Chem. Senses 30 (suppl 1): i78–i79, 2005 doi:10.1093/chemse/bjh122

Possible Changes in Information from the Primary to Higher-order Gustatory Cortices, Studied by Recording Neural Activities during a Taste Discrimination GO/NOGO Task in Monkeys

Hisashi Ogawa, Hirotoshi Ifuku, Tamio Nakamura and Shinichi Hirata

Department of Sensory and Cognitive Physiology, Faculty of Medical and Pharmaceutical Sciences, Kumamoto University, Kumamoto, Japan

Correspondence to be sent to: H. Ogawa, e-mail: sense@gpo.kumamoto-u.ac.jp

Key words: cortical taste neurons, area 3, area G, orbitofrontal cortex, PrCO, event-related activity

Introduction

Several gustatory cortices have been identified in the macaque monkey: the primary gustatory cortices (PGC: areas G, 3 and 1–2) and the higher-order gustatory cortices (HGC), including the precentral operculum (PrCO), orbitofrontal operculum (OFO), insula and orbitofrontal cortex (OFC; area 12). So far, several studies have investigated the response characteristics of taste neurons in the PGC and HGC (Ogawa, 1994; Rolls, 1989; Scott and Plata-Salaman, 1999), and HGC taste neurons are characterized by convergence of various sensory inputs and effects of sensory satiety on taste-responsive neurons in the HGC (Rolls and Scott, 2003). However, it is still a challenge to study differences in coding of taste information between the two areas. During the last decade, we developed a salt-water discrimination GO/NOGO task for monkeys and investigated neural activities in the PGC and HGC to NaCl and water in the cue phase, and sucrose in the reward phase during the task to clarify different coding mechanism of taste perception between the PGC and HGC. We review our recent work in this article.

Salt-water discrimination GO/NOGO task

We used two versions of the GO/NOGO task: a reaction time task and a delayed task with reversal. We used a total of five Japanese monkeys (*Macaca fuscata*). All animal care and use procedures were approved by the Animal Care and Use Committee in our Institute, and were in accordance with the 'Guide for the Care and Use of Laboratory Animal' (National Institutes of Health, USA, 1996). Four of the monkeys were trained to perform a reaction time version of the salt-water discrimination GO/NOGO task. When monkeys received 0.5 ml of NaCl solutions (0.003–0.1 M) (GO cue; GO task), they were asked to press a lever within 2 s to get 0.5 ml of 0.3 M sucrose as reward (GO response). But to obtain reward they had to refrain from pressing when they received 0.5 ml water (NOGO cue; NOGO task). One monkey was trained to perform a delayed version of the task in which he had to perform GO responses only after a LED lighted, some delay after the GO cue (0.1 M NaCl). After 90 % correct responses were reached, trephine holes were opened over the PGC and HGC and recording chambers installed over the hole under sterile conditions during the surgical level of anesthesia initiated and maintained with Ketamine. After the recovery from anesthesia, neuronal discharges were recorded from the PGC or HGC with enamel-coated tungsten or glass-coated elgiloy electrode during the task. After the termination of recordings, the brain was perfused with 10% neutral formalin through the heart for histological reconstruction of the recording sites.

Task control including infiltration of cue and reward stimuli to the mouth of monkeys as well as data logging and analysis were performed with LabVIEW based software on an IBM compatible computer.

Responses to cues

The reaction-time version

The fraction of correct GO responses increased, and the reaction time shortened, depending on NaCl concentration with that for 0.003 M NaCl at a chance level, which indicated monkeys behaved depending on the taste of NaCl. However, neuronal activities to GO cues in the PGC or HGC rarely increased response magnitude or shortened onset latency depending on NaCl concentration (Ito *et al.*, 2001), which is consistent with previous results on monkeys not engaged in any task (Scott *et al.*, 1991). It is suggested that concentration-dependent onset latency of discharges, corresponding to reaction time, are not generated up to the orbitofrontal cortex, and that such discharges may be generated in later stages of generation of motor command for behavioral responses.

The onset latency of neuronal responses was shorter in the regions on the exposed surface of the cortex (area 3 or the PrCO) than in those buried in the sylvian sulcus (area G, insula, area 1–2, OFO) or on the orbitofrontal cortex notwithstanding that they were recorded from the PGC or HGC (Ito *et al.*, 2001). Since efferent projections from area 3 and the PrCO have not been studied, it is not known how they process taste information.

On the other hand, in incorrect trials in which monkeys pressed a lever in response to the NOGO cue, some neurons in the HGC yielded discharges in response to NOGO cues in a way similar to GO responses, suggesting that they represented subsequent GO behavior but not salt taste (Ifuku *et al.*, 2002a).

The delayed version

We systematically reversed the relation between cues and behavioral responses to see where neurons representing subsequent behavior exist. We found four groups of neuronal activities, relating to task reversal (Ifuku *et al.*, 2003). Group I neurons did not change discharge patterns to NaCl or water irrespective of task reversal, probably representing the physicochemical nature (or taste quality) of cues. On the other hand, Group III neurons changed those to NaCl or water but maintained those to GO or NOGO cues, probably representing the subsequent behavioral response. Group II neurons showed discharge patterns intermediate between Groups I and III. Group III contained three subgroups with characteristic response features: Group IIIa neurons yielding phasic discharges after cues, Group IIIb neurons producing tonic discharges lasting up to the LED onset probably carrying memory (Fuster, 1997) and Group IIIc neurons giving rise to phasic discharges twice, first after the cues and second before onset of the LED or lever pressing. Group IV neurons showed transient discharges to any cues irrespective of task reversal, related to attention to the onset of cues, probably caused by contact of cues with the mouth.

Almost all neurons in areas 3 and G, comprising the PGC, showed Group I activity, indicating the involvement in coding the physico-chemical nature of the cues, i.e. they are taste neurons. Area 3 in the precentral region was proved to contain taste neurons. The PrCO contained equal numbers of Group I, III and IV neurons, and area 12 contained mainly Group III neurons. Thus, the HGC is probably involved in higher stages of gustatory processing, e.g. perception of information carried by taste cues, memory, motor-set or motor activity itself for subsequent behavioral response.

Responses to sucrose in reward

In either version of the saltwater GO/NOGO task, we delivered sucrose in the reward phase when animals behaved correctly. We also analyzed neuronal activities to sucrose in the task. Neurons responded to sucrose alone or to sucrose as well as gustatory cues (NaCl and/or water). Either type of sucrose responses showed similar temporal patterns. However, the onset latency of sucrose responses was significantly shorter in the PrCO than in other regions.

After the task was reversed in the delayed version, incorrect responses ensued for several trials in which sucrose was not delivered. Many neurons responsive to sucrose in reward phase (C-type) did not yield discharges in response to sucrose missing, but several did. The latter neurons (C-I-type) fired discharges during the reward phase irrespective of sucrose-delivery discharges on both correct and incorrect trials (Ifuku *et al.*, 2002b). Such C-I-type neurons probably respond to reward, by firing discharges in advance in response to possible delivery. Onset latency was shorter and response magnitude was smaller on incorrect trials than on correct trials. The actual delivery of sucrose might facilitate reward responses. This type of reward-neurons has not been reported yet. A few neurons (I-type) produced discharges only when sucrose was missing. The I-type neurons probably correspond to neurons receiving error signals from the midbrain (Schultz, 2000) or orbitofrontal cortex (Thorpe *et al.*, 1983). A few expectation-type neurons were found in the PrCO, and, at incorrect trials, they continued discharges several hundred milliseconds after the possible time point of sucrose delivery, as suggested by other investigators (Hikosaka *et al.*, 1989). Most PGC neurons were of C type, whereas several HGC neurons, often in area 12, were of C-I-type and some PGC and HGC neurons signaled errors.

Thus, even in reward phase, the PGC probably processes pure gustatory information of reward solution, whereas the HGC may be involved in perception of reward (Rolls, 1989; Rolls and Scott, 2003).

Conclusions

To clarify coding mechanisms in the primary and higher-order gustatory cortices in monkeys, we examined responses to cues and rewarding substances during a reaction time or delayed version of a salt-water discrimination GO/NOGO task. Almost all PGC neurons responded to the physico-chemical nature of cues (purely taste neurons), whereas some HGC neurons represented subsequent behavioral actions or memory for motor action (behavioral context of taste stimulus). On the other hand, most PGC neurons were sucrose-sensitive, responding to sucrose delivered in the reward phase at correct trials, but several HGC neurons, OFC neurons in particular, increased discharges in the reward phase irrespective of sucrose-delivery, probably yielding perspective reward responses, another form of behavioral context of reward phase.

It is clearly indicated that the PCG deals with the gustatory nature of cues and reward, whereas the HGC deals with the behavioral context of them in addition to the gustatory nature.

References

Fuster, J.M. (1997) The Prefrontal Cortex. Anatomy, Physiology, and Neuropsychology of the Frontal Lobe, 3rd edn. Lippincott-Raven, Philadelphia, PA.

Hikosaka, O., Sakamoto, M. and **Usui, S.** (1989) *Functional properties of monkey caudate neurons. III. Activities related to target and reward.* J. Neurophysiol., 61, 814–832.

Ifuku, H., Ohgushi, M., Ito, S. and **Ogawa, H.** (2002a) Neurons *associated with behavioral context errors in the primary and higher-order gustatory cortices in the monkey.* Neurosci. Lett., 319, 121–123.

Ifuku, H., Hirata, S., Nakamura, T. and **Ogawa, H.** (2002b) *Reward-related neurons in the primate fronto-opercular and orbitofrontal cortices recorded during a taste discrimination GO/NOGO task and its reversal.* Jpn. J. Physiol., 52 (suppl.), s170.

Ifuku, H., Hirata, S., Nakamura, T. and **Ogawa, H.** (2003) Neuron*al activities in the monkey primary and higher-order gustatory cortices during a taste discrimination delayed GO/NOGO task and after reversal.* Neurosci. Res., 47, 161–175.

Ito, S., Ohgushi, M., Ifuku, H. and **Ogawa, H.** (2001) Neuron*al activity in the monkey fronto-opercular and adjacent insular/prefrontal cortices during a taste discrimination G0/NOGO task: response to cues.* Neurosci. Res., 41, 257–266.

Ogawa, H. (1994) *Gustatory cortex of primates: anatomy and physiology.* Neurosci. Res., 20, 1–13.

Rolls, E.T. (1989) *Information processing in the taste system of primates.* J. Exp. Biol., 146, 141–164.

Rolls, E.T. and **Scott, T.R.** (2003) *Central taste anatomy and neurophysiology*. In Doty, R.L. (ed.), Handbook of Olfaction and Gustation, 2nd edn. Dekker, New York, pp. 679–705.

Schultz, W. (2000) *Reward processing in primate orbitofrontal cortex and basal ganglia.* Cereb. Cortex, 10, 272–283.

Scott, T.R. and **Plata-Salaman, C.R.** (1999) *Taste in the monkey cortex.* Physiol. Behav., 67, 489–511.

Scott, T.R., Plata-Salaman, C.R., Smith, V.L. and **Giza, B.K.** (1991) *Gustatory neural coding in the monkey cortex: stimulus intensity*. J. Neurophysiol., 65, 76–86.

Thorpe, S.J., Rolls, E.T. and **Maddison, S.** (1983) *The orbitofrontal cortex: neuronal activity in the behaving monkey*. Exp. Brain Res., 49, 93–115.