A NEURAL NETWORK FOR PROCESSING OLFACTORY-LIKE STIMULI

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Several critical issues associated with the processing of olfactory stimuli in animals (but focusing on insects) are discussed with a view to designing a neural network which can process olfactory stimuli. This leads to the construction of a neural network that can learn and identify the quality (direction cosines) of an input vector or extract information from a sequence of correlated input vectors, where the latter corresponds to sampling a time varying olfactory stimulus (or other generically similar pattern recognition problems). The network is constructed around a discrete time content-addressable memory (CAM) module which basically satisfies the Hopfield equations with the addition of a unit time delay feedback. This modification improves the convergence properties of the network and is used to control a switch which activates the learning or template formation process when the input is “unknown”. The network dynamics are embedded within a sniff cycle which includes a larger time delay (i.e. an integer $t_s > 1$) that is also used to control the template formation switch. In addition, this time delay is used to modify the input into the CAM module so that the more dominant of two mingling odors or an odor increasing against a background of odors is more readily identified. The performance of the network is evaluated using Monte Carlo simulations and numerical results are presented.

Introduction. Odors play an extremely important role in the lives of many animals (e.g. Payne et al., 1986). Odors are made up from one or more chemical compounds, called odorants. Of course, not all animals are sensitive to the same range of odorants. Thus, whether a particular chemical is an odorant or not depends on whether it is capable of stimulating the olfactory receptors of, at least, one animal. Most odors, including some pheromones, are a blend of several odorants (Kaissling, 1987), but many odors are complex blends of several tens or even hundreds of odorants (e.g. a lemon odor is composed of at least 70 potential odorants—Sinclair, 1984). The relative proportion of odorant molecules in an odor characterizes its “quality”, while the total concentration of all odorant molecules defines odor “quantity”.

Two essential aspects of the olfactory signal processing problem are:

(a) odor quality should be perceived separately from odor quantity, at least within a range of odorant concentrations;

(b) in so far as is possible, an odor stimulus should be distinguishable even when embedded in a background odor.

When olfactory and other chemosensory receptors are stimulated by a
chemical to which they are sensitive, they fire at a rate that usually increases with increasing odor concentration (e.g. see Selzer, 1984), although saturation will occur at high concentrations. Typically, these chemosensory receptor neurons also exhibit phaso-tonic firing patterns that include some level of adaptation (Maes and Harms, 1986). Thus it is possible that there is a temporal pattern to the code, although ensemble averaging—where the information is related to the average firing rates of several qualitatively different groups of receptor neurons—is thought to be the most likely coding mechanism, at least with respect to salt taste quality in blow flies (Maes and Ruifrok, 1986). Here we will not be specific about the exact coding mechanism employed, although it may help the reader to think of the information processed in the peripheral sensory network as being coded in terms of the graded firing rates of certain neurons.

Before we are able to develop a model, we need to introduce a number of concepts that idealize essential features of the real process. First we define an instantaneous odor stimulus as a point \( \mathbf{o} = (o_1, \ldots, o_n)' \) in an \( n \)-dimensional odorant space \( \Omega \), where the elements \( o_i \) represent the absolute concentration of the \( i \)th odorant. If we define \( \Omega \) as the nonnegative quadrant of \( R^n \), then the quality of an odor is represented by the direction cosines of a vector interpretation of \( \mathbf{o} \); and quantity is just the length of this vector. Higher organisms (including many arthropods) have evolved to be able to detect a large number of chemicals which help individuals to find food and to communicate with other individuals from the same and different species. For these organisms, the dimension \( n \) of \( \Omega \) can be very large. Noise problems aside, it would be ideal if organisms could evolve \( n \) different types of olfactory receptors each dedicated to sensing one of the \( n \) odorants in \( \Omega \). However, several sources of noise are associated with the performance of olfactory receptors (e.g. stochasticity associated with sampling a small number of molecules in the environment, and variability in the spiking rates of individual receptor neurons), making it necessary for organisms to have assemblages of different types of neurons to increase the signal-to-noise ratio to acceptable levels (e.g. see Kaissling and Priesner, 1970). Thus organisms must tradeoff the dimension of \( \Omega \) (i.e. the number of compounds to which they are sensitive) with their ability to resolve points in \( \Omega \). What constitutes the best tradeoff is a complicated problem which involves both the physiology and ecology of an organism. Here we will accept, as given, the notion that the peripheral olfactory system performs—within a range of odorant concentrations—a quality preserving mapping of points in \( \Omega \) onto a much lower dimensional odor perception space. Preserving quality implies that vectors in \( \Omega \) that point in the same direction (i.e. only differ in magnitude) are mapped onto the same points in some appropriate odor quality subspace \( Q \) of the more general odor perception space. The latter includes as well some notion of concentration.