J Neurophysiol 90: 3711–3724, 2003.
First published August 13, 2003; 10.1152/jn.00515.2003.

Representations of the Texture of Food in the Primate Orbitofrontal Cortex: Neurons Responding to Viscosity, Grittiness, and Capsaicin

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Submitted 28 May 2003; accepted in final form 11 August 2003

Rolls, Edmund T., Justus V. Verhagen, and Mikiko Kadohisa. Representations of the texture of food in the primate orbitofrontal cortex: neurons responding to viscosity, grittiness, and capsaicin. *J Neurophysiol* 90: 3711–3724, 2003. First published August 13, 2003; 10.1152/jn.00515.2003. The primate orbitofrontal cortex (OFC) is a site of convergence from taste, olfactory, and somatosensory cortical areas. We describe a population of single neurons in the macaque OFC that responds to the texture of food in the mouth. Use of oral viscosity stimuli consisting of carboxymethylcellulose (CMC) in the range 1–10,000 centipoise showed that the responses of one subset of these neurons were related to stimulus viscosity. Some of the neurons had increasing responses to increasing viscosity, some had decreasing responses, and some neurons were tuned to a range of viscosities. These neurons are a different population to oral fat-sensitive neurons, in that their responses to fats (e.g., safflower oil), to silicone oil $[(Si(CH_3)_2O)_n]$, and to mineral oil (hydrocarbon) depended on the viscosity of these oils. Thus there is a dissociation between texture channels used to sense viscosity and fat. Some of these viscosity-sensitive single neurons were unimodal (somatosensory; 25%) and some received convergent taste inputs (75%). A second subpopulation of neurons responded to gritty texture (produced by microspheres suspended in CMC). A third subpopulation of neurons responded to capsaicin. These results provide evidence about the information channels used to represent the texture and flavor of food in a part of the brain important in appetitive responses to food and are relevant to understanding the physiological and pathophysiological processes related to food intake, food selection, and the effects of variety of food texture in combination with taste and other inputs that affect food intake.

INTRODUCTION

The texture of food is an important factor that influences the pleasantness of a food and how much is eaten. An example is that a crisp food can become quite unpleasant if it becomes soggy. Not only can the texture of food critically affect the acceptability of foods (e.g., meat, potato chips, cornflakes, and celery; Bourne 2002), but also texture can affect the identification of foods. For example, Schiffman (1977; Schiffman et al. 1978) demonstrated that only 40.7% of pureed foods were correctly identified by young nonobese adults. Part of the biological utility of sensing the texture of a food is that it is frequently a cue to its freshness. In addition, somatosensory signals from food in the mouth provide cues about whether a food is safe, and ready, to swallow. The texture of a food is a cue used in sensory-specific satiety, in that eating a meal of one texture of food will decrease the pleasantness of that food relative to other foods with identical tastes and smells (Rolls et al. 1982). Thus the texture of food, as well as the taste, smell, and sight of food, are important cues to its pleasantness, and how much of a particular food is eaten (Rolls 1999). However, little is known about the representation of the sensory information about the texture of food in parts of the brain important in behavioral responses to food such as the orbitofrontal cortex (OFC) and amygdala (Rolls 1999).

The aim of the investigation described here is to advance our understanding of the separate types of sensory representation in the brain of the texture of food in the mouth. It is important to understand the factors that make particular foods palatable, given that clinical disorders of food intake are increasingly common, and sensory cues such as texture are important in assessing, for example, how fatty versus nonfatty a food is, and high dietary fat intake is strongly implicated in the etiology of cardiovascular morbidity and deaths (Keys 1970). The OFC was chosen as the brain area in which to investigate this because there is a great deal of evidence showing that it contains representations of other properties of foods such as their taste, smell, and fattiness, and that the neuronal responses in it are relevant to the control of appetite in that their responses to these stimuli are modulated by hunger (see Rolls 1997, 1999, 2003; Rolls and Scott 2003). Given that oral viscosity inputs are demonstrated here to be combined on some neurons with taste responsiveness, it will be of interest in future studies to investigate where this convergence first occurs.

In previous investigations of the sensory signals about the palatability of food that are important in the regulation of feeding in primates (see Rolls 1995, 1997, 1999; Rolls and Scott 2003), it has been shown that the primate OFC contains the secondary taste cortex (Baylis et al. 1994), and that taste neurons that are found in it (Rolls et al. 1990) respond to the taste of food only when the monkey is hungry (Rolls et al. 1989). There are also projections from the primary olfactory cortex to the OFC (Carmichael et al. 1994), and the responses of neurons in this secondary and tertiary olfactory cortex represent the reward value of the odor of food, in that the neurons here show olfactory sensory-specific satiety (Critchley and Rolls 1996a; Rolls and Rolls 1997). The flavor of food is represented, and probably formed, in this region in that, in addition to unimodal taste and olfactory neurons in this region, other single neurons respond to both taste and olfactory stimuli

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(Rolls and Baylis 1994) and learn olfactory-to-taste associations (Rolls et al. 1996). In addition to these inputs, there is a somatosensory input to the OFC from the somatosensory cortex (Carmichael and Price 1995). Neurons that respond to what is probably in part a somatosensory stimulus, tannic acid (which is prototypical for astringency), are found in the OFC (Critchley and Rolls 1996b). Rolls et al. (1999) discovered a neuronal representation in the macaque OFC of fat in the mouth and showed that the sensing mechanism is based on the texture (somatosensory) and not the chemical (gustatory) properties of the fat in that the same neurons are activated by nonfat compounds with a similar slick texture such as silicone oil and mineral oil (pure hydrocarbon). Rolls et al. (1999) also showed that some of these neurons show multimodal convergence in that they can also be activated by taste and/or by olfactory stimuli.

In this study, we extend these previous investigations showing taste, olfactory, visual, and 2 somatosensory representations (fat texture and astringency) in the OFC by showing that in addition it contains somatosensory representations of the viscosity of food in the mouth; of gritty texture; and of capsaicin (which is present, e.g., in chili pepper). These separate representations in the OFC provide evidence that there are separate somatosensory information channels from the mouth to the OFC for not only fat texture and astringency, but also for viscosity, for gritty texture, and for capsaicin-related compounds. The investigation of this representation in primates is important because the OFC is very much less developed in nonprimates (Rolls 1997, 1999; Rolls and Scott 2003) and is proving to be an excellent model for the details of what is represented in the human OFC, as shown by human neuroimaging studies in humans. The neuroimaging studies show that many of the stimuli described activate the OFC and provide a representation of the pleasantness of sensory stimuli such as food taste (De Araujo et al. 2003; Kringelbach et al. 2003; O'Doherty et al. 2001; Small et al. 1999), food smell (O'Doherty et al. 2000; Rolls et al. 2003b), and touch (Rolls et al. 2003a). However, the neuroimaging studies tell us very little about how the information is represented and what the separate information channels are, for which neurophysiology at the single or multiple single neuron level is essential (Rolls and Deco 2002; Rolls and Treves 1998). Movement of the texture stimulus in the mouth as produced by tongue movements, chewing, and swallowing is important for the perception of texture; to provide evidence on the texture signals that are sent under normal physiological condition of operation of the system, it was important in this study to allow the macaques to be free to move the stimulus in the mouth and swallow it normally. In any case, setting up an artificial stimulation device to generate oral texture stimuli would probably not be tolerated by the macaques in the same way as foods and related substances placed in the mouth.

The design of the experiments was to test the neurons with a set of stimuli that included exemplars for the prototypical tastes (sweet, salt, bitter, and sour) plus umami and water, a one log unit– spaced viscosity series in the range 1–10,000 centipoise (cP), fatty oils and oils with a similar texture but different chemical composition such as silicone oil and mineral oil to investigate whether fats use a separate information processing channel to other textures, a gritty texture stimulus consisting of microspheres in suspension, and capsaicin. [For those not familiar with viscosity values, it may be helpful to note that the viscosity of water at 20°C is about 1 cP, of the corn oil used for cooking is typically 50–60 cP, and of treacle (known in the United States as blackstrap molasses) is typically 5,000 to 10,000 cP. The perceived thickness of a viscosity series increases approximately linearly with the logarithm of the viscosity; see Christensen 1979; Theunissen and Kroeze 1995.]

METHODS

Subjects

The recordings were made in 3 hemispheres of 2 rhesus macaques (*Macaca mulatta*) (one female weighing 2.6–3.3 kg and one male weighing 5.1–5.6 kg; 38 neurons were from the female, and 32 from the male, and the neuronal populations were similar, in that for no stimulus did the responses differ significantly). The monkeys were pair-housed in foraging home cages. To ensure that the macaques were willing to ingest the test foods and fluids during the recording sessions, they were on mild food (150 g of nutritionally balanced mash plus fruits, boiled chicken eggs, nuts, seeds, and popcorn) and fluid (unrestricted access to water only 1 h/day) deprivation, in that both were provided after the daily recording session. The monkeys showed steady increases in body weight. All procedures, including preparative and subsequent ones, were carried out in accordance with the "Policy on the Use of Animals in Neuroscience Research" of the Society for Neuroscience, and were licensed under the UK Animals (Scientific Procedures) Act 1986.

Recordings

Recordings were made from single neurons in the OFC, which included areas in which taste and olfactory responses were previously described (see Rolls 1997, 1999; Rolls and Baylis 1994; Rolls and Scott 2003), using neurophysiological methods as described previously (Rolls et al. 1990, 1999; Scott et al. 1986a,b). The recordings were made with epoxylite-coated single-neuron tungsten microelectrodes (FHC, Bowdoinham, ME; unzapped, 5–10 MΩ at 1 kHz). After several tracks when the impedance had fallen below 2 MΩ we recoated the electrodes with epoxylite (6001M, Epoxylite, Bradford, UK) resulting in 5- to 10-MΩ impedance and good isolation (Verhagen et al. 2003a). The signal-to-noise ratio was typically 3:1 or higher.

For on-line monitoring of neural activity and for determining the randomized permutation stimulus sequence during an experiment a computer (Pentium) with real-time digital and analogue data acquisition collected spike arrival times and displayed a peristimulus time histogram and rastergrams, and displayed the number of spikes in 1- and 3-s poststimulus periods. The spikes for this system were derived from an oscilloscope Schmitt trigger set to trigger on spikes in the signal from the microelectrode after amplification and band-pass filtering (500–5,000 Hz). To ensure that the recordings were made from single cells, the interspike interval was continuously monitored to make sure that intervals of <2 ms were not seen, and the waveform of the recorded action potentials was continuously monitored. The data were also collected using a Datawave Discovery (Tucson, AZ) system that digitized the signal (12 bit, 16 kHz) for 8 s after stimulus onset. The spikes were sorted off-line using the cluster cutting method provided with the Datawave system, and this procedure was straightforward in that the data were collected with single-neuron microelectrodes that typically recorded from only one neuron at a time with a high signal-to-noise ratio (>3:1). Figure 2 (*inset*, *top left*) shows the very good isolation of the spikes of a single neuron achieved by virtue of the high-impedance single-neuron recording microelectrodes and the cluster cutting. In all cases, apart from 5, the neurons described

here were recorded at separate recording sites. The recording sessions lasted 4–6 h and were conducted daily. To prevent visual associative input from evoking neural activity, we prevented the monkeys from seeing the stimuli and experimenter by a view-obstructing screen. For further details see Rolls et al. (1990). No more than 2 complete experiments, on different neurons, were performed per day to limit the effects of satiety on neural responses. (The total application volume was 70 ml for the full stimulus set including rinses.)

Localization of recordings

X-radiography was used to determine the position of the microelectrode after each recording track relative to permanent reference electrodes and to the anterior sphenoidal process. This is a bony landmark whose position is relatively invariant with respect to deep brain structures (Aggleton and Passingham 1981). Microlesions made through the tip of the recording electrode during the final tracks were used to mark the location of typical units. These microlesions, together with the associated X-radiographs, allowed the position of all cells to be reconstructed in the 50-μm brain sections with the methods described by Feigenbaum and Rolls (1991).

Stimuli

Orbitofrontal cortex neurons were tested for their responsiveness to the set of taste, viscosity, gritty, and oily stimuli, and also capsaicin, at room temperature (23°C) as shown in Table 1. The gustatory stimuli used included 1.0 M glucose (G), 0.1 M NaCl (N), 0.01 M HCl (H), 0.001 M Quinine HCl (Q), and 0.1 M monosodium glutamate (M). The concentrations of most of the tastants were chosen because of their comparability with our previous studies, and because they are in a sensitive part of the dose–response curve. [Concentration– firing rate response functions for single neurons in the primate nucleus of the solitary tract to glucose, NaCl, HCl, and QHCl are shown by Scott et al. (1986a); and in the insula by Scott et al. (1991); further, for each tastant the concentration we used was about 10 times the concentration at which these neurons started to respond, except for glucose, for which a higher concentration was used so that the same solution could be used in satiety experiments; see, e.g., Rolls et al. 1989.] The control stimulus was distilled water, termed V1 because it has a viscosity of 1 cP and is part of the viscosity series. For an additional comparison, the neuronal responses were tested to 20% black currant juice (BJ, Ribena) because with its complex taste and olfactory components and high palatability it is an effective stimulus when searching for and analyzing the responses of cortical neurons (Rolls et al. 1990).

A viscosity series was made with carboxymethylcellulose [CMC (Sigma), high viscosity, MW 700,000, dialyzed, Code C5013), a virtually odorless and tasteless thickening agent used widely in the food industry. To confirm this, we performed psychophysical investigations on 4 expert subjects and found that for no CMC stimulus was the mean intensity, on a 100-mm visual analog rating scale, >3/100 for sweet, salt, bitter, and sour taste, compared with intensity values for the taste stimuli used that were in the range 35–65/100; and that for odor, no CMC stimulus was higher than 3/100. In contrast the rated thickness of the CMC series increased approximately logarithmically from 3/100 (10 cP) to 76/100 (10,000 cP). (The pH for the 10 cP was 6.8, for the 100 and 1,000 cP was 7.0, and for the 10,000 cP was 7.4.) Based on psychophysical data from Theunissen and Kroeze (1995), a log-linear relationship exists between the rated oral thickness of CMC and its apparent viscosity. (The term *apparent viscosity* is used to indicate that the CMC solutions do not behave rheologically as Newtonian fluids: they show shear-thinning behavior.) Viscosity was assessed using a calibrated Brookfield rotary viscometer (type LVT; Brookfield Engineering Laboratories, Middleboro, MA) at 60 rpm (shear rate approximately 12 s^{-1}, spindles 1–4) at 23°C. Concentrations (in g CMC added to 500 ml water) yielding 1, 10, 100, 1,000, and 10,000 cP (V1, V10, V100, V1000, and V10000; reliability ±10%) solutions were: 0.0, 0.1, 2.0, 5.5, and 12.0 g CMC, respectively (values similar to those in Theunissen and Kroeze 1995). The solutions were mixed until they were optically clear. Viscosity was assessed at room temperature after air bubbles had disappeared. (Note that 1 cP = 1 mPa · s.)

The gritty stimulus consisted of hard (Mohs scale 5) hollow microspheres (Fillite grade PG, with 90% having a diameter in the range 33–194 μm, Trelleborg Fillite, Runcorn, UK) made up in methylcellulose to have a measured viscosity of 1,000 cP (100 g of Fillite PG was added to 4.7 g of CMC in 500 ml of water).

To test for and analyze the effects of oral fat on neuronal activity, a set of oils and fat-related stimuli was included. The triglyceride-based oils consisted of vegetable oil, safflower oil, and coconut oil. These were used to examine whether fat is represented in the responses of cortical (taste) neurons. Single cream (SC, 18% fat, vis-

TABLE 1. *Stimuli*

Stimulus	Abbreviation	Concentration	Molecular Weight	Approximate Viscosity (cP)	Chemical Group
Glucose	G	1 M	180	1	Monosaccharide aldohexose
Black currant juice	BJ	20%		1	Mixture
Monosodium glutamate	M	0.1 M	187	1	Amino acid salt
NaCl	N	0.1 M	58	1	Inorganic salt
HCl	H	0.01 M	36	1	Inorganic acid
Quinine HCl	Q	0.001 M	387	1	Alkaloid
Water	V1	5 mM NaCl		1	
CMC	V10	0.2 g + 1 L V1	700,000	10	Polysaccharide
CMC	V100	4.0 g + 1 L V1	700,000	100	Polysaccharide
CMC	V1000	11.0 g + 1 L V1	700,000	1000	Polysaccharide
CMC	V10000	24.0 g + 1 L V1	700,000	10,000	Polysaccharide
gritty	Gritty	100 g Fillite + 9.4 g CMC + 1 L V1	700,000	1000	SiO_2 + polysaccharide
Mineral oil	MO	100%		25	Hydrocarbon mixture
Silicone oil	SiO	100%		100 or 280	Silicon–oxygen polymer
Vegetable oil	VO	100%		55	Fat
Coconut oil	CO	100%		40	Fat
Safflower oil	SaO	100%		50	Fat
Single cream	SC	100%		12	Emulsion
Capsaicin	CAP	10 μM		1	Vanillyl amide

cosity: 12 cP, Coop brand, pasteurized) was used as an exemplar of a natural high fat content food of the type for which we sought to examine the neural representation and sensing mechanisms. All the neurons with fat-related responses described in this and our earlier study (Rolls et al. 1999) responded well to single cream. The monkeys had been raised on their mother's milk, which is a good source of dietary fat. Vegetable oil (VO, viscosity 55 cP at 23°C), coconut oil (viscosity 40 cP at 23°C), and safflower oil (viscosity 50 cP at 23°C) were used as natural high-fat stimuli.

To investigate whether the neurons responsive to fatty-acid– based oils were in some way responding to the somatosensory sensations elicited by the fat, stimuli with a similar mouth feel but nonfat chemical composition were used. These stimuli included paraffin/mineral oil (pure hydrocarbon, viscosity 25 cP at 23°C; Sigma), and silicone oil $(Si(CH_3)_2O)_n$, SiO, 98 cP (Brookfield viscometer calibration fluid) or 280 cP (Aldrich).

The capsaicin was made up as a 10 μM solution (containing 0.3% ethanol). This is about 15 times the human recognition threshold of 0.66 μM (Szolcsanyi 1990).

The stimuli were kept in the dark at −20°C for up to 1 mo. After thawing they were used for up to 5 days and stored overnight at 4°C in the dark. All fatty oils were kept in the dark under N_2 at 4°C to avoid oxidation.

Stimulus delivery

The general method for stimulus delivery and accurate stimulus onset marking (Rolls et al. 1990) was modified by introducing repeater pipettes (Verhagen et al. 2003b). We used repeater pipettes (type Multipette Plus; Eppendorf AG, Hamburg, Germany) and pipette tips (Combitips Plus, 10 ml) that were modified by insertion of a stainless steel wire (0.5 mm diameter) into the lumen 10 mm from the tip. The wire was tightly coiled about 10 times around the tip extending toward the neck and glued at the neck with epoxy glue. For stimulus delivery, the pipette tip (and thus the wire that encircled it and was connected electrically to the fluid inside the pipette) was placed on antistatic conducting foam, which was in turn connected to an impedance-sensitive device that could send a Schmitt-triggered pulse to the data-acquisition system. When fluid was expelled from the pipette and touched the tongue, the impedance to ground changed, and the pulse was triggered. We placed 10-mm-long cones cut from 200 μl Gilson pipette tips onto the tip of the repeater pipette tip, creating a fluid-free lumen, to prevent the system from being triggered when the tip touched the monkey's lips. For reliable triggering, a concentration of 5 mM NaCl was used to make the solution sufficiently conductive for the impedance system to trigger. [This concentration is well below the salivary NaCl + KCl concentration of about 25–30 mM (Bartoshuk 1974; Guinard et al. 1998; Morino and Langford 1978; Nagler and Nagler 2001).] All water-soluble stimuli were thus made up to contain 5 mM NaCl. Oil stimuli were triggered manually by touching the antistatic foam at the time of expelling the fluid from the tip. The tips were wiped clean before each stimulus presentation. To allow for consistent flow patterns, air bubbles in the pipette were removed and the pipette tips were cut back to an opening diameter of 1.5 mm. For chronic recording in monkeys, a manual method for stimulus delivery is used because it allows for repeated stimulation of a large receptive surface despite different mouth and tongue positions adopted by the monkeys (Scott et al. 1986a,b). The stimulus application volume was 200 ± 10 μl because this is sufficient to produce large gustatory neuronal responses that are consistent from trial to trial, and yet which do not result in large volumes of fluid being ingested that might, by producing satiety, influence the neuronal responses (Rolls et al. 1989, 1990).

The monkey's mouth was rinsed with 200 μl V1 (water) during the intertrial interval (which lasted ≥30 s, or until neuronal activity returned to baseline levels) between taste stimuli. The complete stimulus array was delivered in random sequence. Because of the tenacious nature of the oral coating resulting from the delivery of cream or of oil, and also for gritty and capsaicin, four 200-μl rinses with V1 were given, while allowing the subjects to swallow after each rinse. For V1000 and V10000, we used 2 such rinses. All the stimuli shown in Table 1 were delivered in permuted sequences, with the computer specifying the next stimulus to be used by the experimenter. The spontaneous firing rate of the neuron was measured from trials in which no stimulus delivery occurred.

Data analysis

After cluster cutting of the spikes with Datawave software, the numbers of spikes of the single neuron in 80 100-ms time bins starting at the onset of the stimulus were obtained using Microsoft Excel 9.0. Statistical analysis was performed on the numbers of spikes in the 1st 1-s period after stimulus onset, which was sufficiently long to include firing to even viscous liquids, and sufficiently short so that low viscosity taste stimuli were still activating the neurons, as shown in Fig. 2. An ANOVA was performed (with SPSS software) to determine whether the neuron had significantly different responses to the set of stimuli, and if so, post hoc LSD *t*-tests were performed to test for significant differences between individual stimuli. If the main ANOVA was significant, 2 further ANOVAs were performed to test for differences in neuronal responses between the set of taste stimuli (G, N, H, Q, M, and V1); and between the members of the viscosity series V1– V10000. Systat 10 was used for the generation of Pearson product-moment correlation coefficients calculated between the stimuli using the responses of all the neurons analyzed, and graphical presentation of stimulus similarity using multidimensional scaling (loss function: Kruskal; regression: mono) and cluster analysis (linkage: average, distance: Pearson).

A taste cell was defined by a significant effect in the ANOVA performed across the stimulus subset (V1, G, N, M, H, Q) on the number of spikes during the 1st 1 s after stimulus onset. Similarly, the viscosity cell criterion was based on a significant effect in the ANOVA between the set of stimuli V1– V10000. Fat cells were defined by a significant difference between the pooled response rates evoked by the oils (viscosity 25–100 cP, excluding mineral oil when its viscosity was 280 cP instead of 100 cP: 50% of the cells recorded, all from the female monkey), and the pooled rates of V10 and V100; and in addition by a significant difference between the pooled rates evoked by the oils and the spontaneous activity. The critical alpha level was set at $P < 0.05$ (although for most cells, 65/70, the *P* value in the overall ANOVA was <0.001). Two planned comparisons were performed to help identify capsaicin-sensitive or gritty texture– sensitive cells. The test for capsaicin sensitivity was a 2-tailed *t*-test comparing the responses of the neuron to capsaicin and to water. The test for gritty texture sensitivity was a 2-tailed *t*-test comparing the responses of the neuron to the gritty texture stimulus (which has a viscosity of 1,000 cP) and to the 1,000-cP stimulus from the viscosity series made with CMC.

The breadth of tuning metric of Smith and Travers (1979) was calculated as follows. The proportion of a neuron's total response that is devoted to each of the 4 basic stimuli can be used to calculate its coefficient of entropy (H). The measure of entropy is derived from information theory, and is calculated as

$$H = -k \sum_i p_i \log p_i$$

where H is the breadth of responsiveness, k is the scaling constant (set so that H = 1.0 when the neuron responds equally well to all stimuli in the set of size *n*), and p_i is the response to stimulus i expressed as a proportion of the total response to all the *n* stimuli in the set. The coefficient ranges from 0.0, representing total specificity to one of the stimuli, to 1.0, which indicates an equal response to all of the stimuli. The sparseness of the representation *a* can be measured (Rolls and Deco 2002; Rolls and Tovee 1995; Rolls and Treves 1998), by

extending the binary notion of the proportion of neurons that are firing, as

$$a = (\sum_{i=1,N} r_i/N)^2/\sum_{i=1,N} (r_i^2/N)$$

where r_i is the firing rate of the ith neuron in the set of N neurons. The sparseness is within the range 0–1, and assumes the value 0.5 for a fully distributed representation with binary encoding; and $1/N$ for a local or grandmother cell representation with binary encoding. These measures of the fineness of the tuning of neurons are important in understanding the neuronal encoding of information (Rolls and Deco 2002; Rolls and Treves 1998).

Screening cells

While searching for neurons, we continuously applied samples from our stimulus set: G, N, Q, BJ, SC, VO, SO, V100, V1. We also tested for visual responsiveness (to the sight of food, a saline-associated square plaque, the approach of a taste stimulus toward the mouth, objects, faces, head movement, and lip-smacking) and auditory responsiveness (a 500-Hz tone, coo-calls, grunts, and vocalization) because stimuli of these types do activate some OFC neurons (Rolls et al. 1996, E. T. Rolls, H. D. Critchley, A. S. Browning, and K. Inoue, unpublished observations). When neurons were insensitive to these stimuli, we classified them as nonresponsive. Only cells responding consistently to at least one stimulus of the array were recorded, all stimuli being applied 4 to 6 times in permuted sequences.

RESULTS

The data described in this study were obtained during recording tracks in 3 hemispheres of 2 monkeys. Out of 1,149 screened neurons in the OFC region, 70 neurons (6.1%) responded in relation to viscosity, gritty texture, capsaicin, fat texture, taste, and/or temperature. [Data on the responses of the set of neurons to fat and to temperature are too extensive to be included here and are the subject of other studies (Verhagen et al. 2003b; Kadohisa, Rolls, and Verhagen, unpublished observations)]. Visual responses (objects, movement) were clear in 14.3% of the total sample and 0.6% showed auditory responses. The remainder of the neurons (78%) were unresponsive to the stimuli used.

Figure 1 shows a neuron (bk299) that is tuned to viscosity, with responses to only 10 and 100 cP from the CMC viscosity series [ANOVA, $F(4,19) = 21.0$, $P \ll 0.001$]. The neuron did not respond to the gritty stimulus in a way that was unexpected, given the viscosity responsiveness of the neuron. The neuron had a very significant response to capsaicin (compared with V1, i.e., water, $P < 0.002$), and the neuron did have taste responses, which occurred to all the taste stimuli except sweet [glucose and fruit juice (BJ)] [$F(5,32) = 6.7$, $P < 0.001$]. In addition, Fig. 1 (and other figures in this study) shows the mean response to the following oils: mineral oil, vegetable oil, safflower oil, and coconut oil, which have viscosities that are all close to 50 cP. This neuron did respond to the oils and did so with a response that would be predicted from their viscosity. Thus this neuron represents viscosity independently of whether the stimulus is an oil (e.g., a fat) or a nonoil (the CMC). This is very different from fat-sensitive neurons, which respond to oils including fats but not to the CMC series (Verhagen et al. 2003b). This finding also shows that the CMC is operating within its Newtonian range, in that the responses to the oils (which behave in a Newtonian way) and to the CMC (at least when its viscosity is measured at a shear rate of about 12 s^{-1} at 23°C) are similar. Figure 1 also shows that the neuron did not respond to the gritty stimulus differently than its measured viscosity (of 1,000 cP). This shows the analysis whereby this neuron was classified as being viscosity sensitive, and in a way that was independent from effects of slickness as produced by oils, and of grittiness. This neuron thus illustrates convergence of viscosity-related somatosensory and taste inputs onto a single neuron and in addition shows that this type of viscosity-sensitive neuron responds to oils based on their viscosity.

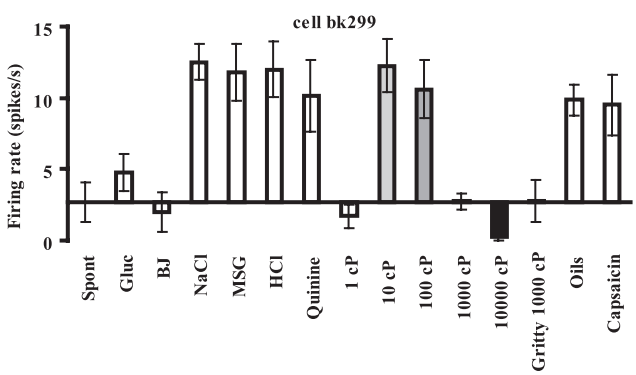

FIG. 1. Firing rates (mean ± SE) of viscosity-sensitive neuron bk299 to viscosity series, to gritty stimulus (carboxymethylcellulose with Fillite microspheres), to taste stimuli 1 M glucose (Gluc), 0.1 M NaCl, 0.1 M MSG, 0.01 M HCl, and 0.001 M Quinine HCl, to fruit juice (BJ), and to capsaicin. Spont, spontaneous firing rate. "Oils" indicates mean response to mineral oil, vegetable oil, safflower oil, and coconut oil, which have viscosities all close to 50 cP.

An example of a viscosity-responsive neuron (bo94) is shown in Fig. 2, in a poststimulus time histogram (PSTH) and rastergram. This neuron showed a graded increase in its firing with higher viscosities of the CMC viscosity series. At the higher viscosities the response tended to last longer, and this probably reflects the fact that it takes longer for the thick viscosity stimulus to clear from the mouth by swallowing. The responses to the different members of the viscosity series calculated over the first 1-s poststimulus period were significantly different from each other [$F(4,17) = 11.6$, $P < 0.001$], allowing us to classify it as a viscosity-responsive cell. The firing rate responses presented in the diagrams in this study are calculated over the 1st 1 s of the presentation, because with longer measurement periods, neuronal responses to the tastants had started to decline (see Fig. 8), as the tastants were removed from the mouth by swallowing. We note, however, that none of the results described here would have been qualitatively affected if a different measurement period of 3 or 5 s had been used.

Figure 3 (*top*) shows an example of a viscosity-sensitive neuron (bk244) [$F(4,19) = 4.1$, $P = 0.015$] that did not have taste responses [$F(5,31) = 1.85$, ns]. An additional property illustrated by this neuron is that it responded to the 50-cP oils in the way that would be predicted from the viscosity responsiveness measured with the CMC series. The neuron did not have a response to capsaicin that was significantly different from that to water.

We also observed neurons that did respond to the CMC viscosity series but not to the oils. This type of neuronal response, which also illustrates how neurons can be tuned to a range of viscosities, is exemplified by the neuron shown in Fig. 3 (*bottom*). The neuronal responses show an upward trend with increasing viscosity (V1– V1000), and a reduction at V10000

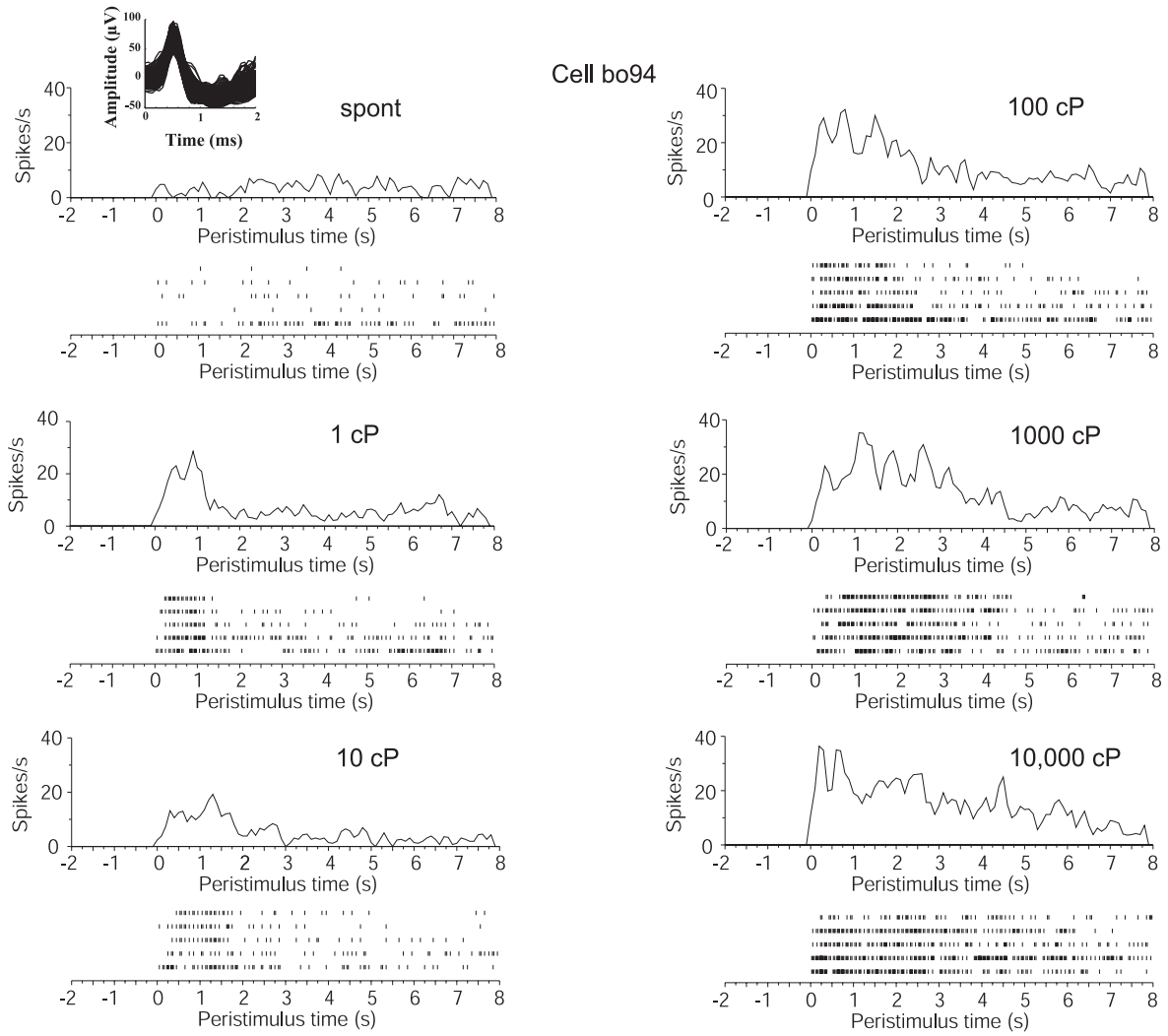

FIG. 2. Poststimulus time histogram (PSTH) and rastergram of neuron (bo94) responsive to viscosity of fluids in mouth. The response of the neuron depended on viscosity (labeled 1–10,000 cP) of CMC (carboxymethylcellulose) series of stimuli. Spont, spontaneous firing rate. Recording on each trial started at *time 0*, when stimulus was delivered. PSTHs were Gaussian smoothed with SD of 1 time bin, each 100 ms wide. *Inset*, *top left*: overlapped waveforms of 4,097 of recorded spikes of single cell.

[$F(4,18) = 4.0$, $P = 0.017$]. However, none of the oils evoked significant activity. Thus the responses of this neuron show a way in which OFC neurons can discriminate between fat texture and viscosity, by in this case responding to information conveyed through a viscosity information channel but showing no response if the viscosity is associated with a stimulus with an oily texture. This neuron did respond to the capsaicin significantly differently from water, and responded to some but not other tastes [$F(5,22) = 8.7$, $P < 0.001$].

The way in which each of the 20 viscosity-sensitive neurons responded to the different members of the viscosity series is shown in Fig. 4, in which the abscissa is the viscosity of the stimulus on a log scale for the 5 viscosity stimuli in the range 1–10,000 cP. (The effects produced by V1, V10, V100, and so forth can be clearly identified.) The neurons were divided into 2 sets based on a cluster analysis using the responses to V1–V10000 [shown in Fig. 9 (*top*)]. The first set of neurons in the diagram (bo94– bo175c2) tended to have increasing firing rates as a function of viscosity. (Sometimes 10,000 cP CMC did not produce a large response, perhaps because it was so viscous that sufficient coverage of the oral cavity was not produced in the 1st 1 s.) The 2nd set of neurons in Fig. 4, from bo4 to bo35c2, tended to have responses that decreased as a function of viscosity. Both sets of neurons included examples of neurons that were tuned to a particular part of the viscosity range. Both sets also included neurons that had neuronal firing rates that were proportional to the log of the viscosity.

Figure 5 (*top*) shows the firing rates of neuron bo35c2, which responded to the gritty texture stimulus (CMC with Fillite microspheres) in a way that would not be predicted from the CMC viscosity series by its viscosity, which was 1,000 cP. The neuron had rather less than significantly different responses to the different viscosity stimuli [$F(4,19) = 2.5$, $P = 0.08$], and a significantly different response between the gritty 1,000-cP stimulus and the smooth CMC 1,000-cP stimulus ($P < 0.036$). The neuron's response to the oils (viscosity $\approx$ 50 cP) was a little larger than the response predicted from the CMC viscosity series. The neuron did have a taste input [1 M glucose (Gluc), 0.1 M NaCl, 0.1 M MSG, 0.01 M HCl, and 0.001 M Quinine HCl] [$F(5,22) = 9.1$, $P < 0.001$], and did have a statistically significant response to capsaicin. This cell thus shows that some neurons responded to the gritty stimulus

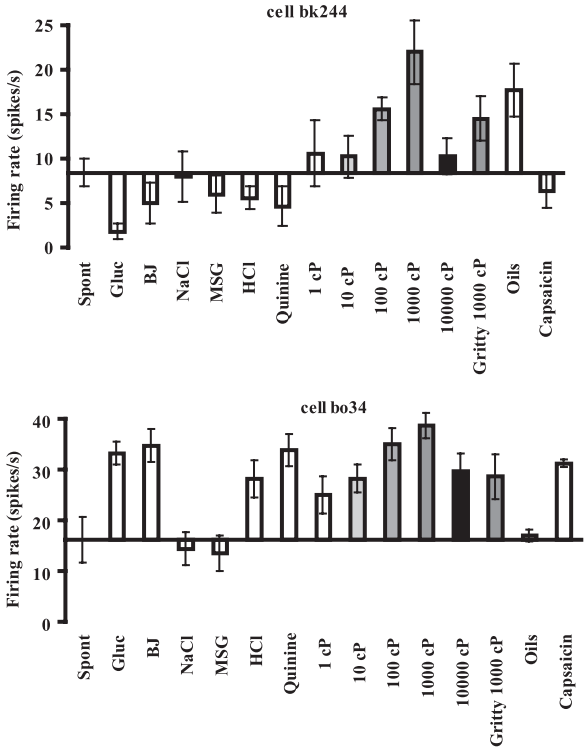

FIG. 3. *Top*: firing rates (mean ± SE) of viscosity-sensitive neuron bk244, which did not have taste responses. Firing rates are shown to viscosity series, to gritty stimulus (CMC with Fillite microspheres), to taste stimuli 1 M glucose (Gluc), 0.1 M NaCl, 0.1 M MSG, 0.01 M HCl, and 0.001 M Quinine HCl, and to fruit juice (BJ). Spont, spontaneous firing rate. *Bottom*: firing rates (mean ± SE) of viscosity-sensitive neuron bo34, which had no response to oils (mineral oil, vegetable oil, safflower oil, and coconut oil, which have viscosities all close to 50 cP). Neuron did not respond to gritty stimulus in a way that was unexpected, given viscosity of stimulus, was taste tuned, and did respond to capsaicin. Other conventions in this and subsequent figures are as for Fig. 1.

independently of viscosity. Eight neurons of this type were found, 15.1% of the sample of 53 tested with this stimulus. These were a special group of neurons, in that the neurons classified as viscosity-sensitive responded to the gritty stimulus in a way that would not be predicted based on the measured viscosity of the gritty stimulus [see examples in Figs. 1 and 3 (*bottom*)].

The responses of a neuron (bo18) that responded to the capsaicin differently from its solvent, water (V1 in the viscosity series), are shown in Fig. 5 (*bottom*). The difference in response was statistically significant ($P < 0.001$). The neuron had different responses to different tastes [$F(5,19) = 3.7$, $P = 0.017$], but not to different viscosities [$F(4,17) = 0.96$, ns]. Eight neurons of this type were found, 15.7% of the sample of 51 tested with this stimulus from the set of 70 responsive cells in this study.

The representation by the population of neurons of the similarity of the stimuli was approached with multidimensional scaling, based on the 1st 1 s of poststimulus activity, and was performed on the responses of the 70 neurons included in the analyses (see Fig. 6). (Fifty-six neurons that were responsive to viscosity and/or taste, with 14 further neurons that responded to other oral stimuli such as temperature, constituted the 70 neurons. These 70 neurons were included in all the population analyses so that not only the stimuli included in the experiments described here, but also oral temperature stimuli, could be included in a comprehensive analysis of the encoding provided by this population of neurons. The rationale was to show in the multidimensional space the relative separation of the viscosity, gritty, capsaicin, and taste stimuli that are the focus of this study within the space spanned by the whole population of 70 cells. We note that post hoc analysis shows that the results are qualitatively similar for both the whole data set of 70 neurons and the reduced data set of 56 neurons that respond to the stimuli that are the focus of this work, so that Fig. 6 faithfully shows the relative separations. More numerical indications of the way the population separates the stimuli are shown by the correlation linkage values between different stimuli shown in Fig. 7.) The location of the different stimuli in the multidimensional space shows that the population of neurons responds differently to the different members of the viscosity series; and in addition that as a whole the population represents taste stimuli, and does so separately from viscosity. This is made clear by the fact that all the viscosity stimuli fall outside the space enclose by the taste stimuli. In addition, both the gritty texture stimulus and capsaicin fall outside the part of the space in which the viscosity series is mapped, providing evidence that they are encoded separately.

The representation of the similarity of the stimuli by the population of neurons was also approached with cluster analysis, based on the first 1 s of poststimulus activity, and was performed on the responses of the same 70 neurons (Fig. 7). The organization of the dendrogram is striking. The stimuli that are close to each other in the dendrogram are somewhat expected, for example, G and BJ; N and M; V1, V10, and V1000; V1000 and V10000. It is of interest that the gritty texture is represented as being as different from both V1000 and V10000 as V1000 and V10000 are from each other.

The average time courses of the responses of the 20 viscosity-sensitive neurons to the different members of the viscosity set are shown in Fig. 8. Not unexpectedly, the less-viscous stimuli tended to have responses that lasted for ≤2 s, and the more viscous stimuli tended to produce longer responses (≤4–5 s), related probably to the speed with which the stimuli were cleared from the mouth by tongue and mouth movements and swallowing. It was notable, as illustrated in Fig. 2 for individual trials, that these neurons did not have responses that were phasic and locked to mouth movements, but instead had relatively continuous firing, characterized by an initial peak when the stimulus was delivered (more evident in Fig. 2 than the average case shown in Fig. 8), which on average decreased slowly as shown in Fig. 8. Thus the firing of these OFC neurons was clearly related to sensory effects produced by the stimuli (comparable to the continuous feeling of viscosity produced by a viscous stimulus in the mouth), rather than to motor actions produced by the monkey.

To examine whether the neurons with increasing versus decreasing responses as a function of viscosity (see Fig. 4 and dendrogram at the *top* of Fig. 9) had different responsiveness to tastes, the average responses of these 2 sets of neurons are shown in Fig. 9. Apart from the significant differences (indicated by an asterisk) in the responses to the viscosity stimuli, these two sets of neurons did not have very different average tuning to the tastants, with the only significant difference in taste tuning being a rather larger response to 0.1 M NaCl of the

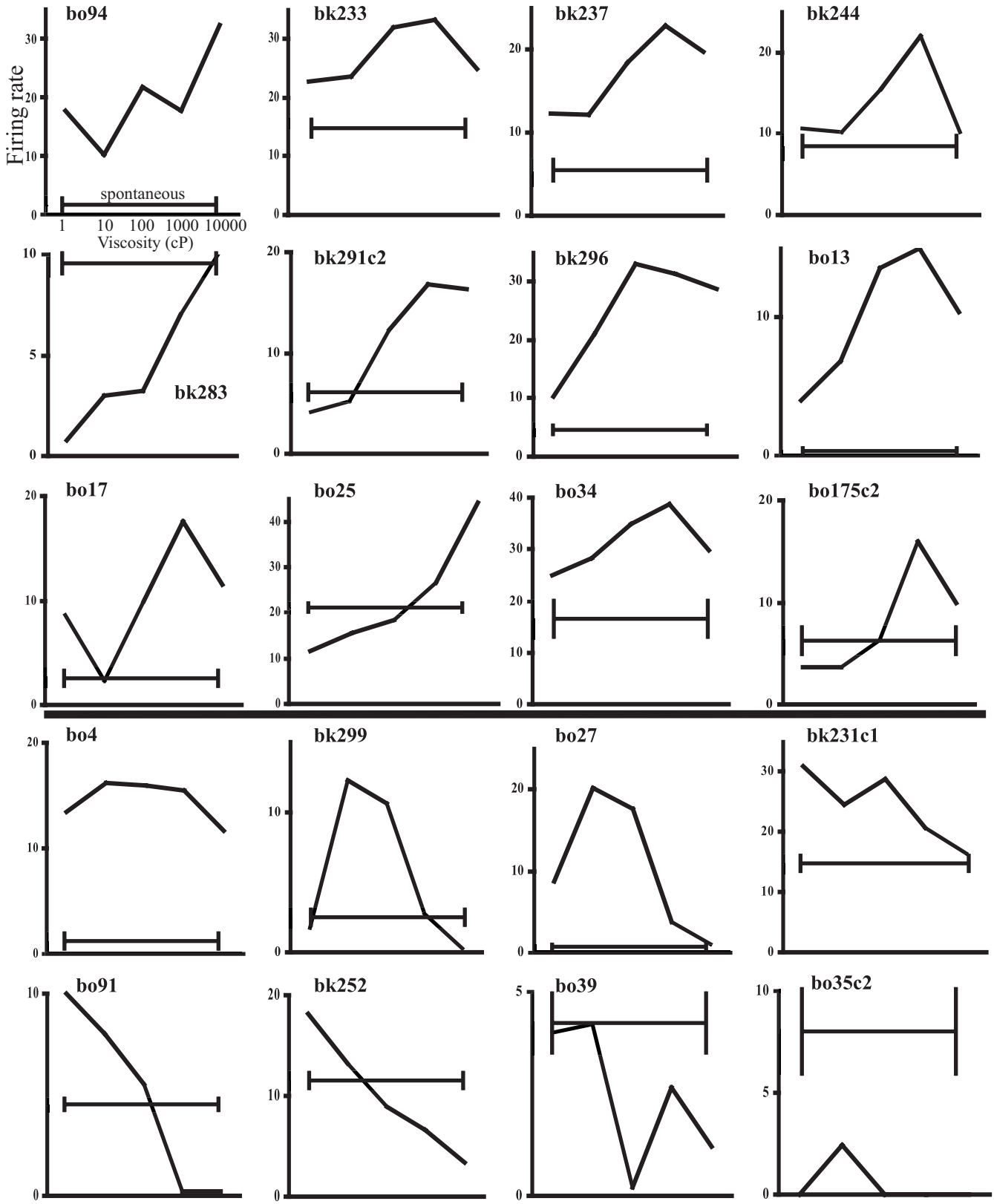

FIG. 4. Response functions of all viscosity-sensitive neurons to 1, 10, 100, 1,000, and 10,000 cP CMC. Mean ± SE of spontaneous firing rate shown for each neuron.

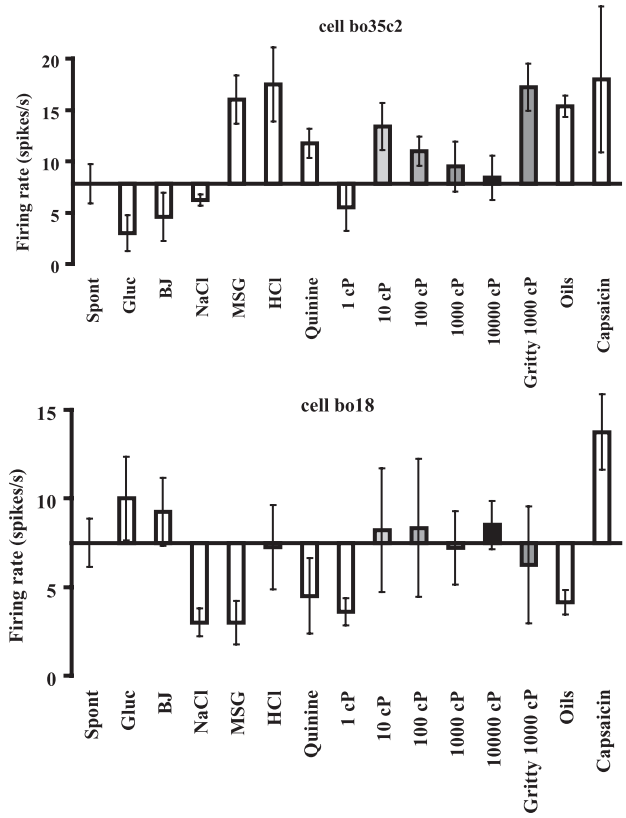

FIG. 5. *Top*: firing rates (mean ± SE) of neuron bo35c2, which responded to gritty texture stimulus (CMC with Fillite microspheres) in a way that would not be predicted by its viscosity (1,000 cP). Neuron's response to oils (viscosity = 50 cP) was slightly greater than response predicted from CMC viscosity series. Neuron did have a taste input [1 M glucose (Gluc), 0.1 M NaCl, 0.1 M MSG, 0.01 M HCl, and 0.001 M Quinine HCl; BJ, fruit juice], and did respond to capsaicin. *Bottom*: firing rates (mean ± SE) of neuron bo18, which responded to capsaicin stimulus differently from water (the 1-cP stimulus).

neurons with increasing response functions to viscosity (*cluster 1* in Fig. 9).

Of the 70 neurons in the sample, 20 were classified as viscosity sensitive. Of these 70, 5 had responses to viscosity

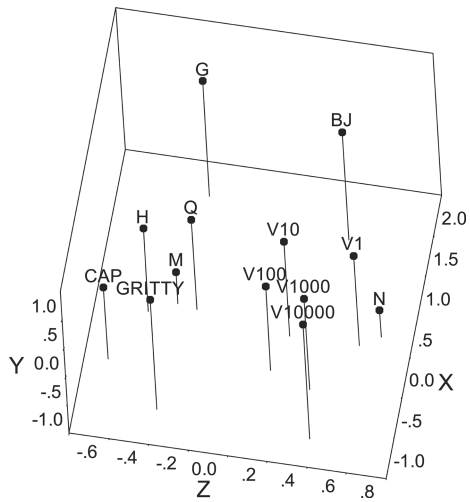

FIG. 6. Stimulus space (multidimensional scaling) of stimulus similarity based on across-neuron response profiles of 70 neurons. V1–V10000, viscosity series. G: 1 M glucose; N: 0.1 M NaCl; M: 0.1 M MSG; H: 0.01 M HCl; and Q: 0.001 M Quinine HCl; BJ: fruit juice. This 3-D space accounted for 79% of variance.

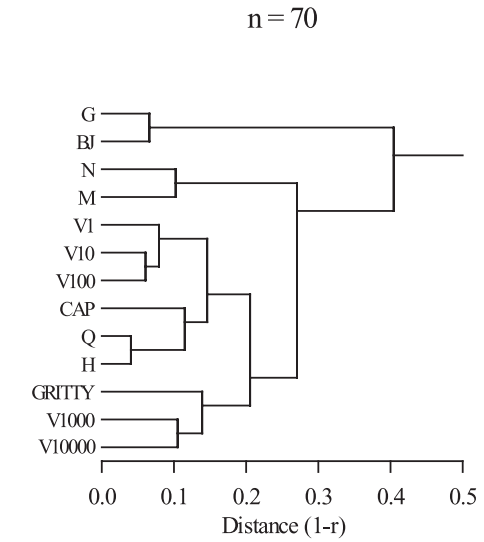

FIG. 7. Stimulus dendrogram based on 70 orally responsive neurons in study. $(1 - r)$ = measure of dissimilarity of clusters (r is correlation coefficient). V1–V10000, viscosity series. G: 1 M glucose; N: 0.1 M NaCl; M: 0.1 M MSG; H: 0.01 M HCl; and Q: 0.001 M Quinine HCl; BJ: fruit juice.

but not taste stimuli, 36 had responses to taste but not viscosity stimuli, and 15 had responses to viscosity and taste stimuli (see Fig. 10). The fact that there are unimodal taste and unimodal viscosity-sensitive neurons indicates that these types of stimuli can be represented separately in the OFC.

To examine whether the taste responsivities of the neurons with and without viscosity inputs are different, we show them in Fig. 11. It is evident that the neurons with gustatory (G) inputs unimodally (which form the larger proportion of taste neurons in this brain region) are more likely to be tuned to (i.e., have best responses among the taste stimuli) sweet (G), whereas the (smaller proportion of) neurons with viscosity and taste (multimodal) inputs are more likely to be tuned to salt (N) stimuli or to be driven by multiple tastants ($\chi^2 = 20.4$, df = 5, $P < 0.002$). The breadth-of-tuning metric (Smith and Travers 1979) to H, Q, N, and G of the neurons with both taste and viscosity inputs was 0.86 ± 0.05 (mean ± SE), and of neurons with taste but not viscosity inputs was 0.74 ± 0.05 (P =

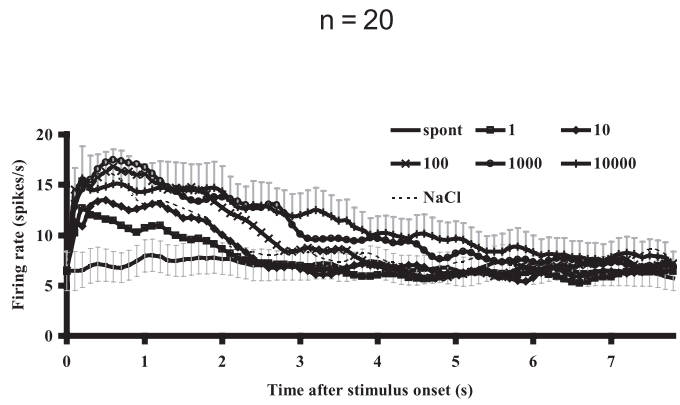

FIG. 8. PSTHs averaged across 20 neurons with statistically significant viscosity tuning, for viscosity series and for 0.1 M NaCl. Spont, spontaneous firing rate. Means and SE of firing rates are shown. Triangular 5-point smoothing (with weights 1, 2, 3, 2, 1) was applied to time series data binned at 100 ms per bin.

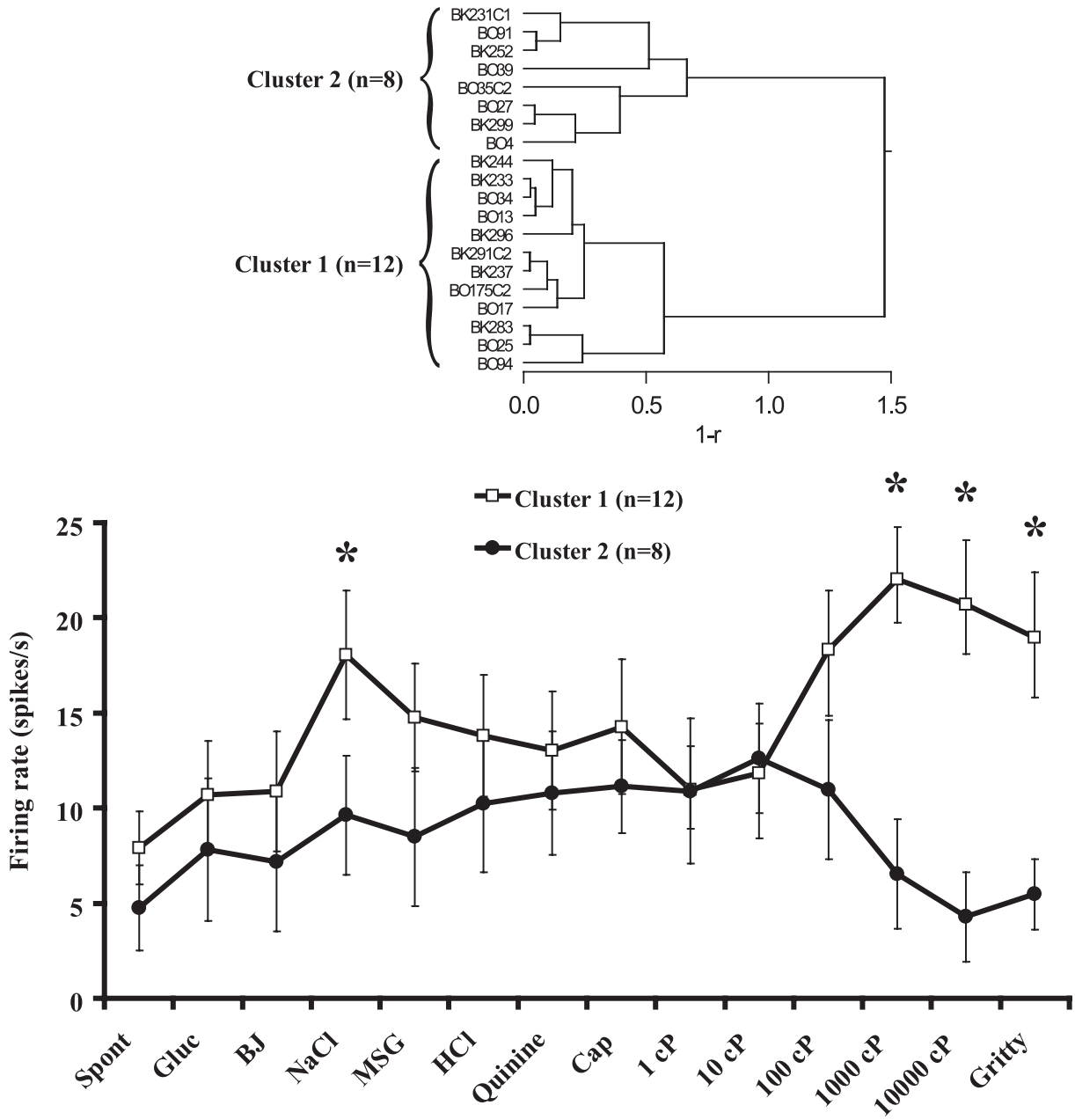

FIG. 9. *Bottom*: mean firing rates (±SE) to set of stimuli across 2 groups (based on cluster analysis on basis of responses to CMC series) of viscosity-tuned neurons. *Cluster 1*: group of neurons that had increasing firing rate response functions as viscosity increased. *Cluster 2*: group of neurons that had decreasing firing rate response functions as viscosity increased. *: significant difference for this stimulus between responses of 2 groups of neurons. *Top*: dendrogram based on responses to V1–V1000 of 20 viscosity-sensitive neurons to show clustering that gave rise to 2 groups.

0.052). The corresponding sparsenesses are 0.78 ± 0.05 and 0.64 ± 0.04 ($P = 0.022$).

Localization of recordings

The reconstructed positions of the 70 neurons in this study are shown in Fig. 12. The uni- or multimodal responses of the neurons are indicated by different symbols. The viscosity-sensitive neurons discovered in this study are located in the caudolateral aspect of the OFC, in a region in which gustatory neurons were also found. The regions within which recordings were made are delimited by arrows.

DISCUSSION

The results in this study describe the discoveries of neurons in the CNS related to the viscosity of food in the mouth, and to the grittiness of food in the mouth. The results also describe the discovery of neurons tuned to capsaicin in the primate OFC.

The neurons tuned to viscosity had different tuning to the members of the viscosity series (see Figs. 4 and 9), and, if they had taste inputs, had different taste tuning to each other, so that their responsiveness did not reflect any single factor such as the palatability of the stimulus. Indeed, as a population they provide a good representation of the viscosity of whatever is in the

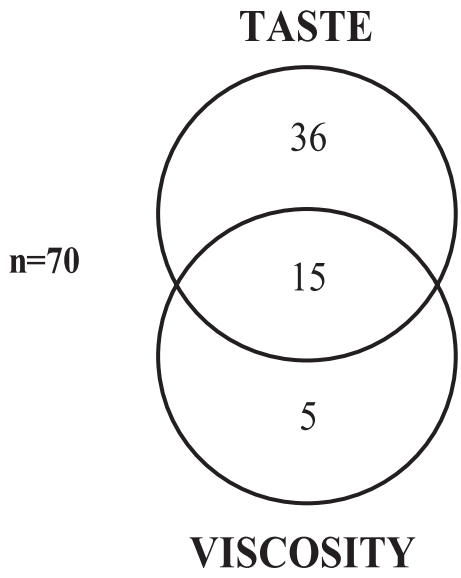

FIG. 10. Venn diagram showing numbers of neurons responsive to viscosity and/or taste stimuli in sample of 70 analyzed.

mouth, which would enable different viscosities to be identified, as shown by the tuning of the different neurons in Fig. 4, and by the multidimensional space shown in Fig. 6 and the dendrogram shown in Fig. 7.

The majority of the neurons described here as viscosity responsive responded to the oils in the same way as they did to the corresponding viscosity measured with the CMC stimulus set. Part of the interest of this is that the oils behave as Newtonian fluids; that is, their viscosity is independent of the shear rate. It is known that many food and related substances behave rheologically in a non-Newtonian way. For example, the apparent viscosity of the CMC is known to have its highest value at very low shear rates, and to decrease at higher shear rates. The value we measured using the Brookfield rheometer was at a shear rate of 12 s^{-1}. One reason that we chose this value was that for humans the relevant shear rates of foods in the mouth are estimated to be 10–50 s^{-1} (Christensen 1979; Stanley and Taylor 1993). The use of the oils in our study at least helps to anchor the neuronal data we described to a well-quantified viscosity, provided by the oils that behave as Newtonian fluids. Moreover, at least some OFC neurons respond to both oil and CMC in the same way when the viscosity is measured at a shear rate of 12 s^{-1}, providing further evidence that measurement of the viscosity of CMC at this shear rate provides values that are realistic in terms of the actual shear rates produced in the mouth (Verhagen et al. 2003b).

The perceived thickness of CMC in the mouth shows a significant ($r^2 = 0.93$; $P = 0.002$) logarithmic relationship with viscosity, with the viscosity measured with the same Brookfield viscometer type and shear rate (Theunissen and Kroeze 1995; see also Christensen 1979). Some of the neurons we recorded in the OFC (see Fig. 4, bk283, bo25, and bk252) also had an approximately linear response to the log unit–spaced CMC series, and may underlie this psychophysical result.

The fact that there are unimodal taste and unimodal viscosity-sensitive neurons indicates that these types of stimuli can be represented separately in the OFC. It also indicates that there is no necessary (i.e., complete) convergence of taste and somatosensory (viscosity-sensitive) inputs at any earlier stage of taste processing (i.e., nucleus of the solitary tract, taste thalamus, and primary taste cortex in the insula/operculum; see Rolls 1997, 1999). The separate representations of viscosity and taste provide potentially for "analytic" as contrasted with "synthetic" psychophysical performance for these modalities. The findings also provide clear evidence for convergence of taste and somatosensory inputs onto some neurons (which could be achieved anatomically in, or before, the OFC). These OFC neurons with gustatory/viscosity convergence could provide a basis for responsiveness to particular combinations of taste and viscosity inputs from the oral cavity. This may be important in allowing sensory effects, including likes and dislikes, to be produced by particular combinations of taste and viscosity inputs. Neurons that respond to particular combinations provide the capability for a process such as synaptic adaptation over a time period of 10 min of continuous stimulation while a particular food is eaten in a meal to provide a mechanism for sensory-specific satiety, in which the pleasantness of other foods not eaten in the meal would remain undiminished (see Rolls 1997, 1999, 2003). The background to this hypothesis is that neurons in the primary taste cortex do not show sensory-specific satiety, whereas one synapse away, in the OFC, neuronal responses that are related to sensory-specific satiety are typical (Rolls 2003).

The fact that the bimodal viscosity– gustatory neurons were less likely to respond to sweet taste than unimodal taste neurons (see Fig. 11) could possibly be related to dietary experience, in that the wet mash fed daily to the monkeys easily forms a viscous paste in the mouth, and is not sweet. Sensory–sensory (taste– viscosity) associative learning might thus have led to this type of convergence, and is a property of this brain region established already for olfactory to taste, and visual to taste, association learning (Rolls et al. 1996).

We note that, although human functional MRI (fMRI) results are consistent with those described here in showing for example that the OFC is strongly activated by textured whole food stimuli such as tomato juice and chocolate (Kringelbach et al. 2003), the details of the representation as described here, with both unimodal neurons, and bimodal neurons showing convergence, together with the details of the tuning to viscosity stimuli, and the separateness of the representation from gritty and capsaicin, could not be shown by fMRI studies.

Some OFC neurons (8/51 tested) had responses to capsaicin

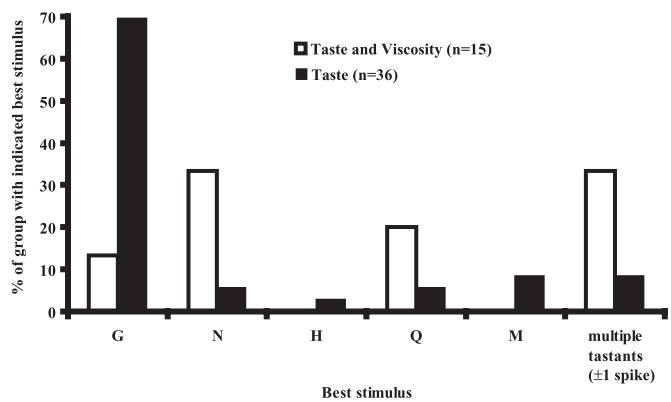

FIG. 11. Proportion of neurons with best response to each taste stimulus. Neurons are divided into 2 groups: those that responded to gustatory and viscosity series stimuli; and those that responded only to gustatory stimuli.

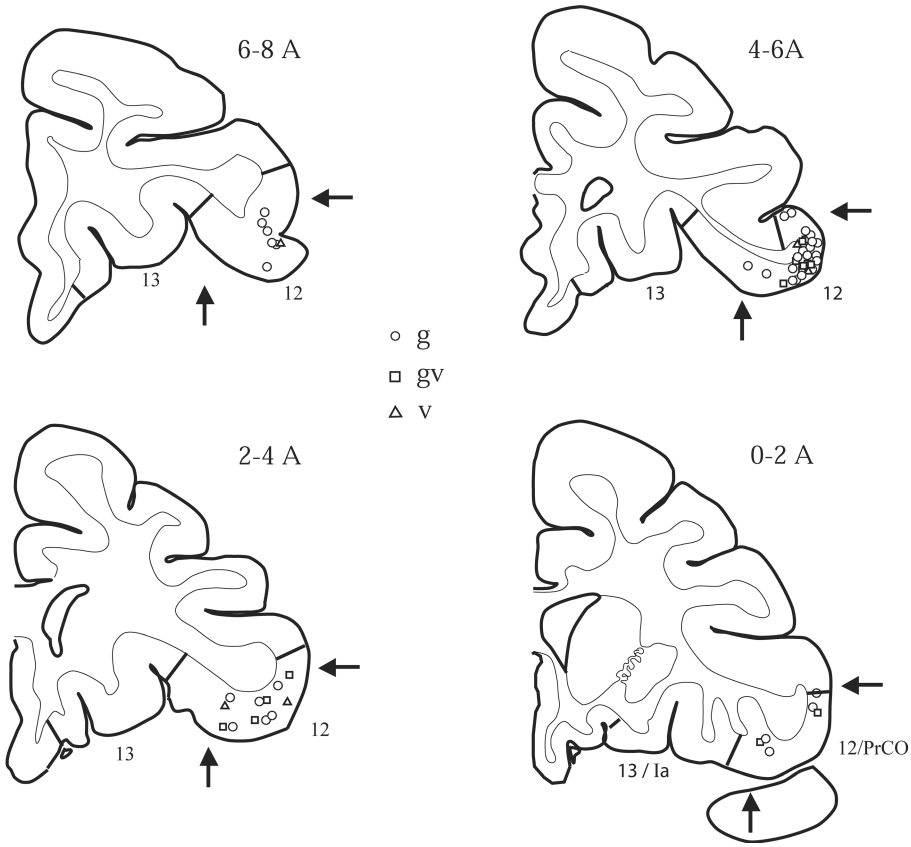

FIG. 12. Reconstructed positions of neurons in this study. Symbol with which location of each neuron is indicated shows whether neuron was tuned to g (taste), v (viscosity), or to combinations of these. Neurons were located within orbitofrontal cortical area. (For one macaque reconstructions are based on histology and X-ray data for every track, for 2nd macaque, on X-ray data for every track and a standard atlas calibrated in X-ray-coordinates.) 6-8 A shows that coronal section was taken 6–8 mm anterior to sphenoid process used as a landmark (Aggleton and Passingham 1981), and which is at approximately A-P level of optic chiasm. Architectonic boundaries as described by Carmichael and Price (1994) are indicated.

that were different from those to water. There is evidence that the pungent sensation of capsaicin is mediated by the vanilloid receptor subtype 1 (VR1). This receptor is a transient receptor potential-type protein (Caterina and Julius 2001), and mice genetically devoid of it do not show inflammation-mediated hyperalgesia (Caterina and Julius 2001). The VR1 receptor is sensitive to polymodal stimuli (mechanical, thermal, and chemical), which can cause tissue damage, and has been found in unmyelinated type C and thinly myelinated Aδ neurons of the spinal cord, in the lung, bladder, gastrointestinal tract (Nozawa et al. 2001), and oral cavity (Caterina and Julius 2001). VR1-positive neurons of the oral cavity of rat are located around taste buds, specifically in the subepithelial lamina propria in fungiform, circumvallate, and foliate taste papillae (Ishida et al. 2002). The discovery of neurons in the OFC that respond to capsaicin, and the evidence for separate encoding from other stimuli such as viscosity, grittiness, and taste, reported here, show that at a high level of the processing of oral stimuli in the brain, there is a separate representation of capsaicin from that for other oral stimuli. Interestingly, Simons et al. (2003) report a peripheral site of taste suppression by oral capsaicin, as measured in the rat nucleus of the solitary tract (NTS). Moreover, they report that 8 of 34 NTS cells responded to 330 μM oral capsaicin.

Grittiness refers to geometrical textural characteristics of particles: their size and shape. With increasing particle size the textural terms used are powdery, chalky, grainy, gritty, lumpy, and beady. Sand and pear stone cells are examples of particles that yield a gritty oral texture (Bourne 2002; p. 267). Particles are detected by the tongue, which has the most acute tactile sensibility of any part of the body, and hard palate (Bourne 2002; p. 39). Like viscosity, the presence of particles can affect food texture and food liking. For example, graininess is not liked in smooth foods so that the maximum particle size for optimal smoothness for chocolate is 13–25 μm, and for margarine fat crystals 22 μm (Bourne 2002; p. 39; Lyle 1993). Lyle (1993) showed that the perception of grittiness depends on the size, shape, and hardness of particles, in that soft and rounded polyethylene particles with a diameter of ≤80 μm were not perceived as gritty, whereas hard and sharp garnet particles were perceived as gritty above 10–20 μm (Lyle 1993). The hard, round microspheres we employed (33–194 μm) evoke an oral gritty texture quite similar to that of fine sand.

The fact that the viscosity-sensitive neurons had responses that were based on the sensory stimuli, and not on mouth movements, is consistent with all the neurophysiological evidence we have accumulated that the OFC represents sensory stimuli (including taste, olfactory, visual, and somatosensory as produced by tannic acid and fat; see Rolls 1999, 1997; Rolls and Scott 2003) rather than motor responses. This point is of particular importance in understanding the effects of damage to the OFC in humans, which leads humans to keep choosing a previously rewarded and now no longer rewarded stimulus (Rolls et al. 1994). This, it can be argued, is not likely to be a motor perseveration, but instead an inability to reverse stimulus-reinforcement association learning, in that motor responses are not represented in the OFC, but instead the stimuli needed to perform stimulus-reinforcement association learning are. Consistent with this, a reversal impairment has now been demonstrated in humans with discrete surgical lesions of the OFC performing a reversal task in which one of the 2 stimuli

must be selected on every trial, making a motor perseveration account implausible (Hornak et al. 2003a,b).

In this context, it is of interest that some of the somatosensory inputs described here could be primary (innate or unlearned) reinforcers. In particular, capsaicin, which can act through the VR1 receptor as a nociceptive stimulus (Caterina and Julius 2001), in a food may tend to make it unpalatable, although in combination with other foods in cuisine, and with learning (Rozin et al. 1986), it can become palatable. The discovery that another primary reinforcer (in addition to those included in Table 10.1 of Rolls 1999) is represented in the primate OFC extends Rolls's theory of emotion (Rolls 1999) by providing another putative primary reinforcer that genes may provide to specify the goals for actions.

Although here the reward value of the textured stimuli has not been manipulated, by for example feeding the monkey to satiety to decrease the reward value of the stimulus, and then remeasuring the neuronal response, it is rather likely that the neurons described here do play a role in representing the reward/punishment value of different textures. This point is based on the findings that feeding to satiety decreases the responses of OFC neurons to taste (Rolls et al. 1989), olfactory and visual (Rolls et al. 1996), and fat (Rolls et al. 1999) inputs. Consistent with this, at the human neuroimaging level, there is evidence that the pleasantness of olfactory (O'Doherty et al. 2000; Rolls et al. 2003b) and whole food stimuli (Kringelbach et al. 2003), and of the taste of water (De Araujo et al. 2003), is represented in the OFC.

In conclusion, the data presented here show that OFC neurons can be specifically tuned to 3 new types of somatosensory stimulus: oral viscosity, grittiness, and capsaicin. These are in addition to separate somatosensory inputs described previously that allow fat (Rolls et al. 1999; Verhagen et al. 2003b) and astringency (Critchley and Rolls 1996b) to be represented independently of the 3 somatosensory information channels described here. In addition to these separate representations provided by some neurons, other neurons respond to combinations of viscosity and/or taste and/or gritty and/or capsaicin and/or fat inputs (see above and Verhagen et al. 2003b), thereby providing a rich representation of the sensory properties of food in the mouth, in which particular combinations of the above properties can be represented separately from the components. This allows for subjective and behavioral responses that can be based on particular combinations of these inputs, providing for great sensory capability in choosing and learning about particular complex foods, and in extending the flavor space. This provides the required computational basis both for sensory-specific satiety (which can then be computed by making it a property of the combination-sensitive neurons in the OFC that they habituate over the course of a meal); and for learning associations between the complex sensory properties of a food and its nutritional consequences with the property that the associations do not overgeneralize to other similar foods or the components from which the food complex is formed (see Rolls 1999; Rolls and Deco 2002; Rolls et al. 1989).

DISCLOSURES

This research was supported by Medical Research Council Grant PG9826105 to E. T. Rolls.

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