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A Molecular Basis of Olfaction: Odorant-Specific Electric-Field Emission

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ABSTRACT

The olfactory system is capable of distinguishing individual odorants from among a virtually unlimited number. Fish, for example, detect changes in the electric field environment induced by prey and other sources. Floral electric fields exhibit variations in pattern and structure, which can be discriminated by bumblebees. We have constructed an electric field sensor, which, in the course of focussing on achieving maximum sensitivity and consistency, ultimately resembles features of the insect sensorium. A “fingerprint” 3D plot (time, frequency range, voltage amplitude), representing the emitted electric field profile, is presented for each of a variety of odorants and other chemicals. The substance-specific electric-field emission and identification is not impeded by containers or barriers or distance.

Key words: olfaction, olfactory, odorants, pheromones, smell, electric field, electromagnetic radiation, electric field sensor, insect antennae

INTRODUCTION

All matter continuously generates electric fields, a manifestation of atomic structure, specifically, electron density and energies. Consequently, the electric field, reflecting the electron profile, is unique, i.e. a “fingerprint”, for every atomic and molecular species. Electric field measurements have been reported to provide data for analyses of biomolecular structure and dynamics (Wang et al. 2013), structural characterization of DNA hybridization (Cherstvy 2013), chain length of volatile compounds (Wang and Haick 2013), identification of gases (Pinakoulaki et al. 2006) and molecular size, shape, charge density, distribution and site of chemical reactivity (5). Evidence is reported for the major role of electrostatic fields in both the high specificity of substrate/enzyme interaction and enzymatic catalysis (Fried and Boxer 2017). The physico-chemical mechanisms, based upon nanoscale electrostatics may explain and unify the motions of chromosomes during prometaphase, metaphase, and anaphase (Gagliardi 2002). Potential differences that are established across the cell membrane generate electric fields that modulate the organizational and functional properties of protein assemblies such as proton ATPases (Coster and Chilcott 2002).

That animals detect changes in the electric field environment induced by prey and other sources has been demonstrated. It has been long known that electric fish communicate and identify sex, age, and other features within the species by means of electric fields. In the wide variety of insects that sense chemicals in their environment, the receptive antennae are coupled to sensory neurons. In some cases, the antennae have fine hairs, sensillae, that contain sensory neurons. Bumblebees use the fine mechanosensory hairs covering their bodies to detect weak electrical fields by the flowers they feed on and pollinate (Garral and Martin 2011). That the bees show preference for certain plants indicates the identifying nature of the emitted electric field. That stereoisomer pairs of odorants smell the same (Brookes et al. 2009) is consistent with their identical electron profiles, and, accordingly, the electric-field profiles of both isomers.

Insects use several senses to forage, detecting floral cues such as color, shape, pattern and volatiles. Clarke et al. (Clarke et al. 2013) report that, like visual cues, floral electric fields exhibit variations in pattern and structure, which can be discriminated by bumblebees and that this modality may facilitate rapid and dynamic communication between flowers and their pollinators. As a bee approaches a flower, the floral electric field distorts the field around the bee's body, and these distortions deflect the mechanosensory hairs, causing in them a lever-like movement which triggers the nerve cells at their base to fire off signals.(Any movement of an object or organism perturbs the ambient electric fields, eliciting a specific pattern of disturbance. For example, commonly deployed security motion-sensors can distinguish electric-field 'fingerprints' of human size, position and limb movements. Electric fields were measured emanating from honeybees in various contexts, including during the "waggle dance": the figure eight-shaped circuit performed by foragers upon their return to the nest to communicate the location of rewarding flowers to nest mates (Greggurs et al. 2013). Fruit flies were able to discriminate the odorant, acetophenone that contained normal hydrogen atoms from that where the hydrogen atoms were replaced by heavier deuterium atoms. The nucleus of the deuterium atom contains a proton in addition to the neutron found in the hydrogen atom. The electric field profiles would be different in the two isotopes (Franco et al. 2011).

MATERIALS AND METHODS

The sensor: an array of eight hair-thin antennas, 10 mm apart. Each channel has an antenna buffer that transforms the high impedance to low impedance followed by a gain stage where the gain can be adjusted from 2 to 11 so that all antennas are matched. The power for the sensor is provided by the data acquisition USB connection to the computer. The NI-6009 OEM data acquisition by National instruments is used to digitize all eight channels. LabView is used for data analysis. The substances were contained in 10 ml glass vials situated 3 meters distant from the sensor. For each test period of data acquisition, the vials were exposed to the sensor for 60 seconds in order to obtain an optimal SigmaPlot signature. The orientation of the 3D plots are shown in a form which permits optimal visual comparisons between substance-specific profiles.

FIGURE 1

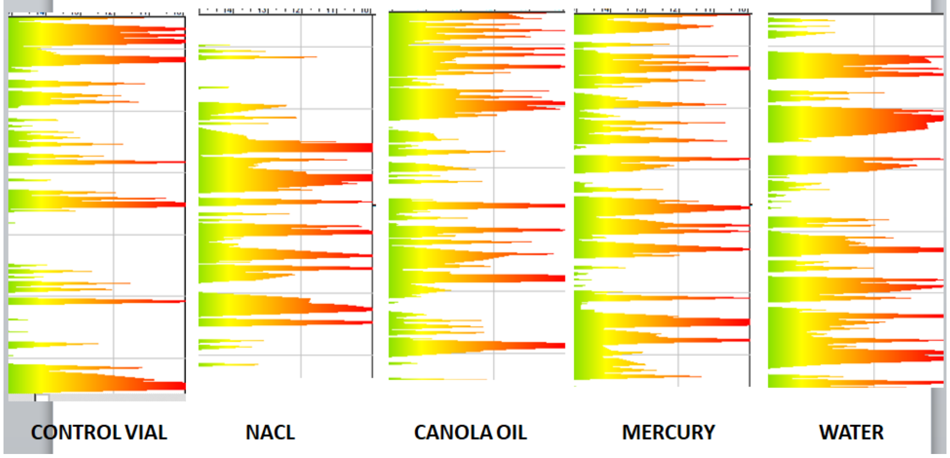

FIGURE 2

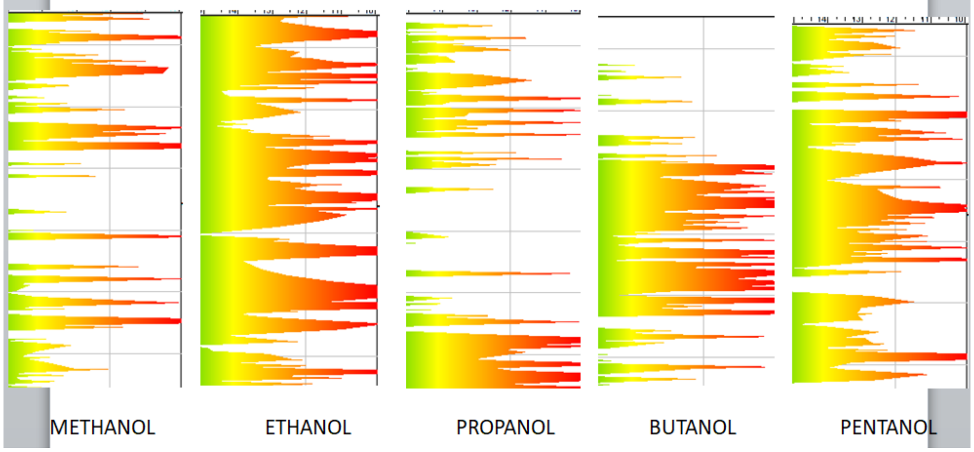

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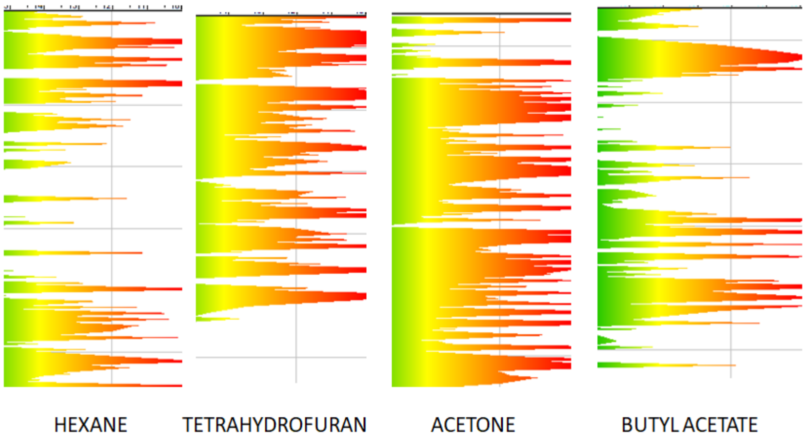
FIGURE 3



RESULTS AND DISCUSSION

The electric-field profiles of a variety of chemical agents are shown in Figures 1, 2 and 3. The substances were contained in10 ml glass vials situated 3 meters distant from the sensor. For each test period of data acquisition, the vials were exposed to the sensor for 60 seconds in order to obtain an optimal SigmaPlot signature. The orientation of the plots are shown in a form which permits optimal visual comparisons between substance-specific profiles. Left axis: time, 0-60 seconds; bottom axis: amplitude, maximum 1 mV rms; right axis: frequency range, 280-420 Hz. (We have observed electric field signatures from radioisopes. Current focus is on generation of an algorithm to enable real-time digital identification of chemical substances.) The glass vials can themselves be further enclosed in other structures. The continually emitting and propagating electric field is unimpeded by walls and barriers; the charge on one side of a wall is in balance with that on the other side.

Our imposition of an external modulating frequency provided a more coherent and reproducible background carrier and, as a consequence, a more consistently reproducible electric-field signature. In the elasmobranch skate, a voltage-gated calcium channel and calcium-activated potassium channel couple to mediate electrosensory cell membrane voltage oscillations, which are modulated by external weak electrical signals (Lu and Fishman,1995; Ai et al. 2017; Rajaraman et al. 2015). Virtually all of the thousands of insect species possess mechanisms that produce vibrations. These mechanical movements themselves provide a steady output and, as a consequence, a steady background, i.e. carrier frequency range, of electric field expressed as chirping, buzzing and other species-related sounds. Such vibratory responses occur during conditions of stress, feeding, mating, aggression and other behaviors, circumstances in which electric fields are emitted from odorants, pheromones, and flora.

We propose that the mechanism whereby insects identify and differentiate among many odorants, pheromones and plant species can be extrapolated to animal olfaction in general. The passive electric field emission from atoms and molecules, that reflects their individual, unique electronic profile, is received by appendages, whose ultra-fine structure appears to be a feature that endows exquisite sensitivity and power to identify an unlimited number of molecular signatures. In both insects and man, these electric field detectors, antennae and cilia, are coupled to neurons whose activation by impinging electric fields, propagate to the brain where they are processed, interpreted and stored.

The extraordinary sensitivity and discriminatory power of these miniscule appendages, found on all cells and in all species, presupposes an evolutionary advantage, evidenced by the preferential and overwhelming proliferation of insect species and populations. Electric field sensing is the earliest form of biological communication (Bellono et al. 2017), a highly conserved modality and operative in all cells and species.

This primitive sensing function has been adopted by the visual and auditory systems. For example, light to cilia in retinal cells is absorbed by light-sensitive proteins, channelrhodopsin and halorhodopsin (Wietek and Prigge 2016). Both proteins are ionic channels and simultaneously perform phototransduction and electric excitation. In the inner ear, the outer hair cells mechanically amplify low-level sound that enters the cochlea. Again, structural movement generates an electric field fingerprint. This so-called somatic electromotility found in all land vertebrates is affected by the closing mechanism of the sensory ion channels at the tips of the hair bundles (Barral and Martin 2011). In the brain inter-neuronal communication is not restricted to synaptic transmission, but includes functionally significant endogenous electric fields (Baer and Collello 2016; Green and Mykytyn 2014; Goldwyn and Rinzel 2015).

Primary insect odorant ‘receptors’, in general, appear to be ion channels. For example, Sato et al. (Sato et. 2008) cultured cells from silk moth, fruit fly or mosquitos responded with extracellular calcium influx and cation-non-selective ion conductance upon stimulation with odorant. Direct evidence for odorant-gated ion channels was obtained by patch-clamp recording of Xenopus oocyte and K293Tcell membranes. The application of geosmin, in flies an alerting odorant, to a single sensillium transiently increased [Ca2+]i in a concentration-dependent manner and direct activation of ion channels by odorants and the resulting excitation of the olfactory receptor cell. The heteromeric insect olfactory receptor complex forms a cation nonselective ion channel directly gated by odor or pheromone ligands independent of G-protein signaling pathways (Touhara 2009). Similarly, the generation of some electric fields relies upon ion channels. For example, in prey fishes voltage production was greatest at the mucous membrane-lined mouth and gills, which are sites of direct ion exchange with the environment (Bedore and Kajiura 2013).

Ion channels in the antennae/cilia appear to be the primary target of electric fields from matter. The electric fields are converted to electrical signals through a variety of ion-conducting channels in the ciliary membrane, which result in changes in concentrations of ions leading to excitation of impinging neurons. Accordingly, an electric field 'fingerprint' of a substance is imprinted in the brain as a molecular-specific pattern of multiple sensory-neuron activation. Stevens reports that, in the fruit fly brain, any given odorant activates its own population of large-input neurons which, in turn, recruits from the thousands of next-stage neurons a small subset that serves as an odorant signature (Stevens 2015).

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