Temporal coding of taste mixtures in the nucleus of the solitary tract of the rat

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Introduction

Recent work in our lab has shown that **spike timing** in taste responses in the nucleus of the solitary tract (NTS) contributes to taste coding in a subset of cells. Temporal patterns of the taste response in these cells enabled the discrimination of taste quality more accurately than spike count alone. The current project was designed to investigate whether the temporal characteristics of NTS taste responses also convey information when tastants of **two different taste qualities are presented simultaneously as a mixture**.

Materials and Methods

Surgery and Data Collection

- All animals were fully anesthetized with urethane and prepared surgically for electrophysiological recording in the NTS.
- Extracellular recordings were made from single cells in the NTS with etched tungsten microelectrodes. Waveforms associated with single cells were isolated using the software package Spike2 (CED).
- Taste stimuli consisted of **four single tastants:** NaCl (0.1 M), Sucrose (0.5 M), HCl (0.01 M), and Quinine (0.01 M) and **six binary mixtures:** NaCl (0.1 M) **+**HCl (0.01 M), NaCl (0.1 M) **+**Sucrose (0.5 M), NaCl (0.1 M) **+**Quinine (0.01 M), HCl (0.01 M) **+**Sucrose (0.5 M), HCl (0.01 M) **+**Quinine (0.01 M), Sucrose (0.5 M) **+**Quinine (0.01M).
- Each trial consisted of a 10 sec baseline (no stimulus presented), 10 sec distilled water, 5 sec stimulus presentation, 5 sec wait, and 20 sec distilled water rinse. Each block of four single tastants and six mixtures was repeated for as long as the cell was well isolated.

Quantitative Analysis of Taste Temporal Coding

- Information conveyed by response-related spike timing was analyzed with a **family of metrics that quantify the similarity of two spike trains** in terms of the number of spikes, i.e. spike count, and spike timing (D^{spike}). The level of temporal precision (termed "q") at which information conveyed by spike timing was maximized was determined for each cell. The distances among taste responses, as measured by D^{spike}, at that value of q, were then used as input to a **multidimensional scaling analysis (MDS). The results of the MDS indicated the organization of taste responses in terms of the similarity of the spike timing of their responses.**

I. Metric Space Analyses:

- The distance between two spike trains was measured by the "**minimum cost**" of changing one spike train into the other. Each spike that was deleted or added incurred a cost of 1. In addition, the cost of moving a spike by an amount of time "t" was set at "qt", where q is in units of 1/s. If q was set at zero, the distance (cost) between the two trains would simply be the difference in the number of spikes. (Victor and Purpura, 1997)

In this analysis, shifting a spike in time by $1/q$ makes just as much of a difference as deleting the spike altogether. Thus, if we define the **"temporal precision"** of coding as the difference in the timing of the occurrence of two spikes that makes just as much of a difference to the nervous system as a deletion of a spike, then "$1/q$" is the measure of the temporal precision or temporal resolution. Spike trains are considered similar only if they have approximately the same number of spikes, and these spikes occur at approximately the same times, i.e., within $1/q$ or less.

II. Multidimensional Scaling Analysis (MDS):

- MDS is often used in data visualization for exploring similarities or dissimilarities in data. "Objects" (taste responses in this case) are arranged in hypothetical "taste space" such that their distances from one another correspond to their relative similarity (as measured by D^{spike} in this case).
- The output of MDS analysis allows a graphical depiction of the similarities and differences among taste responses in terms of their temporal characteristics.

III. Breadth of Tuning:

- To determine the breadth of tuning, an uncertainty measure was used (Smith and Travers, 1979). The formula for uncertainty is as follow:

$$U = -1.66\left(\sum_{i=1}^{4} P_i \log P_i\right)$$

where P_i represents the proportion of the total response to each of four single taste stimulus. Values closer to zero indicate narrow tuning; values closer to 1 indicate broad tuning. The average response across the first 3 presentations of each single taste stimulus was used in this analysis.

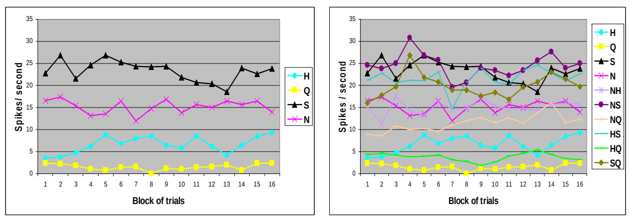
Summary of Results

Table 1: Results of analyses of temporal coding

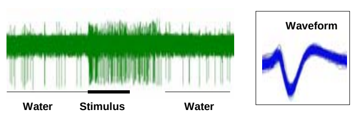
Cell Name	Total Trials	Best Response	Tuning (0~1)	q_{max}	H_{count} (bits)	H_{max} (bits)	H_{max}-H_{count} (bits)	$H_{shuffle}$ (bits)	$H_{exchange}$ (bits)
Cell 1	160	S	0.79	5.66	1.83	2.61	0.78	0.15 •	2.21•
Cell 2	188	N	0.80	2	1.49	2.42	0.94	0.38 •	2.17
Cell 3	166	H	0.90	5.66	1.28	1.99	0.71	0.38 •	1.89
Cell 4	146	S	0.39	2.83	1.62	2.15	0.52	0.50 •	2.19
Cell 5	114	N	0.67	4	1.78	2.41	0.62	0.56 •	2.12
Cell 6	95	H	0.73	0.71	1.79	2.33	0.54	0.73 •	2.21
Cell 7	100	N	0.91	1.41	1.76	3.02	1.26	0.74 •	2.77
Cell 8	170	N	0.69	2.83	1.69	2.02	0.33	0.37 •	1.67 •
Cell 9	92	H	0.77	1	2.02	2.55	0.54	0.79 •	2.30
Cell 10	99	N	0.60	2	1.55	1.61	0.06	0.68 •	1.42
Cell 11	81	H	0.77	8	1.69	2.49	0.81	0.79 •	1.97
Cell 12	137	N	0.66	2.83	1.03	1.26	0.23	0.47 •	1.09
Cell 13	107	N	0.67	8	1.96	2.29	0.33	0.46 •	2.08
Cell 14	59	H	0.76	5.66	1.90	2.65	0.75	0.96 •	2.69
Cell 15	100	N	0.68	4	1.49	2.20	0.71	0.57 •	2.10
Cell 16	84	N	0.77	2	1.61	1.98	0.37	0.77 •	1.88
Average			0.72	3.66	1.66	2.25	0.59	0.58	2.05
Std. Err.			0.03	0.58	0.06	0.11	0.07	0.05	0.10

For all analyses of information, the maximum value of H is 3.32 bits ($\log_2 10$).
H_{count}: The transmitted information calculated based on spike count. H_{max}: The maximum value of transmitted information based on spike timing. q_{max}: The value of q when information is at its maximum value. $H_{shuffle}$: The information obtained from 10 to 40 surrogate data sets in which the tastants associated with each response were randomly scrambled measured at q_{max}. $H_{exchange}$: The information obtained from surrogate data sets with the same number of spikes and the same rate envelope (time course) as the actual taste responses, but with different spike timing. Red dots indicate a statistically significant difference from H_{max}.

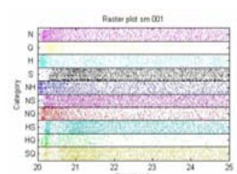
(A) Response magnitude (5 sec response – spontaneous rate) (Cell 1)



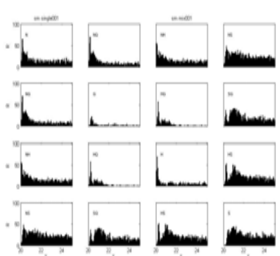
(B) Raw data (Cell 1)



(C) Raster plot of taste response (Cell 1)

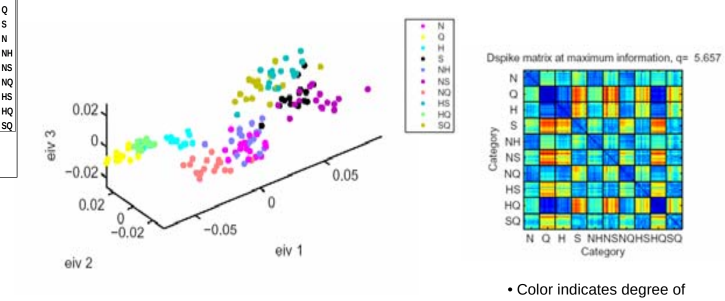


(D) Post-stimulus time histograms (Cell 1)



- Results of the metric space analyses in 16 cells were summarized at Table 1.
- In general, the temporal characteristics of taste responses were shown to contribute a significant amount of information to the overall discrimination of tastants and their binary mixtures. This was evidenced by the observation that values of H_{max} were always larger than values of H_{count}. The average value of H_{count} was **1.66 ± 0.06**, and the average value of H_{max} was **2.25 ± 0.11**.
- Differences in the time course of the response across tastants contributed information to encoding differences among taste stimuli for all 16 cells, above and beyond the information contained in spike count alone ($H_{max} > H_{count}$). In 14 of the 16 cells, differences in the rate envelope of the responses entirely accounted for this additional information (H_{max} does not significantly exceed $H_{exchange}$ at q_{max}). For the remaining two cells, information was also contained in the precise timing of spikes ($H_{max} > H_{exchange}$ at q_{max}, $p<0.05$).
- Figures (A) through (E) are the results from one cell (Cell 1). Response magnitudes for the four single tastants were consistently distinguishable over 16 block of trials, but the response magnitudes of six binary mixture show serious overlap with those of single tastants.
- D^{spike} comparisons of taste responses taken at q_{max} were used as input to construct a **three dimensional taste space** (Figure E). The taste space illustrates that the temporal patterns of taste response were reliable (the points representing responses to the same stimulus were closer to each other) and distinguishable (the clouds of responses to different taste stimuli were distinguishable in the taste space).

(E) MDS taste space and matrix of D^{spike} values (Cell 1)



• Each point in this taste space represents one trial of taste response.

• Color indicates degree of similarity of taste responses in terms of spike timing.

Discussion and Conclusions

- **Contribution of temporal coding to taste mixture discrimination:** The temporal characteristics of taste responses were shown to contribute a significant amount of information to the overall discrimination of single tastant and their binary mixtures.
- **Comparison with surrogate data sets:** In all cells, the time course of the response contributed to coding of the 10 taste stimuli. In 14/16, the contribution of the time course of the response was entirely explained by the firing rate envelope for each tastant. In 2/16, the firing rate envelope did not fully account for the added information in the response time course, implying that the detailed arrangement of spikes in time also plays a role.
- **Temporal reliability:** The results of the metric space and MDA analyses showed that all responses to the same taste stimulus (single tastant or binary mixture) evoked spike trains with similar temporal structures. In the taste space, responses to different taste stimuli generally occupied distinct and largely non-overlapping regions.

References:

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[3] Smith DV and Travers JB (1979) *Chem Sense Flav*, 4, p215-229.