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Gustatory Responses in the Nucleus Tractus Solitarius of the Alert Cynomolgus Monkey

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SUMMARY AND CONCLUSIONS

1. Multiunit and single neuron responses to taste stimuli in the nucleus tractus solitarius (NTS) of alert cynomolgus monkeys were analyzed.

2. Intensity-response functions, including neural thresholds to glucose and quinine HCl, agreed well with psychophysical reports, implying that the cynomolgus monkey and human share the same dynamic range of sensitivity to prototypical taste stimuli.

3. The NTS is chemotopically organized: neurons most responsive to HCl are more common in the posterior gustatory area, whereas those most responsive to glucose and NaCl are located in the anterior NTS. Responsiveness to quinine is more widely distributed but tends toward the anterior.

4. Efforts were made to determine if neurons could be divided into a discrete number of types, as determined by their sensitivities to the prototypical stimuli. The clearest distinction was between those that did or did not respond well to HCl. Beyond this, neuronal categories were not obvious.

5. Individual neurons were quite broadly sensitive to our stimulus array, so that, for the typical NTS cell, no one of the four prototypes evoked a majority of the discharges. This extreme breadth of tuning suggests that taste-quality information in the monkey might be incorporated in relative discharge rates across the neuron population.

6. Correlations among patterns of activity to the four prototypical stimuli indicated that only HCl and quinine HCl have closely related taste qualities.

INTRODUCTION

Several investigators have recorded taste-evoked responses from the chorda tympani and glossopharyngeal nerves of anesthetized monkeys (4, 11, 14, 19, 24, 31, 32). From these studies it is known that activity in the peripheral nerves of primates shows many of the general features seen in rodents and other mammals. Spontaneous levels of activity are comparable at 2 spikes/s (32). Neurons are rather broadly responsive to representatives of the putative basic tastes: sucrose (sweet), NaCl (salt), HCl (sour), and quinine (bitter). Alkaloids activate the system at the lowest concentrations followed in ascending order by acids, salts, and sugars (19, 24). Evoked activity rises approximately linearly with the logarithm of stimulus concentration throughout the dynamic range of each neuron. Time courses are comparable with salts and acids evoking sharp onsets, whereas sweet stimuli elicit tonic rhythmic activity (32). Yet there are some differences in the monkey. Responses are found in the gustatory nerves of the green monkey (*Cercopithecus aethiops*) to proteins (monellin and thaumatin) that humans describe as sweet but which evoke no activity in the rodent (4). In the macaque there is a separation of bitter-tasting alkaloids from the acids and salts to which they are positively related in rodents (32). In the squirrel monkey, all three classes of non-sweet tastes dissociate (24). Fructose correlates well with salts in the squirrel monkey but not in rodents. In general, these findings agree with data from psychophysical studies.

There are also reports of taste-evoked activity from the primate central nervous system

(3, 37) though these have not been primarily directed toward an analysis of the gustatory neural code. Recordings from monkeys would extend our knowledge of the coding process to subjects more closely related to humans and so would allow a more meaningful comparison between neural and psychophysical results. The relevance of the neural data to human perception could be further enhanced by studying primates who are alert and tasting solutions in a behavioral setting. Recent autoradiographic experiments by Beckstead and colleagues (1, 2) have precisely delimited the gustatory relays in monkey brain stem, and so made them accessible to electrophysiological study. The present manuscript defines the functional location and extent of the first central gustatory relay in the nucleus tractus solitarius (NTS) of the cynomolgus monkey. It characterizes the sensitivity of NTS to the basic taste stimuli and provides evidence for chemotopic organization within the nucleus. Finally, it offers a preliminary analysis of the functional attributes of individual gustatory neurons in the primate.

METHODS

The methods employed for recording were similar to those described earlier (6, 27–30) and will be presented here only in partial detail.

Subjects

The subjects were two male cynomolgus monkeys (*Macaca fascicularis*) weighing 3.8–4.0 kg during the course of data collection.

Surgery

Full sterile precautions were observed throughout surgery. Each monkey was sedated with an intramuscular injection of ketamine and anesthetized with intravenous thiopentone sodium. Atropine (0.1 ml/kg) was administered to prevent excessive salivation, and glycerine was placed in the eyes to prevent their drying. The monkey was placed in a Kopf stereotaxic instrument, and his position was confirmed by X-ray photography. Respiration rate and depth of anesthesia were monitored throughout surgery. A section of skull directly over the medulla was removed and replaced with a stainless steel ring to which a microdrive could be fitted during recording sessions. A second small section of skull was removed just anterior to this to accommodate an assembly of four deep electrodes whose positions served as constant referents relative to which the location of the recording electrode could be determined on each recording track by X-ray photography. Both implants were fixed in place with dental acrylic. Finally, two stainless steel tubes (8 mm OD, 6 mm ID, 5 cm length) were cemented to the skull cap front and back, through which horizontal support bars could be inserted during data collection. Long- and short-acting antibiotics were administered over the next 2 wk, after which recordings began.

Recording

1) Sessions. Daily recording sessions lasted up to 6 h. Each monkey was transferred from his home cage to the primate chair where his head was supported through the tubes provided as part of the implant. He was otherwise free to move and normally adopted a relaxed sitting position. His comfort was continuously attended to, and he was offered food intermittently throughout the recording session.

2) Electrodes. Electrodes were glass-insulated tungsten, plated with gold and platinum black (18), and had tip sizes of from 1×2 to 2×4 μm. Such a composition combined the sturdiness required to penetrate through 45 mm of tissue with the fineness needed to isolate small somata from the densely packed gustatory NTS.

Electrodes were systematically positioned from track to track using a Kopf X-Y positioner attached to the implanted ring. The dura was anesthetized with 0.15 ml Xylocaine, and a sterile stainless steel guide tube (0.1 mm OD), within which the sterile electrode was protected, was passed through it. The electrode was then lowered to a predetermined depth ($\sim$10 mm dorsal to NTS) and advanced using a Trent-Wells hydraulic microdrive and chronic adaptor system.

3) Electrical system. Neural activity was passed through a high-input impedance field-effect transistor mounted on the microdrive. It was amplified by conventional band-pass filtered amplifiers and displayed at high-speed time base (1 ms/cm) on the main oscilloscope. Action potentials of a single cell were identified by consistency of amplitude and waveform and by the requirement that two spikes never occur within a 2-ms interval. Accepted spikes were converted to transistor-transistor logic pulses for on-line analysis. They were also displayed on a second oscilloscope and audio monitor, providing additional visual and auditory cues that permitted corrections as minor changes in recorded voltage occurred with electrode drift. Single and multiunit data, stimulus onset trigger, where applicable, and voice commentary were also stored on magnetic tape for off-line analyses.

Stimuli and stimulus delivery

Thirty-three stimuli were employed. These included eight concentrations, in half log molar steps, of each of the four prototypical stimuli (10^{-3} – 3.0

M glucose; 10^{-3} – 3.0 M NaCl; 10^{-5} – 3×10^{-2} M HCl; 10^{-6} – 3×10^{-3} M quinine HCl) plus 20% blackcurrant juice concentrate (Beecham Products, Brentford, U.K.). Blackcurrant juice was included because it is both highly palatable to the monkey and complex in taste quality so that most neurons were responsive to it. This combination of attributes made it an effective probe stimulus for locating NTS.

Stimuli were delivered in quantities of 0.5 ml through a hand-held syringe. Manual delivery was used in the alert monkey because it permitted repeated stimulation of a large and nearly constant receptive field through compensation for the different mouth and tongue positions adopted as the palatability of the solutions varied. The monkey learned to block or partially avoid the delivery of chemicals through fixed tubes placed in the mouth.

To mark stimulus onset for time course analyses a wire, shielded to its tip, was inserted into the lumen of the syringe. Stimulus contact with oral tissues completed a circuit through the animal, but one with sufficient impedance to maintain current levels two orders of magnitude below the threshold for electric taste (5, 8, 25)[1]. The signal was amplified and stored on magnetic tape.

Stimulus delivery was followed within 10 s by a 1.0–1.5 ml deionized H_2O rinse. At least 30 s of rest was permitted between stimuli, and if there were indications that either the behavioral (licking, grimacing) or neural activity had not returned to prestimulus levels, this period was extended.

Fluid consumption

Monkeys were fed and offered water ad libitum at the end of each daily recording session so that they began the succeeding day ~18 h food-and-water deprived. During a typical recording session, a subject would consume ~200 ml of fluid and several pieces of fruit over a 5-h period. There was initial concern that increasing satiety might affect taste-evoked responses, but a specific test of this issue showed such an effect does not occur (40). Over a 5-day week of data collection, monkeys took 25–50% of their food and 50–100% of their fluid during recording sessions.

Analysis

1) Multiunit. The voltage trigger level in multiunit records was adjusted to accept the activity of approximately 20 neurons[2]. Preceding the delivery of each sapid stimulus or H_2O, a 5-s on-line count of spontaneous activity was taken that served as a base line against which to compare the immediately following evoked response. Thus, activity elicited by sapid stimuli or H_2O was always calculated relative to spontaneous activity at the same site.

2) Single unit. Gustatory neurons in NTS responded differentially to the taste solutions used in this study. They could be clearly distinguished from somatosensory neurons that altered their discharge rates during touch to the mouth, mouth movements, and the application of deionized H_2O. The on-line analysis of evoked spike rates was a significant aid in distinguishing gustatory from somatosensory cells.

A PDP-11 computer counted action potentials and performed basic statistics on line. It also calculated and displayed the time course of spontaneous and evoked neural activity (peristimulus time histograms) in 50-ms bins. Spike counts provided material for derived analyses that included calculations of interneuronal and interstimulus correlation coefficents, multidimensional scaling routines, and cluster analyses as detailed in the results of this paper. These were conducted on a B7700 computer.

Localization of recording sites

The position of each recording site was determined in two ways. First, following each track, X-ray photographs were taken from frontal and lateral perspectives. Relative recording positions could then be reconstructed to within 250 μm by reference to the deep electrodes permanently implanted in diencephalic and telencephalic structures during surgery. The positions of the deep electrodes were subsequently determined histologically. Second, in the final several sessions, microlesions were made through the recording electrode (60 μA for 60 s, electrode negative). At the end of these experiments the subjects were tranquilized with ketamine and given a lethal intravenous injection of pentobarbital sodium. They were then perfused with 0.9% saline followed by formal saline. Their brains were stored in sucrose formalin for at least 7 days after which 50 μm serial frozen sections were cut and stained with cresyl violet. Myelin was also stained in 25-μm sections according to the method of Gallyas (12).

RESULTS

Location and extent

The hindbrain region containing neurons responsive to chemical stimulation of the

[1] If nonionic stimuli were prepared in fully deionized H_2O, there was insufficient conductivity to activate the circuit. Adding as little as 60 μg/l NaCl (1.0 μM solution) remedied this while remaining four orders of magnitude below the taste threshold for salt.

[2] The estimate that 20 cells contributed to the typical multiunit record derives from our observations that the mean spontaneous rate of a gustatory unit in NTS was 1.2 spikes/s, and the mean evoked response to the sapid solutions used here was 5.0 spikes/s. In the multiunit records, spontaneous activity averaged 32 spikes/s and evoked activity 62 spikes/s, implying that the multiunit response included 12–27 neurons.

tongue is nearly cylindrical (Fig. 1). It ranges from 3.5 to 5.5 mm lateral to the midline, from 0.5 to 3.0 mm posterior to the auditory meatus (ear bar 0), and has a dorsoventral extent of up to 0.8 mm, typically 1–2 mm above ear bar zero. Relative to the midline, its main axis is oriented at ~20° to the anterolateral. It is overlain along much of its extent by the medial vestibular nucleus (1). At its rostral and lateral boundaries are neurons responsive to lingual or perilingual touch in the spinal trigeminal nucleus, pars oralis. Ventrally it is bound by more somatosensory cells in the main body of pars oralis.

Multiunit responses

SENSITIVITY TO BASIC STIMULI. The first task was to determine the concentration range over

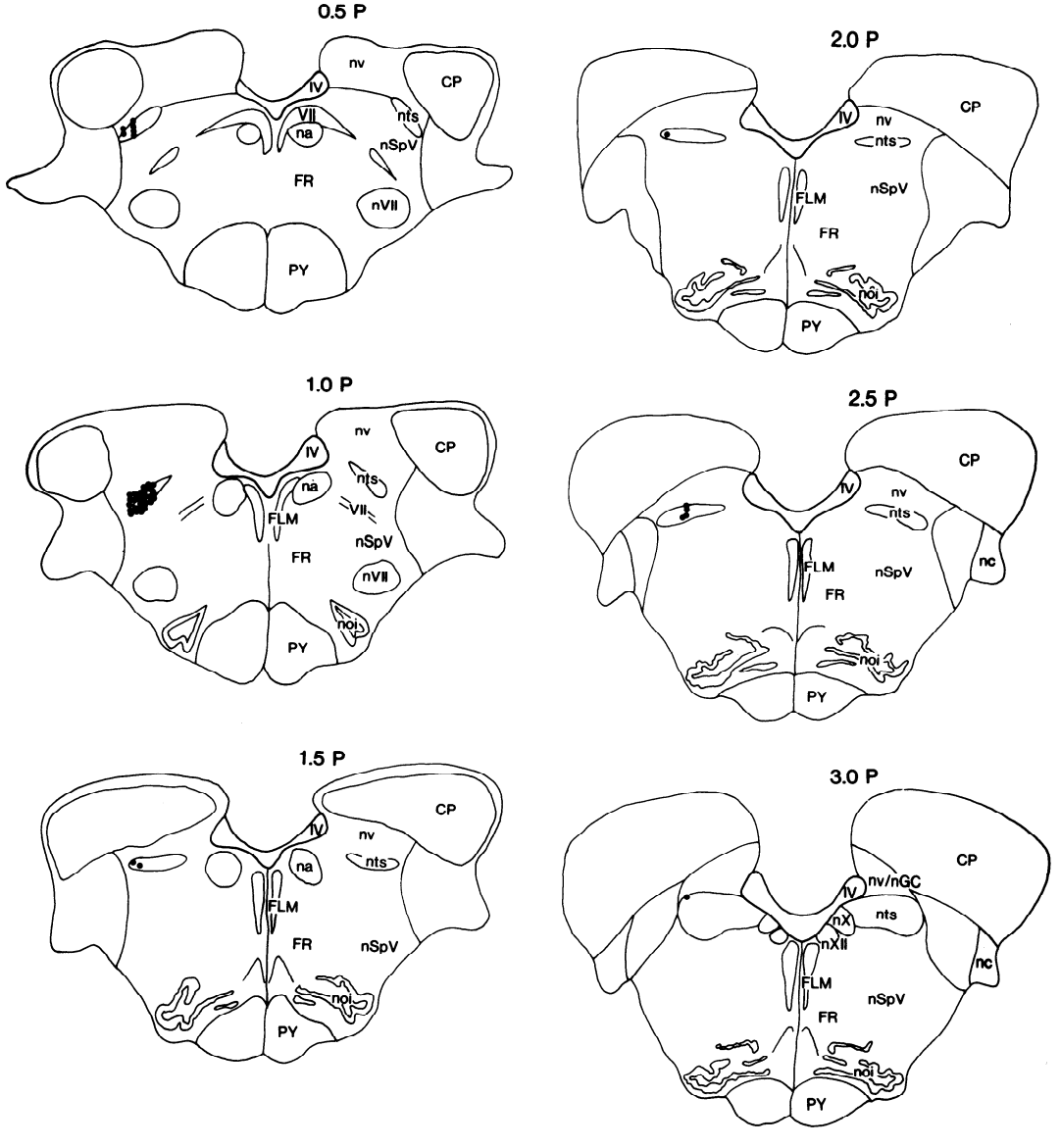

FIG. 1. Coronal sections through the medulla indicating the extent of gustatory nucleus tractus solitorius (NTS) and the locations of single taste neurons whose responses were included in this study. Abbreviations are: CP, cerebellar peduncle; FLM, fasciculus longitudinalis medialis; FR, formatio reticularis; na, nucleus abducens; nc, nucleus cochlearis; nSpV, nucleus tracti spinalis nervi trigemini; nts, nucleus tractus solitarius; nv, nucleus vestibularis; nv/nGC, nucleus vestibularis/nuclei gracilis et cuneatus; noi, nucleus olivaris; nVII, nucleus n. facialis; nX, nucleus dorsalis n. vagi; nXII, nucleus n. hypoglossi; PY, pyramidal tract; IV, 4th ventricle; VII, n. facialis.

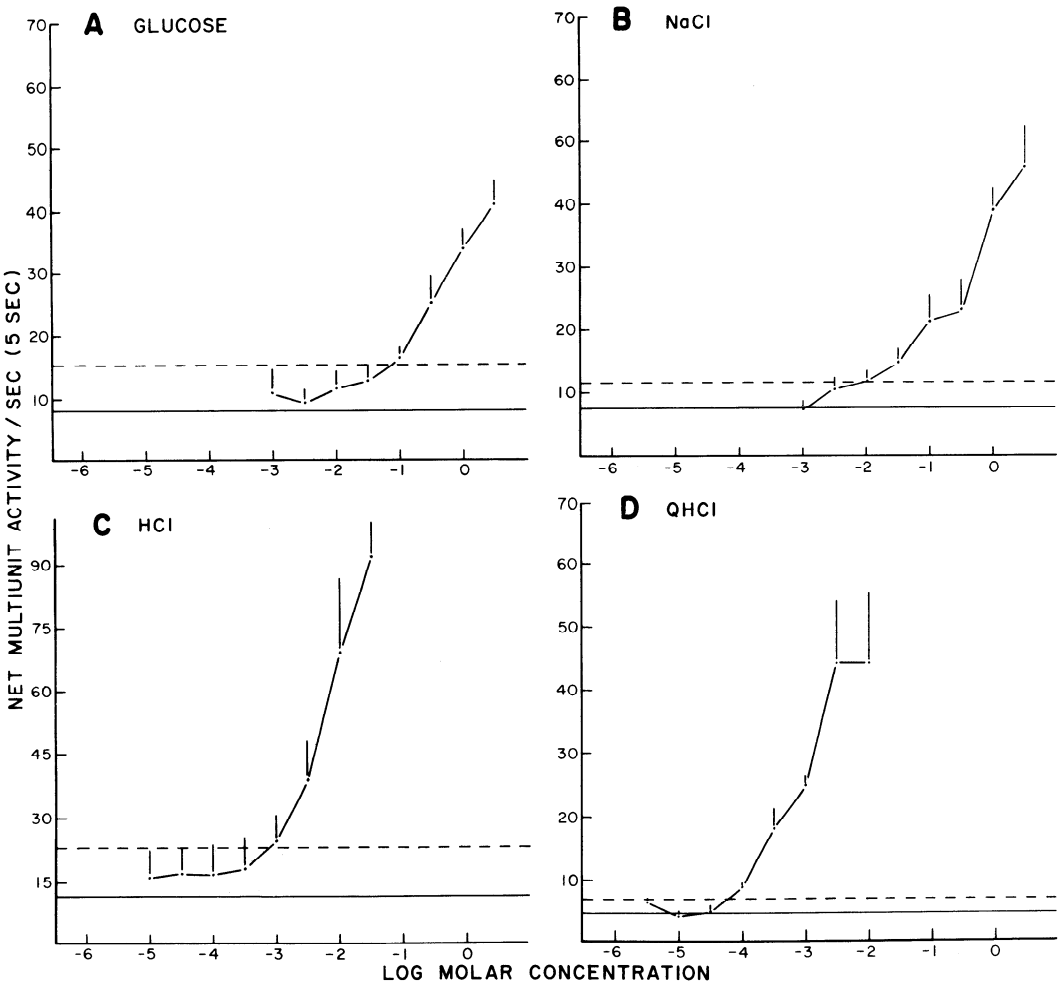

FIG. 2. Intensity-response functions plus SEs for prototypical stimuli. *Solid horizontal line*, mean response to H_2O. *Dashed lines*, response thresholds defined as 1.66 SD ($P < 0.05$) above H_2O response.

which the monkey's taste system is sensitive. The two critical intensities for each chemical were neural threshold and a midrange stimulus to use throughout the remainder of this study. Using previous experiments on the chorda tympani as guides (19, 24, 32), concentration series were conducted for each stimulus that serves as the prototype for a basic taste quality: glucose[3], NaCl, HCl, and quinine HCl. Multiunit activity evoked by each stimulus over a 3.5 log molar range is shown in Fig. 2. Each point represents the mean of 20–30 responses (evoked/spontaneous) elicited during recordings from several sites within NTS.

The neural threshold for each chemical was defined as the concentration at which the taste-evoked activity exceeded the water-evoked response by 1.66 SD ($P < 0.05$). The comparison with water-evoked activity was made to account for any somesthetic responses that may have contributed to the multiunit record. By this definition neural thresholds were 1×10^{-1} M glucose, 1×10^{-2} M NaCl, 1×10^{-3} M HCl, and 1×10^{-4} M quinine HCl.

Standard concentrations for this experiment were chosen on the basis of the concentration-response functions of Fig. 2, the acceptance behavior of the monkeys, and our need to effectively activate the taste system. For glucose,

[3] Though sucrose is normally considered the prototype for sweet taste, the monosaccharide glucose, whose taste is closely related, was used here. This was done so that, in parallel experiments, the effects of glucose-induced satiety on gustatory responsiveness to glucose could be determined.

HCl, and quinine HCl, the choice was one log unit above neural threshold. The concentration-response function for NaCl rises more gradually from threshold. Thus an intensity two log units above threshold was chosen, though in retrospect this was perhaps one-half log unit higher than necessary. Standard concentrations, then, were 1.0 M glucose, 1.0 M NaCl, 0.01 M HCl, and 0.001 M quinine HCl.

CHEMOTOPIC ORGANIZATION. The magnitude of the response evoked by each stimulus was dependent on the recording location within the NTS. The anteroposterior extent of the gustatory relay is nearly 3 mm. As records were taken from progressively more anterior sites, there was a significant tendency for the responsiveness to HCl to decline, whereas the sensitivity to all other stimuli increased. Figure 3 details this chemotopic arrangement. Responses evoked by the standard concentration of each stimulus are calculated as a ratio of the response to deionized H_2O from the same site. This serves to control for a possible somesthetic-evoked component and for the number of neurons accepted into the multiunit record by the threshold setting. Each point represents the mean activity evoked by 2–10 applications of each stimulus (and 4–30 applications of H_2O) at a given location. The relationship between multiunit activity and anterposterior position was significant for all five taste stimuli as shown by linear regression analyses. This crude chemotopic organization provides one possible mechanism for quality coding.

TIME COURSE. Each stimulus evoked activity that had a characteristic time course (Fig. 4). Most discriminable was the response to glu-

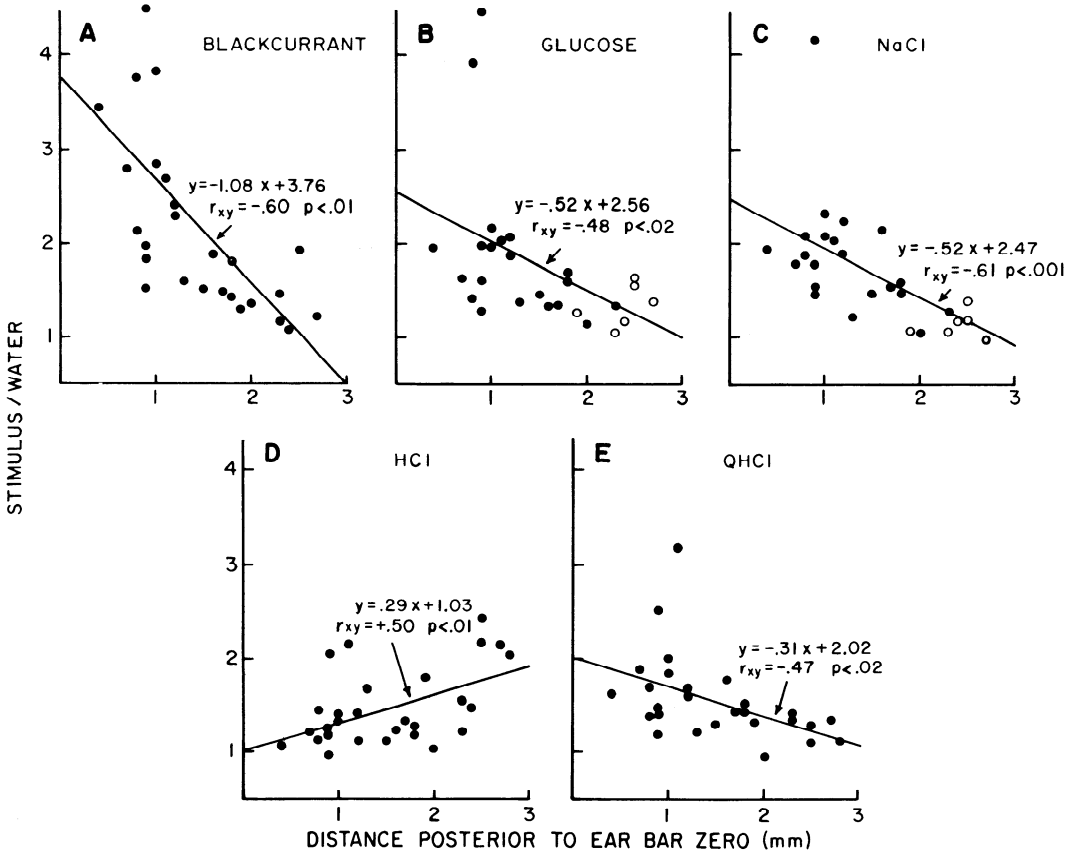

FIG. 3. Magnitude of multiunit response to each stimulus as a function of anteroposterior position in the nucleus tractus solitarius (NTS). Response magnitude is calculated as a ratio of the activity evoked by distilled H_2O at the same location. *B*: *open symbols*, values extrapolated from the responses to 0.3 M sucrose; *C*: *open symbols*, values extrapolated from responses to 0.3 M NaCl.

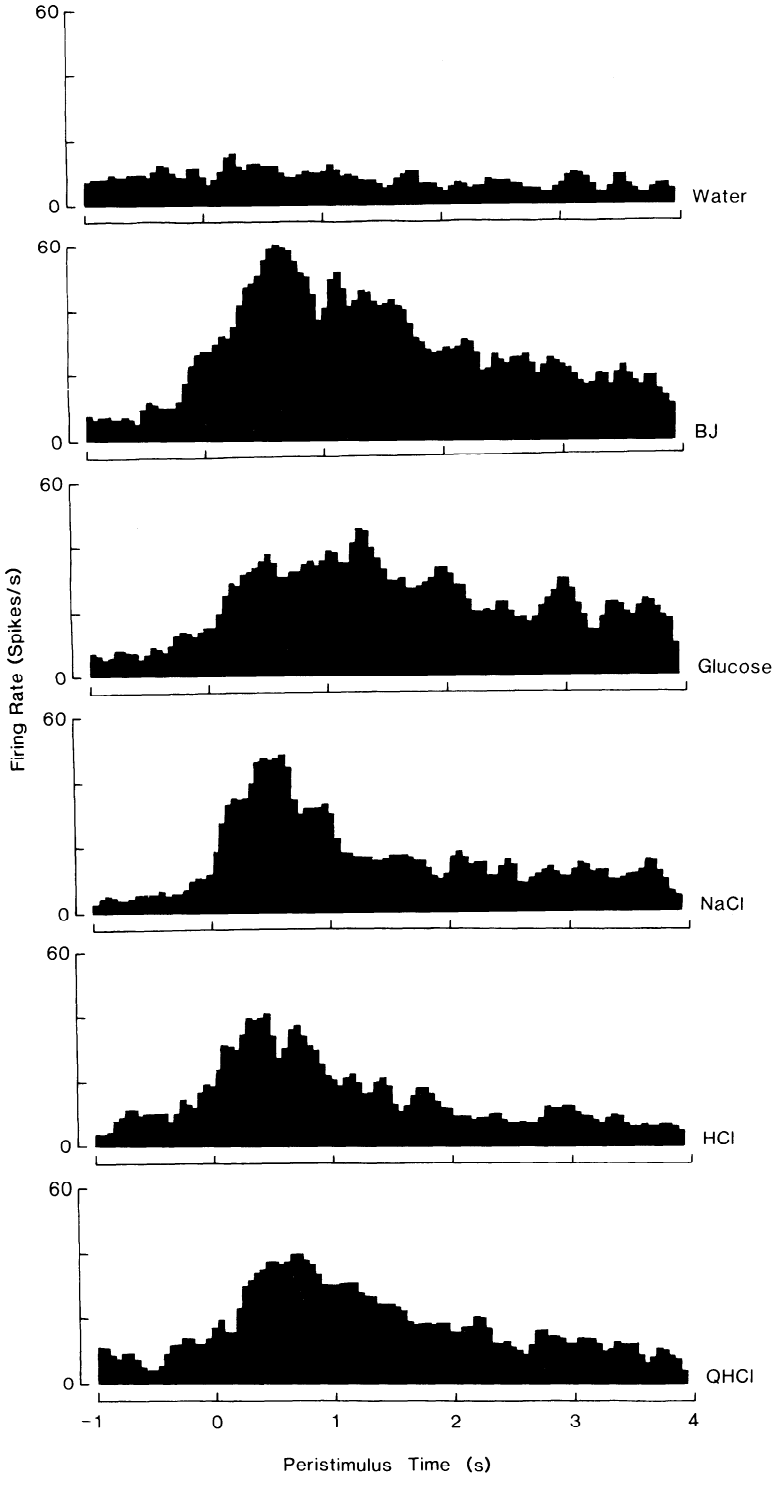

FIG. 4. Peristimulus time histograms of multiunit responses to distilled H_2O and 5 sapid stimuli. Each poststimulus time histogram (PSTH) shows activity averaged over recordings from 17 sites, with 3–6 presentations at each site. Bin widths, 50 ms.

cose that was less phasic than those evoked by other stimuli (activity peaks at 1,200 ms following stimulus onset vs. 600 ms for nonsweets), but which sustained a higher tonic level. There was also some tendency for glucose to evoke a rhythmic response, with ~700 ms between swells of activity. Such a time course may also characterize the rodent's neural response to sweet stimuli (24).

Single neurons

Isolation of single taste neurons in the medulla of the behaving monkey could not usually be maintained for more than several minutes. This was due to the small size and high density of gustatory somata and also to the force exerted on this region as the monkey moved. Many large body movements, transient respiratory activities (yawning, coughing), and extreme facial movements (gaping, chewing) compromised the signal-to-noise ratio of a neuron's responses. Still, the activity of 52 neurons from throughout the gustatory NTS was recorded during control periods and during application of deionized H_2O and sapid solutions. In Fig. 5 a photographic record of one cell's response to the simulus array is presented. If neural isolation remained certain, as many as six replications of each stimulus presentation were made. The following characteristics were found.

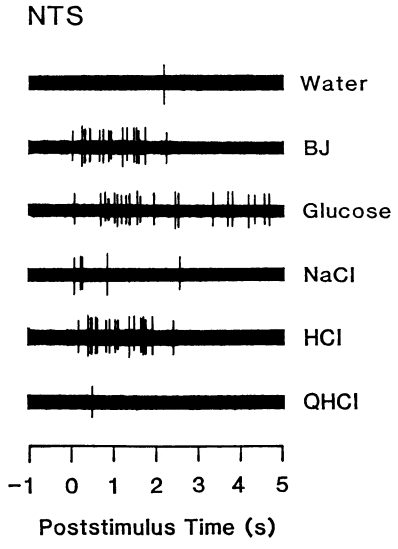

FIG. 5. Photographic record of the responses of a nucleus tractus solitarius (NTS) neuron to 1 application of the stimulus array (neuron 35 of Table 1).

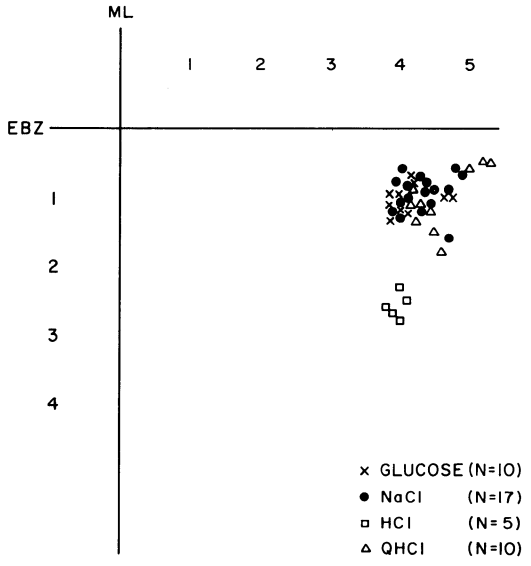

FIG. 6. Approximate locations of 42 neurons in gustatory nucleus tractus solitorius (NTS) labeled according to the prototypical stimulus that evoked the maximum response. ML, midline; EBZ, interaural line (ear bar 0); distances in millimeters.

SPONTANEOUS ACTIVITY. Gustatory neurons in NTS were not highly active, with a mean spontaneous rate of 1.2 ± 0.6 spikes/s. Thus for all but the most active cells, inhibition was precluded as a response option. We adopted a rather strict response criterion of spontaneous rate ±2.33 SD (i.e., $P < 0.01$) measured over a 5-s period following stimulus application. This is more stringent than the criterion we used to define a multiunit response ($P < 0.05$) for two reasons. First, in the multiunit record there was likely to be a small nonsensory contribution that would not have been influenced by stimulus application and that would thus constrain the limits of a multiunit response. Second, the spontaneous rates of many neurons were so low that a lesser criterion would have defined several response thresholds below 1.0 spike/s. The strict criterion we adopted required what appeared to be a more reasonable rate of evoked activity (see Table 1).

EVOKED RESPONSES.

1) Chemotopic organization. Mean evoked responses, in spikes per second measured over 5 s for each stimulus, were: deionized H_2O =

2.0; 20% blackcurrant juice = 6.1; 1.0 M glucose = 4.7; 1.0 M NaCl = 5.6; 0.01 M HCl = 3.5; 0.001 M quinine HCl = 4.4. However, the responsiveness of individual neurons was partly a function of location, with sensitivity roughly corresponding to the multiunit activ-

TABLE 1. *Fulfillment of response criterion by individual neurons*

Neuron	Spontaneous Rate ± SD	Criterion	Response, spikes/s					
			H_2O	Blackcurrant	Glucose	NaCl	HCl	QHCl
1	2.0 ± 0.7	3.5	*3.8*	*5.3*	*4.7*	*5.2*	*15.4*	*9.8*
2	1.9 ± 0.8	3.8	3.3	2.5	*10.2*	2.0	*33.0*	*11.7*
3	0.8 ± 1.0	3.1	2.8	0.2	*3.6*	1.6	*5.0*	*3.5*
4	0.7 ± 0.7	1.6	*2.2*	*5.4*	*2.4*	*9.7*	*2.1*	1.2
5	1.2 ± 0.6	2.6	2.3	*4.3*	2.2	*3.7*	*3.1*	*7.0*
6	3.5 ± 0.9	5.6	4.4	*15.3*	*8.7*	*7.2*	*7.3*	*10.9*
7	0.7 ± 0.3	1.5	1.4	*6.5*	*4.4*	*2.4*	1.3	*1.5*
8	1.6 ± 0.8	3.5	1.9	*8.7*	2.8	*10.3*	2.6	*6.3*
9	0.7 ± 0.3	1.4	0.9	*1.8*	*1.4*	*2.8*	0.7	*4.3*
10	1.1 ± 1.4	4.4	4.2	2.3	*9.4*	*12.7*	3.5	3.6
11	1.5 ± 0.4	2.6	1.4	*3.1*	*4.2*	*3.5*	2.3	*5.1*
12	1.1 ± 0.4	2.1	*2.3*	*5.8*	*3.3*	*4.5*	*2.4*	*5.0*
13	2.2 ± 0.4	3.2	3.1	*6.3*	*5.0*	*5.3*	*4.6*	*7.3*
14	1.0 ± 0.4	2.0	1.8	*2.7*	1.6	*3.2*	*2.6*	*2.7*
15	1.5 ± 1.2	4.4	1.2	*6.7*	*5.0*	*6.8*	*5.5*	*10.5*
16	3.4 ± 0.9	5.5	5.0	*22.1*	*10.7*	*9.9*	*8.6*	*11.7*
17	1.3 ± 0.5	2.6	*6.5*	*14.5*	*3.0*	*13.5*	*3.0*	*4.5*
18	1.4 ± 0.5	2.7	1.9	*5.3*	*11.0*	*8.9*	*6.0*	2.4
19	0.4 ± 0.2	1.0	0.7	*4.2*	0.9	*6.2*	*2.3*	*3.4*
20	0.4 ± 0.3	1.1	0.6	*8.1*	*1.2*	*1.9*	*2.0*	*3.2*
21	2.6 ± 1.0	5.0	3.7	*8.7*	*10.8*	4.3	4.5	*6.3*
22	1.2 ± 0.7	2.7	1.9	*3.8*	*3.6*	*4.3*	1.9	1.7
23	2.1 ± 0.9	4.1	2.2	*9.8*	*8.8*	*9.4*	3.3	*3.3*
24	1.4 ± 0.5	2.5	1.6	*7.9*	*5.3*	*9.2*	*2.8*	*3.2*
25	0.1 ± 0.2	0.6	0.5	*4.1*	*1.3*	*1.0*	0.5	*1.1*
26	0.3 ± 0.3	1.1	*1.3*	*3.9*	*2.1*	*1.4*	*1.8*	*1.1*
27	0.4 ± 0.3	1.1	*1.4*	*7.4*	*1.8*	*5.3*	*2.5*	*2.0*
28	1.3 ± 0.6	3.1	2.2	*12.1*	*11.5*	*5.9*	2.6	*4.8*
29	1.5 ± 0.5	3.2	2.7	*3.5*	*4.7*	*4.2*	1.2	2.0
30	2.2 ± 1.0	5.2	2.1	*9.9*	*5.3*	*8.0*	3.8	*7.2*
31	1.7 ± 0.8	4.0	3.6	*10.8*	*6.9*	*4.8*	3.7	*4.2*
32	1.2 ± 0.4	2.9	1.3	*5.3*	*4.8*	*4.0*	2.8	*4.2*
33	0.5 ± 0.4	1.7	0.6	*5.1*	*3.7*	*3.5*	0.7	1.5
34	0.1 ± 0.1	0.5	0.1	*1.0*	*0.6*	*1.7*	0.3	0.2
35	0.8 ± 0.3	1.7	0.5	*4.0*	*3.5*	*3.2*	*1.8*	*1.9*
36	1.0 ± 0.7	2.9	1.2	*7.1*	*3.6*	*7.8*	*3.1*	*4.9*
37	0.5 ± 0.3	1.4	1.1	*6.6*	*3.4*	*4.5*	*1.5*	*2.3*
38	1.5 ± 0.5	3.0	*3.7*	*8.2*	*8.7*	*7.0*	5.2	2.8
39	2.2 ± 0.7	3.9	2.0	*12.8*	*6.6*	*10.2*	*4.2*	*7.7*
40	0.8 ± 0.3	1.6	1.0	*5.4*	*2.8*	*4.3*	*4.2*	*8.2*
41	3.3 ± 2.0	8.0	*23.5*	3.3	6.7	*20.0*	*19.5*	*16.4*
42	1.5 ± 0.7	3.2	2.7	*7.9*	*8.0*	*4.0*	2.2	*3.8*
43	2.0 ± 0.6	3.4	2.2	*9.2*	*4.2*	*7.5*	*4.7*	*5.3*
44	3.2 ± 0.7	4.9	*5.3*	*6.9*	2.7	*8.6*	3.9	*7.3*
45	0.7 ± 0.4	1.7	0.3	*3.4*	1.6	*4.3*	*2.3*	*2.4*
46	1.4 ± 0.4	2.4	1.6	*3.5*	*2.5*	*3.7*	*3.7*	*8.5*
47	0.7 ± 0.5	1.9	*1.9*	*2.4*	1.5	*2.2*	*1.9*	*2.5*
48	0.3 ± 0.3	1.4	0.5	*3.1*	*1.6*	*3.3*	*2.0*	*1.7*
49	0.4 ± 0.5	1.6	*2.1*	*4.7*		*4.0*	*5.4*	*5.4*
50	0.9 ± 0.4	1.9	1.2	*3.8*	*3.6*		1.2	*7.5*
51	0.2 ± 0.3	0.9	*1.4*	*6.4*	*8.8*	*8.9*	*3.6*	*3.2*
52	1.0 ± 0.5	2.1	1.7	*2.3*	*2.8*	*3.2*	*2.2*	

Responses in *italic* fulfill $P < 0.01$ criterion.

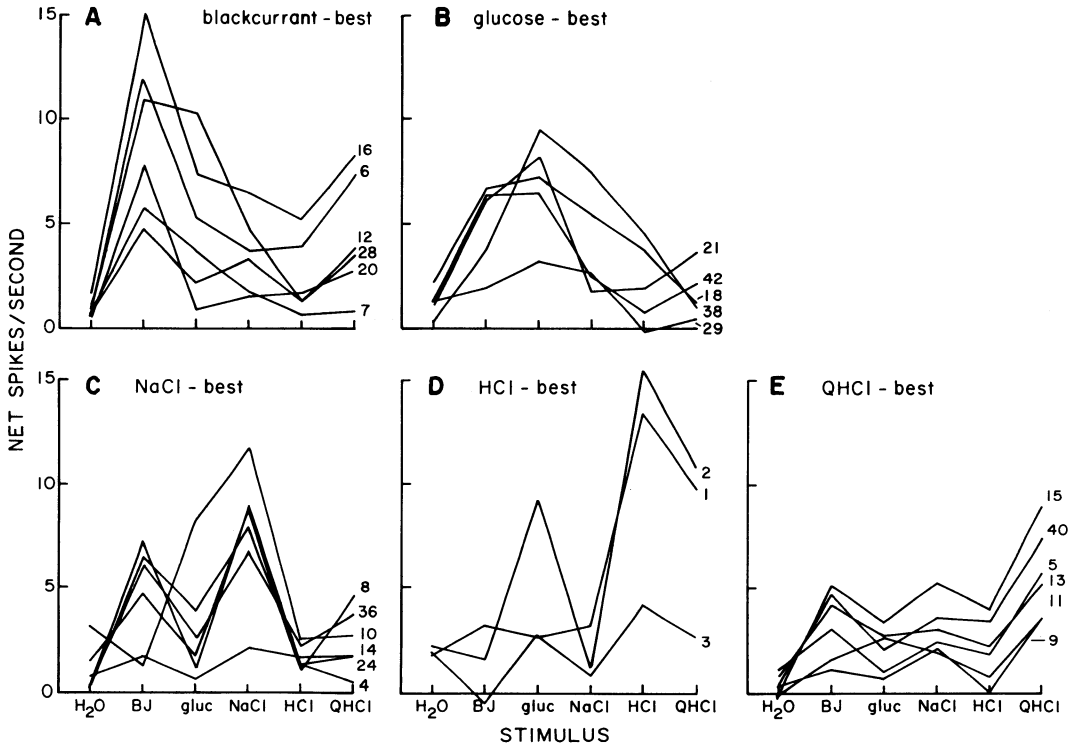

FIG. 7. Representative sensitivity profiles organized according to best stimuli. Approximately half the neural sample is shown. Each neuron is numbered as in Figs. 8 and 9 and in Table 1. BJ, blackcurrant juice.

ity of that area. The locations of 42 cells[4] are marked in Fig. 6, with each cell labeled according to its maximum response to one of the four basic taste qualities. Activity evoked by HCl is greatest among neurons in the posteromedial part of the nucleus, whereas glucose and NaCl responsiveness peaks anteriorly. Responsiveness to quinine HCl is more widespread but tends to increase anteriorly. Statistical analysis confirmed that neurons responding best to HCl were distributed differently from those responding best to other gustatory stimuli (chi square = 36.7, df = 1, $P < 0.001$).

2) Breadth of sensitivity. Of 48 neurons tested with all solutions, 20 (42%) fulfilled our criterion for responding to all four basic qualities at these moderate-to-high concentrations, 20 (42%) responded to three stimuli, 8 (17%) to two, and none was specifically sensitive to one quality. Conversely, the percentages of neurons that responded to each stimulus were 25% to H_2O, 92% to blackcurrant juice, 86% to glucose, 92% to NaCl, 63% to HCl, and 86% to QHCl. The distribution of responses is represented in Table 1.

To quantify the range of sensitivity, the breadth of tuning metric developed by Smith and Travers (35) was applied.[5] This is a calculated coefficient of entropy (H) for each cell that ranges from 0.0, representing total specificity to one stimulus, to 1.0, indicating an equal response distribution to the four prototypical stimuli. The mean coefficient for

[4] These 42 neurons were all isolated in one monkey in whom a thorough electrophysiological mapping was performed. The remaining cells analyzed in this manuscript (n = 10) were recorded from the second monkey within these same boundaries, but the nucleus was not methodically mapped.

[5] $H = -k \sum_{i=1}^{n} p_i \log p_i$ where H = breadth of responsiveness, k = scaling constant (here k = 1.661 so that H = 1.0 when the neuron responds equally to all four prototypes), p_i = proportional response to each of n compounds (in this case, n = 4).

NTS neurons in the monkey was 0.87 (range, 0.63 to 0.99), which is higher than that reported in other species (see DISCUSSION). There was no evidence that the breadth of tuning varied systematically across the nucleus.

3) Neuron types. The existence of gustatory neuron types is a subject of continuing debate. One way of addressing this issue is to determine if there is a discrete number of profiles to which all taste neurons conform.

In Fig. 7 are representative sensitivity profiles of taste neurons that responded best to blackcurrant juice (7*A*) and to each of the four prototypical taste stimuli (7, *B–E*). These profiles imply some tendency toward recurring neuron types in the monkey NTS. Good sensitivity to blackcurrant juice (Fig. 7*A*) implies moderate sensitivity to glucose and quinine, less to NaCl, and least to HCl. Sensitivity to glucose (Fig. 7*B*) carries with it a prediction of moderate responses to blackcurrant juice and NaCl, and less to HCl and QHCl. The sawtooth profiles of Fig. 7*C* suggest that a neuron that responds to NaCl will also show sensitivity to blackcurrant juice. Although five stimulus qualities plus H_2O yield a rather sparsely defined profile for each gustatory

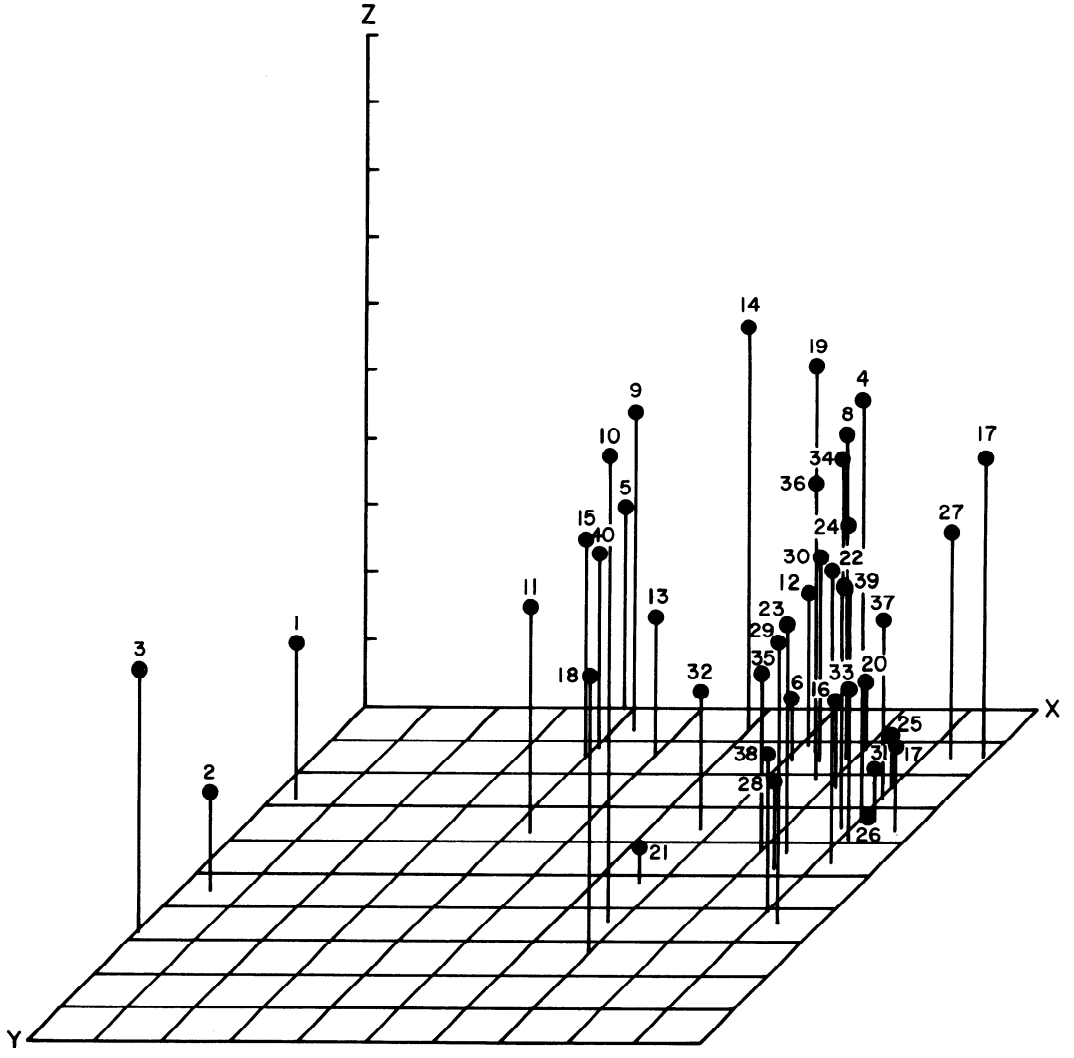

FIG. 8. Three-dimensional representation of the similarities among neuronal profiles. The x-dimension accounts for 72.1% of data variance; y-dimension, 11.0%; z-dimension, 10.6%, and 6.3% is unaccounted for in 3 dimensions.

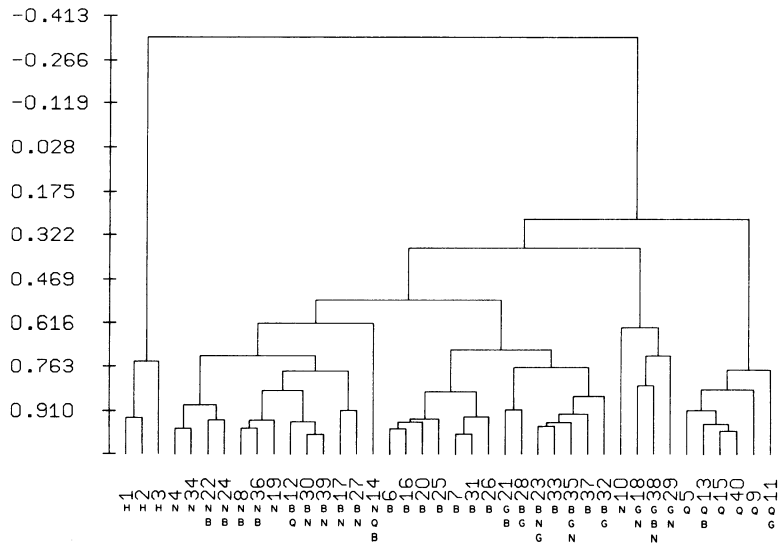

FIG. 9. Cluster analysis of the neuron space shown in Fig. 8, depicted as a dendrogram. Each cell is numbered in sequence in which it was recorded. Beneath each is indicated the stimulus to which it responded best, followed by any other chemical that evoked >80% of best response. Abbreviations: B, blackcurrant juice; G, glucose; N, NaCl; H, HCl; Q, QHCl.

neuron, it may permit a preliminary analysis of the existence of neuron types. We compared 40 profiles by means of the Pearson product-moment correlation coefficient. Neurons with similiar sensitivities should generate coefficients near +1.0, whereas those with opposite sensitivities would produce negative coefficients. With 40 cells (i.e., $n = 40$) there were 780 comparisons [$n(n - 1)/2$] to be made. These were organized in a correlation matrix that in turn was used to construct a multidimensional space (Fig. 8) in which neurons with similar profiles were closely aligned (15). Thus the existence of gustatory neuron types, as defined by recurring sensitivity to the five stimuli plus H_2O employed here, would be indicated by clusters of cells in the space, whereas a lack of neuron types would be signaled by a homogeneous distribution throughout. Figure 8, in three dimensions, provides at least a suggestion of neural segregation according to response patterns. The three most isolated cells (*cells 1–3*) have profiles depicted in Fig. 7*D* and are maximally sensitive to HCl. The next most distinct group (*cells 5, 9, 11, 13, 15, 40*) is all profiled in Fig. 7*E* and is most responsive to quinine. Beyond these, clusters are not obvious. To determine the extent to which further groups exist, a cluster analysis (39) was performed on the same data. This analysis appears in Fig. 9 in the form of a dendrogram. Neurons are numbered along the abscissa in the order in which they were isolated. The correlation between the two most similar profiles (*cell 7* and *cell 31*, $r = +0.99$) is represented by the lowest horizontal connecting line. Then other similar pairs are connected until a connection between pairs occurs at a height representing the mean correlation among the cells involved. As more dissimilarity is permitted, larger groups are connected

TABLE 2. *Interstimulus correlations in monkey NTS*

	W	B	G	N	H	Q
W						
B	+0.20					
G	+0.24	+0.32*				
N	+0.36*	+0.44†	+0.19			
H	+0.30	−0.08	+0.32*	−0.12		
Q	+0.12	+0.26	+0.19	+0.03	+0.60‡	

Correlations among the patterns of activity evoked by each stimulus across the 48-neuron sample. * $-P < 0.05$; † $-P < 0.01$; ‡ $-P < 0.001$. The significant correlation between glucose and HCl is largely attributable to responses of neuron 2, whose profile appears in Fig. 7*D*. Abbreviations as in Fig. 9; W, water.

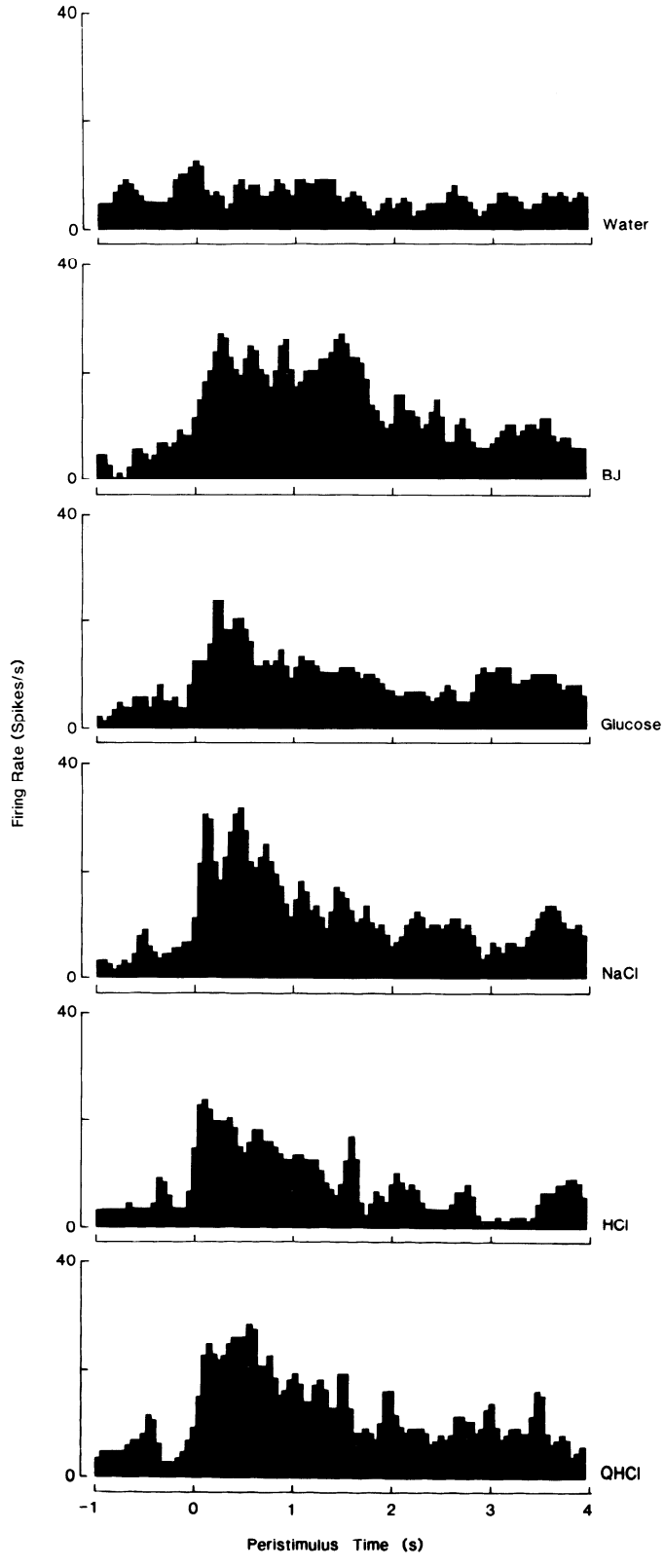

FIG. 10. Peristimulus time histograms of neural responses averaged across 17 single taste cells. Bin widths, 50 ms.

until all neurons are incorporated into the dendrogram. The more tightly a cluster is intercorrelated, the lower will be the horizontal line connecting its constituent cells. The more isolated a cluster is from other neurons, the longer will be the vertical line leading to it. The cluster analysis corroborates and refines the implications of the neuron space. Most obviously, there are two types of cells: *cells 1–3* and the rest. The clearest distinction among sensitivities in the monkey NTS appears to be acid versus nonacid, both in terms of sensitivities and neural location (see *Chemotopic organization* above). Within the nonacid group, the existence of clusters becomes questionable. The most likely candidate encompasses six cells on the far right (*cells 5–11*) that were also identifiable in the neuron space and that are quinine sensitive. Also possible is a small cluster (*cells 10–29*) that shows good glucose sensitivity. The remaining 27 neurons share the common trait of sensitivity to the complex taste of blackcurrant juice. They show a weak tendency toward division into two large subgroups (*cells 4–27, n* = 12; *cells 6–32, n* = 14), the first combining blackcurrant sensitivity with NaCl, and the second with glucose. Within each of these are poorly defined clusters that reflect the advantage of blackcurrant juice over its companion stimulus or vice versa. Finally, there is an isolated neuron (*cell 14*) that shows nearly equal sensitivity to all stimuli. Thus the analysis of response profiles as an index of gustatory neuron types suggests only the existence of a small group distinct from a majority about which the data do not yet permit further conclusions. Resolution of this issue will require the isolation of a larger neural sample and the application of a more varied stimulus array so as to thoroughly define the response profiles under study.

4) Stimulus quality. The basic stimuli employed in this study should evoke quite distinct response patterns across the neural sample. The correlation matrix of Table 2 generally supports this expectation. Among the four prototypes, only the patterns elicited by HCl and QHCl correlate reasonably well at +0.60. Beyond this, the pattern for blackcurrant juice correlates significantly with those for glucose (+0.32) and NaCl (+0.44). This is expected from the common pools of neurons activated by each of these basic stimuli and blackcurrant juice (see *Neuron types* above). The unexpected positive correlation between glucose and HCl (+0.32) is largely attributable to one record from neuron 2 (whose profile is shown in Fig. 7*D*). With this response excluded from the analysis, the glucose-HCl correlation declines to +0.13. The correlations in Table 2 are in good agreement with those based on chorda tympani records in the monkey (24).

5) Time course. Peristimulus time histograms of single neuron responses to the different gustatory stimuli appear in Fig. 10. Pulsatile gustatory stimulation resulting from tongue movements at ~300-ms intervals contributed to the apparent rhymicity in the responses to some of the stimuli.

DISCUSSION

Advantages of and difficulties with the alert monkey preparation

The advantages of recording from the alert monkey are apparent: the species is phylogenetically close to humans, permitting neural data to be more readily compared with psychophysical results; neural activity is not degraded by anesthetics; and neural and behavioral studies may be performed simultaneously in one preparation. However, working with an alert monkey requires compromises, and those that may impinge on the results of this study will be discussed.

STIMULUS CONTROL. The monkey is free to make tongue, mouth, and jaw movements to enhance appetitive tastes and minimize those that are aversive. Thus, receptive fields that may be freely stimulated by appetitive stimuli may be at least partly protected when aversive stimuli are presented. This is a particular problem for receptive fields on the posterior tongue and may have contributed to the relative weakness of response to HCl, whose effect is greatest among foliate papillae. Mouth movements also required compensatory adjustments in stimulus delivery so as to stimulate a large and rather constant receptive field. Finally, while there is no firm evidence that somesthetic and gustatory afferents converge on individual neurons, somesthetic cells surround and invade the gustatory NTS. Thus differential stimulation of the oral cavity, both by the stimulus application and the monkey's reaction to it, may affect multiunit records by introducing differential somesthetic inputs to

an area devoted largely, but not exclusively, to taste.

NEURAL ISOLATION. The difficulties involved in maintaining unit isolation in NTS center on cell size, density, and brain-stem movement. Each of these is less severe in the rostral gustatory area where somata are probably larger and more sparsely distributed and could therefore be less subject to disturbance as the monkey moves (R. Norgren, personal communication). Thus a majority of our single neuron records come from rostral NTS, and our sample means may be biased in favor of stimuli that are relatively effective there. In addition, the spikes of gustatory neurons that discharge at high frequencies often lose amplitude, compounding the difficulties of isolation in the alert monkey. It is probable, therefore, that our sample underrepresents more active cells.

Thresholds

Neural thresholds were conservatively defined as 1×10^{-1} M glucose, 1×10^{-2} M NaCl, 1×10^{-3} M HCl, and 1×10^{-4} M quinine HCl. These compare well with reported neural thresholds in the macaque chorda tympani nerve based on both whole nerve (19, 24) and single-neuron (32) records. They are also in agreement with behavioral data on the macaque based on discrimination tasks (33), but for most chemicals, are an order of magnitude lower than relatively insensitive preference thresholds (13, 21).

Recognition thresholds in humans are in general agreement with predictions based on our data. Median values from several studies are 0.8×10^{-1} M glucose, 1.0×10^{-2} M NaCl, 0.9×10^{-3} M HCl, and 0.3×10^{-4} M quinine HCl (22). These are at or slightly below our reported thresholds as expected from the conservative criterion ($P < 0.05$) we adopted and imply that the macaque taste system has a dynamic range equivalent to that of the human. This implication is reinforced by the similarity of our data to intensity-response functions recorded from the human chorda tympani nerve (10). The data described above are summarized in Table 3.

Chemotopic organization

MULTIUNIT. Multiunit responses to glucose increase with a slope of 0.52 per anterior millimeter of travel in NTS (Fig. 3*B*). Activity elicited by NaCl rises at the same rate (Fig. 3*C*). Evoked responses to blackcurrant juice increase at twice the rate (slope = 1.08, Fig. 3*A*) implying the recruitment not only of neuronal pools sensitive to NaCl or glucose, both of which blackcurrant juice activates (refer to *Neuron types* above), but also of cells that respond to its complex quality more than to either of these basic tastes with which it is associated. Responses to quinine also increase with anterior progression (Fig. 3*E*) but with a slope of only 0.31, suggesting a more even distribution of bitter sensitivity throughout the nucleus. Sensitivity to HCl decreases with a slope of 0.50 (Fig. 3*D*), providing nearly an

TABLE 3. *Neural and behavioral thresholds in monkey and human*

	Monkey CT			Monkey NTS	Monkey Discrimination	Monkey Preference		Human CT	Psychophysics		
	19	32	24		33	21	13	10	22	26	9
Glucose, all $\times 10^{-1}$ M				1.0					0.8		
Sucrose, all $\times 10^{-1}$ M	1.0	0.3	3.0				0.06	0.5	0.2		0.2
NaCl, all $\times 10^{-2}$ M	0.3	0.1	10.0	1.0	0.5		6.7	1.0	1.0	1.5	4.0
HCl, all $\times 10^{-3}$ M	1.0	1.0	10.0	1.0			8.0		0.9		0.8
QHCl, all $\times 10^{-4}$ M	3.0	2.0	30.0	1.0		6.0	8.0		0.3		0.2

Numbers at column headings refer to references.

exact complement to the rates of increase shown to glucose and NaCl.

SINGLE NEURONS. The simplest demonstration of chemotopia at the single neuron level comes from the categorization of cells by best stimulus (Fig. 6). In agreement with conclusions based on multiunit records, HCl-best neurons are posterior in gustatory NTS, glucose and NaCl-best cells are anterior, and quinine-best cells are more widely distributed. However, a more complete picture of the chemotopia in NTS may be gained by relating a neuron's anteroposterior position to its sensitivity profile, as defined by its responses to the five stimuli plus H_2O employed here. The canonical correlation between these two variables yields a coefficient of +0.76 ($P < 0.001$; df = 6). This indicates that 58% (0.76^2) of the total variance in describing a neuron's sensitivity profile, and consequently its location in the neuron space of Fig. 8, is accounted for by its anteroposterior position in the nucleus. The x-dimension of Fig. 8, which is determined purely by the responses of each neuron, becomes a partial recreation of the anteroposterior position of each cell in the nucleus. Thus physical placement is implicated as perhaps the most important feature in predicting the sensitivities of a taste cell in the monkey NTS.

NEURAL AND PSYCHOPHYSICAL COMPARISONS. Others have noted a topographic organization in NTS in the rat (16) and cat (17). These studies indicate that variations in sensitivity throughout the oral cavity are preserved in the CNS. In the rat, responses to 0.1 M NaCl and 0.01 M QHCl indicated that NaCl sensitivity declined with posterior progression across the nucleus, whereas QHCl sensitivity increased. In the cat, NaCl, QHCl, and HCl were used. The same topographic arrangement for NaCl and QHCl was inferred[6] plus a sharply increased sensitivity to HCl as stimuli approached the posterior receptive fields. Except for the modest increases in reponses to QHCl that we recorded in anterior NTS, this neural organization appears to be preserved in the monkey.

In a psychophysical study, Collings (9) found sensitivity to the basic taste qualities to vary across the tongue in a manner consistent with what our data would predict. The anterior tongue showed greatest sensitivity to sucrose, NaCl, and QHCl, whereas citric acid sensitivity peaked more posteriorly. This concordance between topographies based on neural records in the cynomolgus monkey and human psychophysics implies that the two species possess the same chemotopic organization and that it is maintained from receptor to CNS. The anatomical data of Beckstead et al. (2) suggest that any anteroposterior chemotopic arrangement in the monkey NTS is preserved in a lateromedial dimension in the gustatory thalamus. Such an organization permits the spatial distribution of evoked activity to serve as a factor in the neural code for taste quality just as tonotopia aids in auditory and retinotopia in visual coding.

Neuron types

The neural profiles analyzed through multidimensional scaling (Fig. 8) and cluster analysis (Fig. 9) provide some support for the existence of at least two types of gustatory neurons: those responsive and those not responsive to HCl. Cells of the former group compose only 3 of the 40 profiles analyzed. This proportion is undoubtedly an underrepresentation of the actual cluster size that results from the difficulty of maintaining isolation on cells in the posterior part of the nucleus, where acid sensitivity predominates. In any case, it is notable that acid versus nonacid appears to be the clearest distinction in the monkey NTS, whereas in both the rat (7, 34) and hamster (36) it is sweet sensitivity that is most differentiable.

Neurons that were responsive to HCl were all located toward the posterior part of the nucleus (Fig. 6). There were no cells isolated immediately anterior to this area so that, in our records, a physical gap separates acid-sensitive cells from the remainder situated farther anteriorly. A corresponding gap exists along the x-dimension of the multidimensional neuron space of Fig. 8. Thus it is possible that even the acid-responsive neurons do not constitute a distinct neuron type but define one end of an interrupted gradient of responsiveness. In further explorations of the nucleus it will be important to note whether the shift in respon-

[6] The chemotopic organization of NTS could only be inferred, for recordings of gustatory evoked activity were made only in the peripheral nerves, which were in turn electrically stimulated to evoke activity in NTS.

siveness to HCl is sufficiently abrupt to warrant the designation of a distinct gustatory neuron type.

Breadth of sensitivity

Breadth of tuning in the monkey NTS may be compared both to peripheral taste responses in the monkey and to NTS breadth in other species. Sato et al. (32) and Pfaffmann et al. (24) report basic breadth information for chorda tympani fibers in cynomolgus and squirrel monkeys, respectively. Both employed more lenient response criteria than ours: Sato et al. (32) defined a response as $P < 0.05$ on the neuron's spontaneous activity distribution for 5 s (vs. our $P < 0.01$); Pfaffmann et al. (24) required an evoked response of 1.5 × spontaneous rate sustained for 5 s (our criterion translates to 2.2 × spontaneous). Among stimuli, our 1.0 M glucose is roughly equivalent to the 0.3 and 0.5 M sucrose used by the other investigators. Beyond this, our NaCl is more concentrated (1.0 vs. 0.3 M), HCl is the same (0.01 M), and our quinine HCl is more dilute (0.001 vs. 0.003 M). A final consideration is that sensitivity to quinine in all mammalian species studied is carried effectively through the glossopharyngeal nerve so that those studying the chorda tympani might record lesser activity than is apparent in NTS. Table 4 presents a direct comparison of the percentages of neurons that fulfill the response criteria for each stimulus (top) and the percentages that respond to four, three, two, or only one of the basic qualities (bottom). Our data are in reasonable agreement with the degree of breadth reported by Pfaffmann et al. (24).

TABLE 4. *Breadth of sensitivity measures for monkey CT and NTS neurons*

	31	24	This Study
A			
Gluc-Suc	48	79	86
NaCl	66	86	92
HCl	55	70	63
QHCl	33	53	86
B			
4/4	6	50	42
3/4	24	29	42
2/4	36	18	17
1/4	34	3	0

CT, chorda tympani; NTS, nucleus tractus solitarius. Percentage of neurons *A*: fulfilling the respective response criterion for each stimulus; *B*: responding to 4, 3, 2, or only 1 of the prototypical taste qualities.

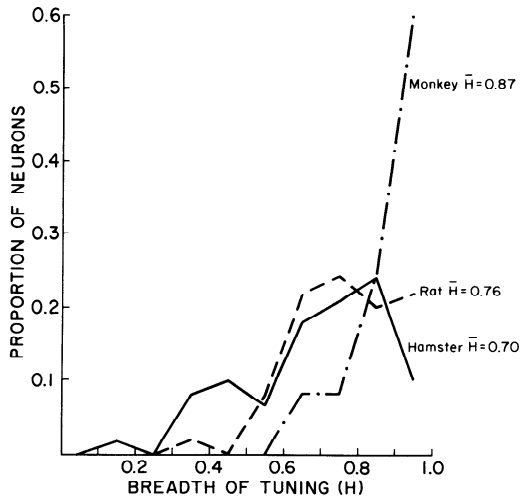

FIG. 11. Distribution of tuning breadth among nucleus tractus solitarius (NTS) taste cells in rat, hamster, and monkey. Fully 60% of the monkey's cells have a coefficient above 0.90, indicating considerable breadth. Rat data from Chang and Scott, unpublished. Hamster data from Travers and Smith (38) (used with permission).

Breadth of sensitivity has also been studied in the NTS of other species, notably the rat and hamster. Applying the entropy coefficient, H, of Smith and Travers (35), our neurons yielded a mean value of 0.87 versus 0.76 in rat (Chang and Scott, unpublished data) and 0.70 in hamster (38). The distribution of neuron breadth in the three species is compared in Fig. 11.

The breadth of sensitivity found in the monkey NTS has implications for the gustatory neural code. It has been suggested that taste coding in the monkey proceeds through independent channels, each devoted to one of the four basic taste qualities (23).[7] However, the extremely broad sensitivities of neurons in the monkey NTS indicate that only a rather

[7] Note that this issue is fully independent of the existence of neuron types. The possible presence of gustatory neuron types does not imply coding through, for example, an independent salt channel, any more than the existence of a pigment predominently sensitive to green light implies an independent green channel for coding color.

small proportion of a cell's response could be invested in any one quality. In fact, the mean proportion of each neuron's response that is evoked by the basic taste into whose cluster the neuron falls is only 0.40. Thus, if coding were done through channels, and if our analyses properly identified the channel through which each neuron worked, only 40% of the evoked neural activity would be signal. Such a statistic argues for a neural code that employs the full range of neuronal responsiveness and does not restrict a cell's contribution to its activity in one putative channel.

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REFERENCES

1. BECKSTEAD, R. M. AND NORGREN, R. An autoradiographic examination of the central distribution of the trigeminal, facial, glossopharyngeal, and vagal nerves in the monkey. *J. Comp. Neurol.* 184: 455–472, 1979.
2. BECKSTEAD, R. M., MORSE, J. R., AND NORGREN, R. The nucleus of the solitary tract in the monkey: projections to the thalamus and brain stem nuclei. *J. Comp. Neurol.* 190: 259–282, 1980.
3. BENJAMIN, R. M. AND BURTON, H. Projection of taste nerve afferents to anterior opercular-insular cortex in squirrel monkey (*Saimiri sciureus*). *Brain Res.* 7: 221–231, 1968.
4. BROUWER, J. N., HELLEKANT, G., KASAHARA, Y., VAN DER WEL, H., AND ZOTTERMAN, Y. Electrophysiological study of the gustatory effects of the sweet proteins Monellin and Thaumatin in monkey, guinea pig and rat. *Acta Physiol. Scand.* 89: 550–557, 1973.
5. BUJAS, Z. Electric taste. In: *Handbook of Sensory Physiology. Chemical Senses,* edited by L. M. Beidler. Berlin: Springer-Verlag, 1971, vol. IV, pt. 2, p. 180–199.
6. BURTON, M. J., ROLLS, E. T., AND MORA, F. Effects of hunger on the responses of neurons in the lateral hypothalmus to the sight and taste of food. *Exp. Neurol.* 51: 668–677, 1976.
7. CHANG, F-C. T. AND SCOTT, T. R. Conditioned taste aversions modify neural responses in the rat nucleus tractus solitarius. *J. Neurosci.* 4: 1850–1862, 1984.
8. CHANG, F-C. T. AND SCOTT, T. R. A technique for gustatory stimulus delivery in the rodent. *Chem. Sens.* 9: 91–96, 1984.
9. COLLINGS, V. B. Human taste response as a function of locus of stimulation on the tongue and soft palate. *Percept. Psychophys.* 16: 169–174, 1974.
10. DIAMANT, H., FUNAKOSHI, M., STROM, L., AND ZOTTERMAN, Y. Electrophysiological studies on human taste nerves. In: *Olfaction and Taste,* edited by Y. Zotterman. Oxford: Pergamon, 1963, p. 193–203.
11. FISHMAN, I. Y. Gustatory impulses in the white faced, ringtail monkey. *Federation Proc.* 18: 45, 1959.
12. GALLYAS, F. Silver staining of myelin by means of physical development. *Neurol. Res.* 1: 203–209, 1979.
13. GLASER, D. Vergleichende Untersuchungen uber den Geschmackssinn der Primaten. *Folia Primatol.* 17: 267–274, 1972.
14. GORDON, G., KITCHELL, R., STROM, L., AND ZOTTERMAN, Y. The response pattern of taste fibers in the chorda tympani of the monkey. *Acta Physiol. Scand.* 46: 119–132, 1959.
15. GUTTMAN, L. A general nonmetric technique for finding the smallest coordinate space for a configuration of points. *Psychometrika* 33: 469–507, 1968.
16. HALPERN, B. P. AND NELSON, L. M. Bulbar gustatory responses to anterior and to posterior tongue stimulation in the rat. *Am. J. Physiol.* 209: 105–110, 1965.
17. ISHIKO, N. AND AKOGI, T. Topographical organization of gustatory nervous system. In: *Olfaction and Taste,* edited by D. Schneider. Stuttgart: Wissenschaftliche, 1972, vol. 4, p. 343–349.
18. MERRILL, E. G. AND AINSWORTH, A. Glass-coated platinum-plated tungsten microelectrodes. *Med. Biol. Eng.* 10: 662–672, 1972.
19. OGAWA, H., YAMASHITA, S., NOMA, A., AND SATO, M. Taste responses in the macaque monkey chorda tympani. *Physiol. Behav.* 9: 325–331, 1972.
20. OGAWA, H., SATO, M., AND YAMASHITA, S. Variability in impulse discharges in rat chorda tympani fibers in response to repeated gustatory stimulations. *Physiol. Behav.* 11: 469–479, 1973.
21. PATTON, H. D. AND RUCH, T. C. Preference thresholds for quinine hydrochloride in chimpanzee, monkey and rat. *J. Comp. Psychol.* 37: 35–49, 1944.
22. PFAFFMANN, C. The sense of taste. In: *Handbook of Physiology. Neurophysiology,* edited by J. M. Field. Washington, DC: Am. Physiol. Soc., 1959, sect. 1, vol. I, chapt. 20, p. 507–533.
23. PFAFFMANN, C. Specificity of the sweet receptors of the squirrel monkey. *Chem. Sens.* 1: 61–67, 1974.
24. PFAFFMANN, C., FRANK, M., BARTOSHUK, L. M., AND SNELL, T. C. Coding gustatory information in the squirrel monkey chorda tympani. In: *Progress in Psychobiology and Physiological Psychology,* edited by J. M. Sprague and A. N. Epstein. New York: Academic, 1976, vol. 6, p. 1–27.
25. PFAFFMANN, C. AND PRITCHARD, T. C. Ion specificity of electric taste. In: *Olfaction and Taste,* edited by H. VAN DER Starre. London: IRL, 1980, vol. 7, p. 175–178.
26. RICHTER, C. P. AND MACLEAN, A. Salt taste thresholds in humans. *Am. J. Physiol.* 126: 1–6, 1939.
27. ROLLS, E. T., BURTON, M. J., AND MORA, F. Hypothalamic neuronal responses associated with the sight of food. *Brain Res.* 111: 53–66, 1976.

28. ROLLS, E. T., BURTON, M. J., AND MORA, F. Neurophysiological analysis of brain-stimulation reward in the monkey. *Brain Res.* 194: 339–357, 1980.
29. ROLLS, E. T. AND ROLLS, B. J. Activity of neurones in sensory, hypothalamic and motor areas during feeding in the monkey. In: *Food Intake and Chemical Senses,* edited by Y. Katsuki, M. Sato, S. Takogi, and Y. Oomura. Tokyo: Univ. of Tokyo Press, 1977, p. 525–549.
30. ROLLS, E. T., SANGHERA, M. K., AND ROPER-HALL, A. The latency of activation of neurons in the lateral hypothalamus and substantia innominata during feeding in the monkey. *Brain Res.* 164: 121–135, 1979.
31. SATO, M. Response characteristics of taste nerve fibers in macaque monkeys: Comparison with those in rats and hamsters. In: *Olfaction and Taste,* edited by D. A. Denton and J. P. Coghlan. New York: Academic, 1975, vol. 5, p. 23–26.
32. SATO, M., OGAWA, H., AND YAMASHITA, S. Response properties of macaque monkey chorda tympani fibers. *J. Gen. Physiol.* 66: 781–810, 1975.
33. SCHWARTZBAUM, J. S. AND WILSON, W. A., JR. Taste-discrimination in the monkey. *Am. J. Psychol.* 74: 403–409, 1961.
34. SCOTT, T. R. AND CHANG, F-C. T. The state of gustatory neural coding. *Chem. Senses* 8: 297–314, 1984.
35. SMITH, D. V. AND TRAVERS, J. B. A metric for the breadth of tuning of gustatory neurons. *Chem. Sens.* 4: 215–229, 1979.
36. SMITH, D. V., VAN BUSKIRK, R. L., TRAVERS, J. B., AND BIEBER, S. L. Gustatory neuron types in hamster brain stem. *J. Neurophysiol.* 50: 522–540, 1983.
37. SUDAKOV, K., MACLEAN, P. D., REEVES, A., AND MARINO, R. Unit study of exteroceptive inputs to claustrocortex in awake, sitting, squirrel monkey. *Brain Res.* 28: 19–34, 1971.
38. TRAVERS, J. B. AND SMITH, D. V. Gustatory sensitivities in neurons of the hamster nucleus tractus solitarius. *Sensory Processes* 3: 1–27, 1979.
39. WISHART, D. *Clustan.* Program Library Unit: Edinburgh Univ., 1978.
40. YAXLEY, S., ROLLS, E. T., SIENKIEWICZ, Z. J., AND SCOTT, T. R. Satiety does not affect gustatory activity in the nucleus of the solitary tract of the alert monkey. *Brain Res.* In press.