Title: Human gustation: when the brain has taste.

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Journal: Current biology : CB

Year: 2015 May 4

Issue: 25

Volume: 9

Pages: R381-3

DOI: 10.1016/j.cub.2015.03.002

DISPATCH

Human Gustation: When the Brain Has Taste

What we put into our mouths can nourish or kill us. A new study uses state-of-the-art electroencephalogram decoding to detail how we and our brains know what we taste.

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Imagine you get lost in the forest and become hungry. You find some rather nice looking berries. Their colouring and fragrance make you think they are ripe and probably tasty. You have also seen a rabbit eating them, with no apparent detriment [1]. So, you eat a handful. You may have just unknowingly poisoned yourself with deadly nightshade (*Atropa belladonna).* Poisons are readily found in plants (e.g. the alkaloids atropine (found in nightshade), arsenic, curare, strychnine, and hemlock) and have historically been particularly effective for both nefarious as well as medicinal purposes (Figure 1). Given the vital importance of our sense of taste, it is perhaps surprising that our understanding of the neural basis of taste perception in humans remains rather rudimentary, particularly when compared with other senses, such as vision, hearing and touch [2]. In a recent issue of *Current Biology*, Crouzet *et al*. [3] provide evidence for just how quickly information about tastes is decoded by the brain and, moreover, how this neural signature relates to perceptual outcome.

Crouzet *et al*. [3] were able to accomplish this by capitalizing on the confluence of two recent methodological advances. The first concerns how to deliver tastants within a laboratory setting. This is no small feat when one is trying to control when, what and for how long a stimulus is delivered. The improvement of experimental procedures has been dramatically helped by the commercial availability of a device that controls the delivery of liquid tastants, called a spray gustometer. The crucial innovations of this device are its ability to control the timing of stimulus presentation (this is essential for eliciting time-locked brain activity as described below), to provide rapid rise-time in terms of stimulus intensity and to minimize confounding affects of changes in somatosensory and temperature inputs in the mouth (there is a constant flow of water interspersed with tastant delivery) [4]. These controls are of critical importance when trying to isolate and characterize the brain response to taste *per se*. However, this method is not without some drawbacks. On the one hand, spraying tastes onto the tongue is ethologically artificial and is thus far removed from how we normally ingest foods. Still, this is an important step forward, as the majority of clinical research on taste still electrically stimulates the tongue [5]. On the other hand, a spray gustometer is in many regards cumbersome and impractical for any but the most motivated of participants. Experiments

are typically quite lengthy because there is a long wash-out period between trials, and participants need to keep their mouths open and tongue immobilized (which can make speaking quite a challenge). Such notwithstanding, spray gustometers allow for both precision in stimulation as well as controlled trial-to-trial variability in the qualities of tastants hitherto unavailable to scientists.

The second methodological advance used by Crouzet *et al*. [3] concerns how to analyze electroencephalographic (EEG) recordings. They applied a multivariate pattern analysis (MVPA) framework to their data. MVPA is not particularly novel from a statistical standpoint. However, it is quite revolutionary when it comes to its application to EEG (or its magnetic counterpart magnetoencephalography; MEG) [6-8], though its origins can be traced to the pioneering works of individuals like Dietrich Lehmann in the 1970s [9]. The basic idea is to use the added information that is available from recording EEG from multiple scalp locations simultaneously to in turn better distinguish between responses to different experimental conditions. It is a bit like geographic surveys — one gets a more detailed picture by collecting data all across the length of a mountain range rather than just from the base and peak. The basic approach with MVPA is to train an algorithm with regard to the differentiating features of responses to a given set of stimuli (e.g. a set of tastants or a set of mountain ranges). Once trained, MVPA then tests to what extent the algorithm can successfully label previously 'unseen' data that were not used during the training. Therefore, MVPA is most effective when recordings and analyses involve a large number of scalp electrodes — something readily feasible with current research and clinical EEG systems [6-7]. A related issue thus concerns the distillation of signals for analysis in EEG research. Typical EEG analyses apply signal averaging to obtain event-related potentials [6-8] and entail selection of one or a few scalp electrodes(presuming that recordings were made from multiple locations on the head) as well as one or a few time periods of interest that bracket established components or other archetypical signals [10]. This type of approach for EEG analysis can have important shortcomings both with regard to statistical rigor as well as neurophysiological interpretability [6-8]. Researchers studying taste, however, often are severely limited when it comes to the numbers of trials that can be reasonably acquired during an experiment [2,4,11]. It may therefore not be quite so surprising that the human brain's response to taste had hitherto remained so poorly characterized. MVPA can dramatically improve this situation by allowing researchers to use the data from all of the recorded channels and to perform analyses at the level of groups, individual subjects or single trials.

By combining a spray gustometer for stimulus delivery and MVPA for the analysis of EEG signals, Crouzet *et al*. [3] show that within the initial ~175ms after a tastant is delivered to the tongue the brain's responses differ according to whether the tastant was salty, sweet, sour or bitter. Because these distinctions were in terms of the topography of the EEG at the scalp [6-8], it means that each tastant activates distinct configurations of brain networks inside the brain. Moreover, the

MVPA analyses revealed that sufficient information was contained within the instantaneous single-subject and single-trial responses to decipher which tastant had been presented on any given trial. This is a remarkable result because it obfuscates the need for signal averaging [8] and thus circumvents some of the aforementioned paradigmatic shortcomings imposed by taste research in general and by using a spray gustometer specifically.

In a further analysis, the authors demonstrate the specificity of the EEG topography for a given tastant as well as for a specific moment in stimulus processing. MVPA-based classification failed when using data from one moment in time to decode later points in time of responses to the same tastant. This classification likewise failed when using data from one tastant to classify responses to another tastant. In other words, topographic information is unique in time and to a specific tastant. Next, Crouzet et al. [3] directly linked the single-trial brain responses with perception. The errors made by the MVPA-based classifier were significantly correlated with those made by the participants themselves. As above, this correlation was apparent starting at ~175ms after the delivery of the tastant. No such correlations were observed with subjective reports concerning either the pleasantness or the intensity of the tastant. Critically, none of this information could be gleaned from the univariate data from a single electrode. This finding underscores not only the added value of MVPA based on high-density EEG montages in basic, clinical and applied research, but also how important it is to consider the dynamics of widely distributed brain networks when characterising sensation and perception [6-8].

Given the relative infancy of our understanding of the neural bases of taste perception in humans, the results of Crouzet *et al*. [3] should in many respects be taken as a rallying cry to show that researchers should be undaunted in the face of a challenging sensory modality such as gustation. Several questions will require continued, extensive research, only a few of which are elaborated here. First, if brain signals provide sufficient information at one instant in time to accurately decode which of four tastants was delivered, then why should discriminant signals persist over time? It will likewise be important to ascertain how information about taste is accrued over time. The MVPA was applied here on each data point independently. While Crouzet *et al*. [3] indeed show that the topography of the response sufficiently varies over time so that decoding of test data from time *x* is unsuccessful if based on training the classifier with data from time *x-y*, they do not at present provide insights on the quantity or quality of information that would be available by accumulating information across time. Resolving this question is likely to also provide insights into the information content of these brain signals.

Second, it is undoubtedly the case that the brain's perceptual discrimination capacity documented in this study is in large part the consequence of accrued experience. The brain decoding methods applied by Crouzet and colleagues are suited not only to characterize the developmental

trajectory of this ability, but also to be implemented in challenging paediatric, geriatric and clinical populations [6-8]. Because the methods are sufficiently powered to study responses to single-trial events in individual participants, it would be feasible to conjoin these methods with genetic assays [12], clinical populations with impaired taste (e.g. as a consequence of neuro-degeneration or chemotherapy) or neuropharmacological interventions. Third, it will be essential to apply these methods to understand the perception of more complex tastes and flavours as well as the multisensory nature of food perception in general [13].

Collectively, these kinds of efforts and more specifically the approach taken by Crouzet *et al*. [3] may provide a better understanding as to why my 4-year-old refuses to eat asparagus, while my 7-year-old adores it and more generally why certain foods may truly be an acquired taste.

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Figure 1. [AU figure title please]
Death of Socrates (1787, Jacques Louis David; image from the Metropolitan Museum of Art, New York, NY, USA). This painting depicts Socrates, who was sentenced to poison himself with hemlock after being convicted of heresy. One cruelty of this manner of execution, particularly in the case of a philosopher like Socrates, is that hemlock has limited effect on the central nervous system (death is ultimately the consequence of respiratory failure). Socrates was aware both of what he was drinking and what it was doing to him as he was dying. (Image: Catharine Lorillard Wolfe Collection, Wolfe Fund, 1931; http://www.metmuseum.org/collection/the-collection-online/search/436105)