pathways in olfactory transduction. *Curr Opin Neurobiol* 1995;5:461–6.
- [3] Atema J. Smelling and tasting underwater. *Oceanus* 1980;23:3–18.
- [4] Atema J. Chemical signals in the marine environment: dispersal, detection, and temporal signal analysis. *Proc Natl Acad Sci USA* 1995; 92:62–6.
- [5] Blaustein DN, Simmons RB, Burgess MF, Derby CD, Nishikawa M, Olson KS. Ultrastructural localization of 5'AMP odorant receptor sites on the dendrites of olfactory receptor neurons of the spiny lobster. *J Neurosci* 1993;13:2821–8.
- [6] Buck LB. Information coding in the vertebrate olfactory system. *Annu Rev Neurosci* 1996;19:517–44.
- [7] Carr WES. The molecular nature of chemical stimuli in the aquatic environment. In: Atema J, Fay RR, Popper AN, Tavolga WN, editors. *Sensory Biology of Aquatic Animals*. New York: Springer-Verlag, 1988. pp. 3–27.
- [8] Carr WES, Gleason RA, Trapido-Rosenthal HG. The role of perireceptor events in chemosensory processes. *Trends Neurosci* 1990;13: 212–5.
- [9] Carr WES, Trapido-Rosenthal HG, Gleason RA. The role of degradative enzymes in chemosensory processes. *Chem Senses* 1990;15: 181–90.
- [10] Cromarty SI, Derby CD. Multiple excitatory receptor types on individual olfactory neurons: implications for coding of mixtures in the spiny lobster. *J Comp Physiol A* 1997;180:481–91.
- [11] Cromarty SI, Derby CD. Inhibitory receptor binding events among the components of complex mixtures contribute to mixture suppression in responses of olfactory receptor neurons of spiny lobsters. *J Comp Physiol A* 1998;183:699–707.
- [12] Daniel PC, Burgess MF, Derby CD. Responses of olfactory receptor

- neurons in the spiny lobster to binary mixtures are predictable using a noncompetitive model that incorporates excitatory and inhibitory transduction pathways. *J Comp Physiol A* 1996;178:523–36.
- [13] Daniel PC, Derby CD. Behavioral olfactory discrimination of mixtures in the spiny lobster (*Panulirus argus*) based on a habituation paradigm. *Chem Senses* 1988;13:385–95.
- [14] Derby CD. Single unit electrophysiological recordings from crustacean chemoreceptor neurons. In: Spielman AI, Brand JG, editors. *CRC Handbook on Experimental Cell Biology of Taste and Olfaction: Current Techniques and Protocols*. Boca Raton, FL: CRC Press, 1995. pp. 241–50.
- [15] Derby CD, Ache BW. Quality coding of a complex odorant in an invertebrate. *J Neurophysiol* 1984;51:906–24.
- [16] Derby CD, Atema J. Chemoreceptor cells in aquatic invertebrates: peripheral filtering mechanisms in decapod crustaceans. In: Atema J, Fay RR, Popper AN, Tavolga WN, editors. *Sensory Biology of Aquatic Animals*. New York: Springer, 1988. pp. 365–88.
- [17] Derby CD, Girardot M-N, Daniel PC. Responses of olfactory receptor cells of spiny lobsters to binary mixtures. I. Intensity mixture interactions. *J Neurophysiol* 1991;66:131–9.
- [18] Derby CD, Girardot M-N, Daniel PC, Fine-Levy JB. Olfactory discrimination of mixtures: behavioral, electrophysiological and theoretical studies using the spiny lobster *Panulirus argus*. In: Laing DG, Cain WS, McBride RL, Ache BW, editors. *Perception of Complex Smells and Tastes*. Sydney: Academic Press, 1989. pp. 65–82.
- [19] Dethier VG. Gustatory sensing of complex mixed stimuli by insects. In: Le Magnen J, MacLeod P, editors. *Olfaction and Taste VI*. London: IRL, 1977. pp. 323–31.
- [20] Di Lorenzo PM. Across unit patterns in the neural response to taste: vector space analysis. *J Neurophysiol* 1989;62:823–33.
- [21] Dionne VE, Dubin AE. Transduction diversity in olfaction. *J Exp Biol* 1994;194:1–21.
- [22] Erickson RP. Stimulus coding in topographic and non-topographic afferent modalities: on the significance of the activity of individual sensory neurons. *Psychol Rev* 1968;75:447–65.
- [23] Erickson RP. Parallel “population” neural coding in feature extraction. In: Schmitt FO, Worden FG, editors. *The Neurosciences: Third Study Program*. Cambridge: M.I.T. Press, 1974. pp. 155–69.
- [24] Fine-Levy JB, Daniel PC, Girardot M-N, Derby CD. Behavioral resolution of quality of odorant mixtures by spiny lobsters: differential aversive conditioning of olfactory responses. *Chem Senses* 1989;14:503–24.
- [25] Fine-Levy JB, Derby CD. Effects of stimulus intensity and quality on discrimination of odorant mixtures by spiny lobsters in an associative learning paradigm. *Physiol Behav* 1991;49:1163–8.
- [26] Fine-Levy JB, Girardot M-N, Derby CD, Daniel PC. Differential associative conditioning and olfactory discrimination in the spiny lobster *Panulirus argus*. *Behav Neural Biol* 1988;49:315–31.
- [27] Friedrich R, Korsching SI. Chemotopic, combinatorial, and noncombinatorial odorant representations in the olfactory bulb revealed using a voltage-sensitive axon tracer. *J Neurosci* 1998;18:9977–88.
- [28] Gentilcore LR, Derby CD. Complex binding interactions between multicomponent mixtures and odorant receptors in the olfactory organ of the Caribbean spiny lobster *Panulirus argus*. *Chem Senses* 1998;23:269–81.
- [29] Girardot M-N, Derby CD. Neural coding of quality of complex olfactory stimuli in lobsters. *J Neurophysiol* 1988;60:303–24.
- [30] Girardot M-N, Derby CD. Peripheral mechanisms of olfactory discrimination of complex mixtures by the spiny lobster: no cell types for mixtures but different contributions of the cells to the across neuron patterns. *Brain Res* 1990;513:225–36.
- [31] Gleeson RA. Intrinsic factors mediating pheromone communication in the blue crab, *Callinectes sapidus*. In: Bauer RT, Martin JW, editors. *Crustacean Sexual Biology*. New York: Columbia University Press, 1991. pp. 17–32.
- [32] Gleeson RA, Ache BW. Amino acid suppression of taurine-sensitive chemosensory neurons. *Brain Res* 1985;335:99–107.
- [33] Glendinning JJ, Hills TT. Electrophysiological evidence for two transduction pathways within a bitter-sensitive taste receptor. *J Neurophysiol* 1997;78:734–45.
- [34] Grünert U, Ache BW. Ultrastructure of the aesthetasc (olfactory) sensilla of the spiny lobster, *Panulirus argus*. *Cell Tissue Res* 1988;251:95–103.
- [35] Hallberg E, Johansson KUI, Elofsson R. The aesthetasc concept: structural variations of putative olfactory receptor cell complexes in Crustacea. *J Microsc Res Technol* 1992;22:325–35.
- [36] Hildebrand JG, Shepherd GM. Mechanisms of olfactory discrimination: converging evidence for common principles across phyla. *Annu Rev Neurosci* 1997;20:595–631.
- [37] Laing DG, Cain WS, McBride RL, Ache BW. Perception of Complex Smells and Tastes. Sydney: Academic Press, 1989.
- [38] Livermore BA, Laing DG. The influence of chemical complexity on the perception of multicomponent odor mixtures. *Percept Psychol* 1998;60:650–61.
- [39] Livermore BA, Hutson M, Ngo V, Hadjisimos R, Derby CD. Elemental and configural learning and the perception of odorant mixtures by the spiny lobster *Panulirus argus*. *Physiol Behav* 1997;62:169–74.
- [40] McClintock TS, Xu F, Quintero J, Gress AM, Landers TM. Molecular cloning of a lobster  $G_{\alpha q}$  protein expressed in neurons of olfactory organ and brain. *J Neurochem* 1997;68:2248–54.
- [41] Pearce JM. A model of stimulus generalization for Pavlovian conditioning. *Psychol Rev* 1987;94:61–73.
- [42] Reeder PB, Ache BW. Chemotaxis in the Florida spiny lobster, *Panulirus argus*. *Anim Behav* 1980;28:831–9.
- [43] Rescorla RA, Grau JW, Durlach PJ. Analysis of the unique cue in configural discrimination. *J Exp Psychol* 1985;111:356–66.
- [44] Restrepo D, Teeter JH, Schild D. Second messenger signaling in olfactory transduction. *J Neurobiol* 1996;30:37–48.
- [45] Rudy JW, Sutherland RJ. Configural and elemental associations and the memory of coherence problem. *J Comp Neurosci* 1992;4:208–16.
- [46] Sandeman DC, Scholtz G, Sandeman RE. Brain evolution in decapod Crustacea. *J Exp Zool* 1993;265:112–33.
- [47] Schmidt M, Ache BW. Antennular projections to the midbrain of the spiny lobster. II. Sensory innervation of the olfactory lobe. *J Comp Neurol* 1992;318:291–303.
- [48] Schmidt M, Van Ekeris L, Ache BW. Antennular projections to the midbrain of the spiny lobster. I. Sensory innervation of the lateral and medial antennular neuropils. *J Comp Neurol* 1992;318:277–90.
- [49] Simon TW, Derby CD. Mixture suppression without inhibition for binary mixtures from whole cell patch clamp studies of in situ olfactory receptor neurons of the spiny lobster. *Brain Res* 1995;678:213–24.
- [50] Smith BH. The role of attention in learning about odorants. *Biol Bull* 1996;191:76–83.
- [51] Smith BH, Getz WM. Nonpheromonal olfactory processing in insects. *Annu Rev Entomol* 1994;39:351–75.
- [52] Steullet P, Derby CD. Coding of blend ratios of binary mixtures by olfactory neurons in the Florida spiny lobster, *Panulirus argus*. *J Comp Physiol A* 1997;180:123–35.
- [53] Steullet P, Flavus T, Radman D, Hamidani G, Zhou M, Derby CD. The aesthetasc-olfactory lobe pathway of spiny lobsters is not necessary for odor-activated searching behavior, odor-associative learning, and discrimination of complex odors. *Soc Neurosci Abstr* 1999;25:125.
- [54] Suga N. Principles of auditory information-processing derived from neuroethology. *J Exp Biol* 1989;146:277–86.
- [55] Xu F, Hollins B, Gress AM, Landers TM, McClintock TS. Molecular cloning and characterization of a lobster  $G_{\alpha s}$  protein expressed in neurons of olfactory organ and brain. *J Neurochem* 1997;69:1793–1800.
- [56] Xu F, Hollins B, Landers TM, McClintock TS. Molecular cloning of a lobster  $G_{\beta}$  subunit and  $G_{\beta}$  expression in olfactory receptor neuron dendrites and brain neuropil. *J Neurobiol* 1998;36:525–36.
- [57] Young MP, Yamane S. Sparse population coding of faces in the inferotemporal cortex. *Science* 1992;256:1327–31.
- [58] Zimmer-Faust RK. The relationship between chemoreception and foraging behavior in crustaceans. *Limnol Oceanogr* 1989;34:1367–74.