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Challenges of Biomimetic Infochemical Communication☆

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Abstract

The natural world abounds with chemical information. Animals rely on chemical communication for behaviors as diverse as finding mates, locating food sources, or avoiding predators. Insects, in particular, are capable of incredibly precise chemocommunication using low-power signaling and processing systems. Most species rely on several compounds to convey specific information, establishing a diverse palette for chemical communication. This complex form of information exchange mediated by chemicals represents an unexplored form of communication and labeling technology that has yet to be exploited. In an attempt to mimic chemocommunication in the insect world, we have developed a new class of technology based on the infochemical communication of moths. We describe how this new class of technology could be realized by combining the latest advances and convergence of expertise in the fields of pheromone biochemistry, entomology, genetics, biophysics, materials science and neuroscience. The principles of signal biosynthesis and molecular detection in olfactory receptors and the central nervous system of insects are discussed. We then describe the technological aspects of implementing a microsystem capable of producing biosynthetic compounds as well as the development of a detector unit comprising a biological cell coating expressing specific ligand receptors and coupled to an acousto-electric transducer.

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Keywords: biosynthesis; olfactory receptor; biosensor; neuromorphic modelling; neuroengineering; robotics; source localization

1. Chemical Communication: Inspiration from Biology

Chemical communication is the ubiquitous language of nature. Chemical messages are utilized by virtually all living organisms to locate food, avoid predators, find mates, or mediate metabolic functions. Words are made of molecules, and sentences can be formed from specific combinations of compounds blended in a spatiotemporal fashion. The persistence and complexity of chemical signals create a highly specific and long-lasting form of communication. With a dictionary bounded only by the limits of biochemistry, such signals establish an incredibly diverse and fascinating mechanism to transmit information over space and time.

Pheromones are species-specific chemicals that mediate a number of complex behaviors. Insects, in particular, utilize a staggering number of pheromones. In fact, the molecular composition of sex attractants have been elucidated for over 1600 species [1]. Most insect pheromones are multicomponent blends of geometric or optical isomers in specific ratios [2]. Many of these attractants are synthesized *de novo* from biosynthetic precursors within the insect itself. Chemical

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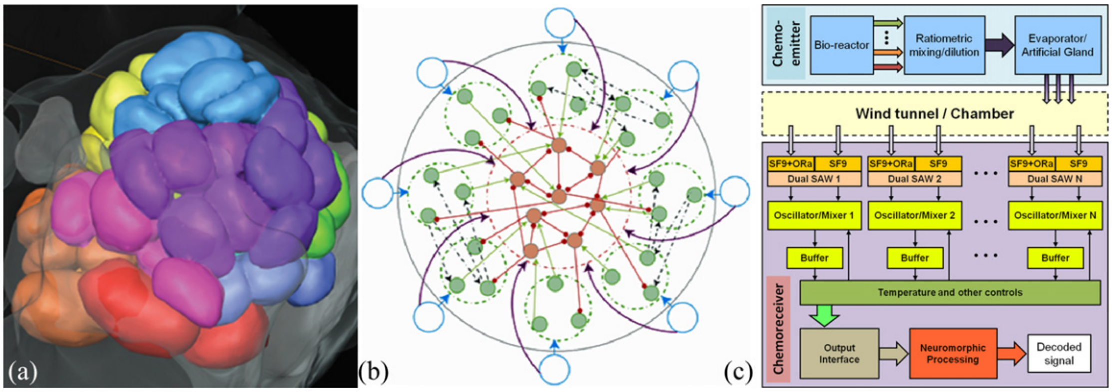

Fig. 1. (a) 3-D reconstruction of a moth antennal lobe showing dense spherical synaptic regions (glomeruli; adapted from [7]); (b) computational schematic of the antennal lobe showing sensory neuron input (blue), projection neuron output (green) and interneuron connectivity (orange); (c) schematic block diagram of a possible biosynthetic infochemical communication system based on a micromachined bioreactor and "artificial gland" chemoemitter, and a chemoreceiver consisting of olfactory receptor-expressing SF9 cells coupled to surface acoustic wave sensors with subsequent neuromorphic processing architecture.

diversity is established through highly sophisticated biosynthetic pathways that alter the variety and order of enzymatic activity to establish different carbon chain lengths, functional groups, and levels of saturation [1]. An understanding of such pathways provides an efficient means to produce an astonishing variety of chemical "sentences", each with specific ratiometric quantities and qualities.

In concert with this chemical symphony, insects have evolved a highly sensitive and specific olfactory system. Insects can detect just a few hundred molecules of odor, making them up to 10 orders of magnitude more sensitive than the human nose. Olfactory detection in insects begins at the antennae. Odorant molecules bind to specific receptor proteins located on the surface of sensory neurons, which are then transmitted to the central nervous system as electrical potentials. Within the brain, these sensor signals are first sent to a region known as the antennal lobe, which is analogous to the mammalian olfactory bulb. Here, the signal from many different receptor types is filtered and processed for further integration with learning, memory, and motor centers. This highly specialized system housed in a tiny, low power biological platform provides immense opportunities to understand the fundamental mechanisms by which high bandwidth chemical information can be detected (Fig. 1).

2. Biological Challenges of Infochemical Communication

Insect chemocommunication provides a remarkable template from which to develop a novel communication system based on chemical information. For specific signals such as sex pheromones, the process can be envisioned in three steps: the signal, the sensor, and the brain. Each of these tasks requires an interdisciplinary exchange between biochemistry, molecular biology, neuroscience, and behavioral ecology. Our biological inspiration for this new form of technology is the Egyptian armyworm, *Spodoptera littoralis*. This moth is an attractive model for infochemical communication due to its intricate chemically-mediated mating behavior. Female *S. littoralis* release a complex signal of 6 monoene and conjugated and non-conjugated diene acetates to attract male conspecifics. To replicate the biosynthetis artificially, we first reviewed the enzymatic routes required to produce this blend [2]. A diacylglycerol acyl transferase from *Acinetobacter sp.* (a wax ester synthase) was identified as a suitable enzyme to convert the alcohol precursor of the major pheromone component into the corresponding acetate. Electrophysiological tests using male antennae revealed the efficacy of enzymatic conversion.

To harness the specificity of the receptor neuron sensors found in the male antennae, we heterologously-expressed olfactory receptor proteins in SF9 cells (from *Spodoptera fugiperda* ovarian tissue). This allowed us to isolate the biological detectors for coupling with an artificial sensor system (see below). In parallel, we assessed the ratiometric coding of the first olfactory processing center of the moth brain, the antennal lobe. We found that the moth brain uses a highly combinatorial, non-linear process for coding complex blends. By unraveling network processing, we found that each neuron utilizes several different spatiotemporal elements to represent the blend electrically. These elements were mathematically represented in a computational model of the antennal lobe that was then used to establish the