Touchable gustatory sensing

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The integration of technologies such as human-machine interfaces and biomimetic intelligent robots has brought about a unique revolution in modern science and technology,[1] recognized as one of the most promising and critical frontier technologies. In the construction of smart robots, sensors are the most crucial units, second only to processor chips in importance. Robots equipped with various supplementary sensors can receive commands and perceive the external environment. Among these, tactile perception is an essential sensory function in which human skin directly interacts with the external environment. This perception arises from the coordinated responses of subcutaneous mechanoreceptors and neurons to different environmental stimuli, as well as the brain's recognition of incoming signals through neural fibers.[2]

The 2021 Nobel Prize in Physiology or Medicine was jointly awarded to David Julius and Ardem Patapoutian for their discovery of temperature and touch receptors. Tactile perception in human skin is a mechanotransduction process where mechanical stimuli activate ion channels, converting stress stimuli into electrophysiological signals.[3] David Julius identified the capsaicin receptor in human skin. Capsaicin, the spicy component of chili peppers, selectively activates sensory neurons to evoke a burning pain sensation. At the biomolecular level, touch and taste share the same mechanistic model of activating ion channels. Tactile sensation, as the most primitive sense in microorganisms, is combined with taste. Organisms perceive the external environment, including temperature, chemicals, and morphology. Today, tactile sensation with gustatory elements provides richer and more significant biological information at the molecular and ionic levels, applicable in health monitoring, clinical diagnostics, and human-machine interactions.

However, most existing object recognition programs have relatively single functions, making it quite difficult to detect taste and touch simultaneously. To achieve this task, researchers have attempted to integrate multiple types of sensors into a single device. However, this requires complex manufacturing processes and peripheral circuits. Furthermore, these traditional solid-state technologies mostly rely on electronic carriers, which are not conducive to the transport of ionic neurotransmitters in organisms and require high operating voltages. Therefore, it is essential to develop low-power, multi-sensory, biocompatible object recognition systems that directly utilize signals generated by the sensors.

In this commentary, we highlight two groundbreaking studies, "Bionic Tactile-Gustatory Receptor for Object Identification Based on All-Polymer Electrochemical Transistor"[4] and "Touchable Gustation via a Hofmeister Gel Iontronic Sensor,"[5] which introduce novel approaches to achieving tactile and gustatory

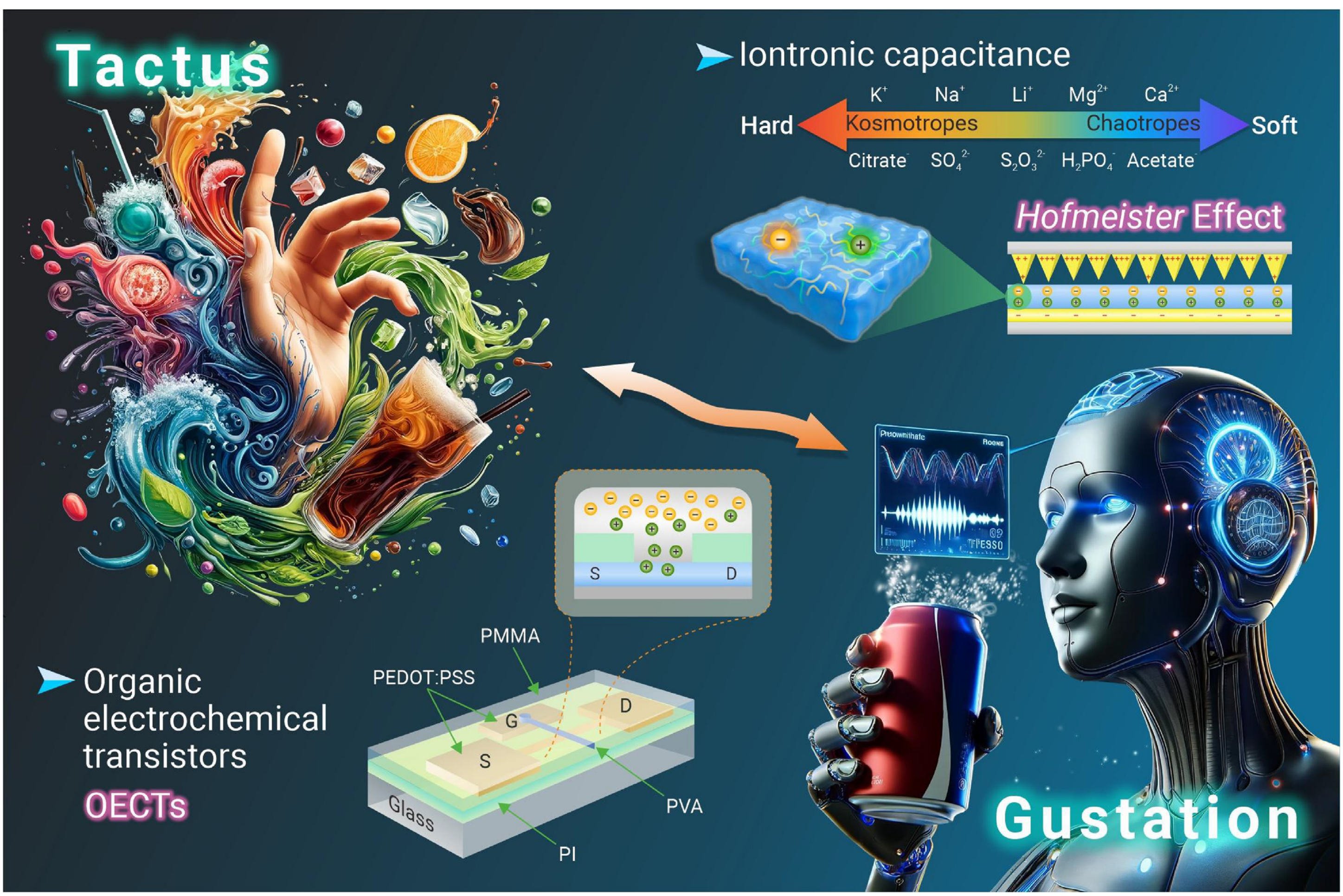

Figure 1. Schematic illustration of iontronic sensor: The ions transport in AECTs and the *Hofmeister* gel iontronic sensor

perception. These studies utilize an organic electrochemical transistor composed entirely of biocompatible polymers as a tactile-taste receptor and a chemical-mechanical interface strategy incorporating the Hoffmeister effect. These studies successfully demonstrate the realization of touch-based taste sensation in a single sensor device by leveraging differences in transduction signals generated by various substances, thus eliminating the need for complex manufacturing processes and interconnecting circuits. This breakthrough holds great promise for endowing tactile and taste perception with unique functionalities, thereby contributing to advancements in human-machine interactions, humanoid robotics, clinical therapies, and the optimization of sports training.

WORKING PRINCIPLE OF THE SENSORS

Figure 1 in the latest research paper presents a novel design of a biocompatible, fully polymeric organic electrochemical transistor (AECT) as a tactile and gustatory receptor for object recognition. Similar to the neurotransmitter transport mechanism in biological organisms, ions migrate to the channel of the AECT in response to external stimuli. When fingers carry distinct charges upon contact with different materials, it results in the application of gate voltage to the AECT. By exploiting this characteristic, the AECT demonstrates the ability to identify the contacted materials.

Additionally, an ion electronic sensor device is proposed, which uses a conductive hydrogel as the dielectric layer in the gel-based ion sensor. This research investigates the Hofmeister effect on the hydrogel, providing a quantitative analysis of the gel's elastic modulus in relation to chemical cosolvents. The gel-based ion sensor enables the differentiation, classification, and quantification of various cations, anions, amino acids, and sugars. The chemical-mechanical interface, modulated by the Hofmeister effect, exhibits real-time responses, converting biochemical signals into electrical outputs. Both studies leverage the differences in signals generated by distinct taste substances, utilizing variations in transduced electrical signals for taste substance recognition, ultimately achieving touch-based taste sensing.

DISCRIMINANT ANALYSIS OF MATERIALS

The key factor enabling tactile taste sensing in both studies is the establishment of a real-time responsive biochemical-mechanical transduction interface, which converts biochemical signals into electrical outputs. Within the AECTs, a friction-induced triboelectric nanogenerator converts mechanical energy into electrical signals, manifesting as contact-induced electrification at the interface. Additionally, inspired by human taste perception, a taste receptor is designed to identify fundamental tastes. The PVA electrolyte represents the thin saliva layer on the human tongue, with various concentrations of taste stimuli injected into the PVA. Introducing AECTs with varying NaCl concentrations into a PDMS mold containing the pure PVA electrolyte enables real-time sensing responses. With fluctuations in NaCl concentration, the drain current (Id) undergoes proportional adjustments. Taste recognition is achieved through the analysis of current fluctuations resulting from signal alterations induced by the tastants.

Utilizing the Hofmeister effect, the gel-based ion-electron sensor incorporates a chemical-mechanical transduction interface into an electric double-layer capacitor sensor. A conductive hydrogel serves as the dielectric layer in the gel-based ion sensor. The hydrogel's mechanical characteristics can be extensively and reversibly modified by controlling the polymer chain aggregation state using hydrated ions or cosolvents. Scanning electron microscopy (SEM) revealed distinct mesh structures in the hydrogel's microstructure for different immersing cosolvents. Information about various chemical components is stored within the gel. The chemical-mechanical interface, modulated by the Hofmeister effect, exhibits real-time responses, converting biochemical signals into electrical outputs. The gel-based ion sensor enables the differentiation, categorization, and quantification of various cations, anions, amino acids, and sugars, facilitating the attainment of tactile taste sensing.

CONCLUSION AND FUTURE PERSPECTIVES

These two studies showcase novel biomimetic sensing technologies based on fully polymeric organic electrochemical transistors and Hofmeister gel-based ion-electron sensors, establishing a real-time responsive biochemical-mechanical transduction interface for converting biochemical signals into electrical outputs. This achievement enables tactile taste sensing. The effective integration of biological sensing and electronic technology opens new possibilities for developing biosensors and human-machine interactions, offering unprecedented potential in fields such as healthcare, humanoid robotics, and sports training.

While significant progress has been made in these technologies, taste perception functionality depends on both the concentration and radius of ions to emulate multi-modal taste recognition. Various tastants are categorized as chemicals, inorganic substances, and organic compounds with diverse functional groups. Consequently, integrating anchoring layers or enzymes into a unified device for detecting various chemical substances poses a significant challenge. Additionally, the full potential of the Hofmeister effect remains untapped, and future research may explore its integration with photonic crystals and graphene to broaden or amplify its impact. Hofmeister gel-based ion-electron sensors hold significant potential in areas such as human-machine interactions, humanoid robotics, clinical therapies, and optimized sports training. The chemical-mechanical transduction interface plays a crucial role in tactile taste transduction, particularly in touch-based taste sensing applications.

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DECLARATION OF INTERESTS

The authors declare no competing interests.