*Proc. Natl. Acad. Sci. USA*
Vol. 93, pp. 10533–10537, September 1996
Psychology

# Mnemonic neuronal activity in somatosensory cortex

**(active short-term memory/monkey/single units)**

YONG-DI ZHOU* AND JOAQUÍN M. FUSTER

Department of Psychiatry and Brain Research Institute, School of Medicine, University of California, Los Angeles, CA 90024

*Communicated by Larry R. Squire, University of California at San Diego, San Diego, CA, July 8, 1996 (received for review April 23, 1996)*

ABSTRACT **Single-unit activity was recorded from the hand areas of the somatosensory cortex of monkeys trained to perform a haptic delayed matching to sample task with objects of identical dimensions but different surface features. During the memory retention period of the task (delay), many units showed sustained firing frequency change, either excitation or inhibition. In some cases, firing during that period was significantly higher after one sample object than after another. These observations indicate the participation of somatosensory neurons not only in the perception but in the short-term memory of tactile stimuli. Neurons most directly implicated in tactile memory are (*i*) those with object-selective delay activity, (*ii*) those with nondifferential delay activity but without activity related to preparation for movement, and (*iii*) those with delay activity in the haptic-haptic delayed matching task but no such activity in a control visuo-haptic delayed matching task. The results indicate that cells in early stages of cortical somatosensory processing participate in haptic short-term memory.**

For more than two decades it has been known that certain neurons in the association cortex of the primate undergo sustained activation while the animal is memorizing an item of sensory information for the execution of a behavioral action in the near term (1). These so-called memory cells were first discovered in prefrontal cortex (2–5), where they appear to be part of neuronal networks that encode a large variety of sensory memoranda associated with impending action. Visual memory cells have been found in inferotemporal association cortex (6–8), and tactile memory cells have been found in parietal association cortex (9). Whereas thus far memory cells have been reported almost exclusively in association cortex, there are indications that they may be found also in somatosensory (9) and visual (10) cortex. Their presence in these cortices may reflect the role of short-term memory in sensory perception, including haptics—that is, the perception by active touch (11). The recognition of an object by palpation requires the integration of temporally separate tactile impressions, which in turn presumably requires some degree of short-term memory already at early stages of the somatic sensory system. The present study explores the somatosensory cortex for evidence of haptic memory cells in monkeys performing a tactile working memory task. The results reveal a substantial proportion of such cells in hand representation areas.

## METHODS

Three adult, male rhesus monkeys (*Macaca mulatta*), weighing 8–10 kg, were the subjects of this research. The monkeys were individually housed and fed an *ad libitum* diet of chow and, periodically, some fruit. Intake of fluid was restricted before experimental sessions. In the course of several months, the animals were trained to perform the haptic delayed matching to sample task described below. After training, microelectrode recording devices were surgically implanted (Nembutal anesthesia) over parietal cortex bilaterally.

The trained experimental animal performed the task in a sound-attenuated chamber with its head fixed, sitting in a primate chair, and facing a vertical panel with an opening at about waist level that provided manual access to the test objects on the other side of the panel (Fig. 1*A*). The opening was closed by a sliding curtain except for object manipulation at the beginning and at the end of a trial. Between trials, the animal had to rest the operating hand on a rounded metal ledge (handrest) and sit quietly in the chair. The other hand was always restrained from access to the test objects by a plate attached to one side of the primate chair. The test objects were two pairs of vertical cylindrical rods of identical dimensions (axis 150 mm, diameter 19 mm) but different surface features (Fig. 1*B*). One pair of rods differed in the direction of parallel ridges (6 mm apart) on their surface: one rod had the ridges along the axis of the cylinder (vertical edges) and the other around its circumference (horizontal edges). The other pair of rods differed in surface texture: one was smooth and the other rough. A trial began with a click signaling the opening of the curtain and the manual access to the sample object in the center of the field beyond the opening (Fig. 1*C*). About 1.5 sec after the click, the animal moved his operating hand away from the handrest to reach out through the opening and grasp the rod's girth, thus feeling its surface; contact with the rod lasted approximately 1–1.5 sec (all contacts of the hand with handrest and objects were electronically monitored, see below). With the return of the hand to its rest, the curtain closed. A delay of 14 sec ensued, during which the sample rod remained out of reach and the hand on the handrest (20-sec delays were used during the recording of some cells). At the end of the delay, a second auditory signal marked the reopening of the curtain and the accessibility of two rods side by side, one of them the sample. The animal then again extended the hand away from the handrest to palpate the two rods and to choose the sample among them. By pulling it slightly, thus signaling a correct match, the animal secured automatic delivery of liquid reinforcement through a spigot to his mouth. Incorrect choice terminated the trial without reward. The sample rod and its relative position at the time of choice changed at random between trials, insuring that the animal did not use spatial clues to perform the task. Electronic switches and sensors registered all trial events, including hand contacts with the objects and with the handrest. During either the pretrial—baseline—period or the intratrial delay, the operating hand had to keep a good contact with the handrest. The removal of the operating hand from the handrest broke an extremely low current (<50 nA) electronic circuit and aborted a trial automatically. Hand rest and hand movements during palpation of the test objects were also monitored by video cameras. With them, the animal's manipulation of the objects could be monitored. A displacement-sensitive transducer was attached to the spring-suspended seat of the animal. The signal from this transducer

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

*e-mail: ydzhou@ucla.edu.

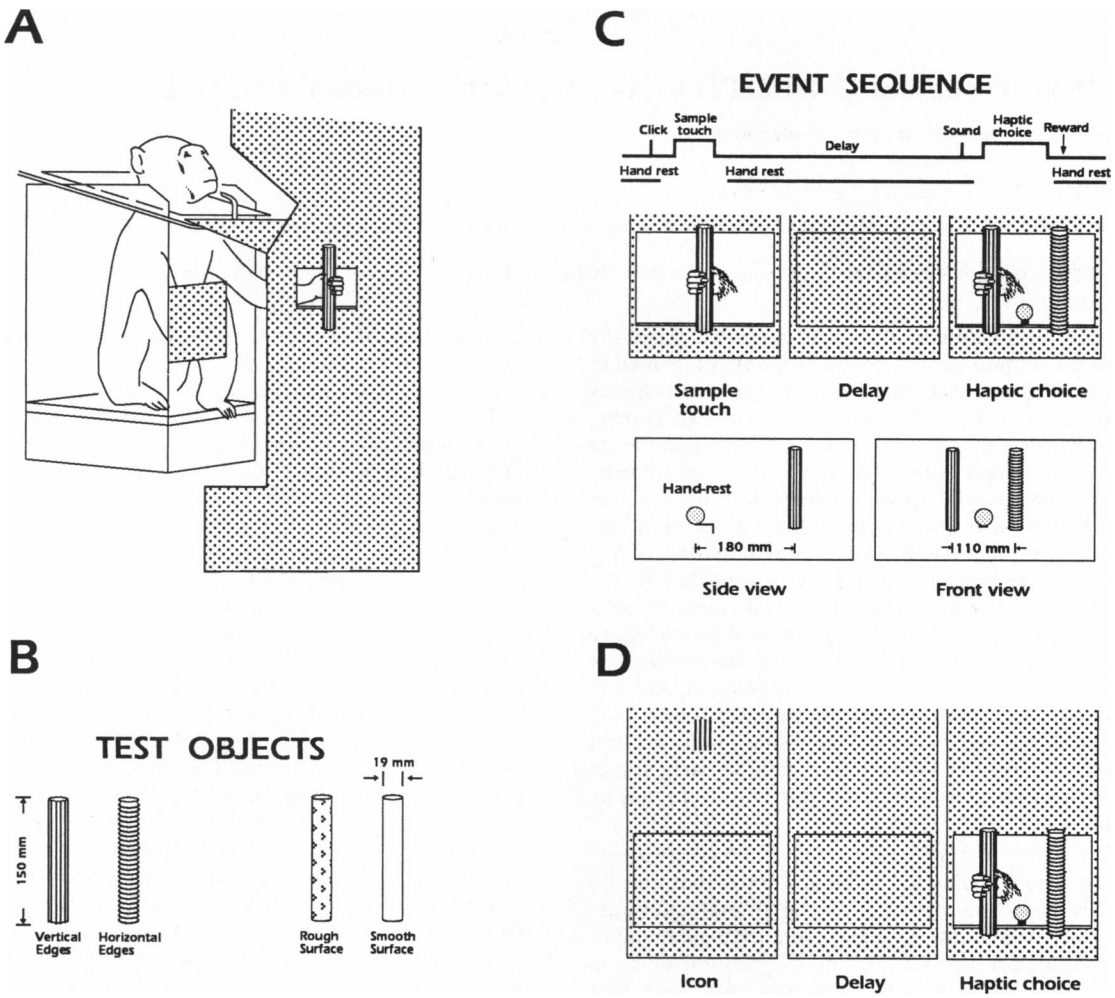


FIG. 1. (*A*) A simplified drawing of the test apparatus. The monkey palpates the sample object. (*B*) Two pairs of objects used in the experiments. The objects of one pair differ in the direction of edges (6 mm apart, vertical versus horizontal) on their surface; those of the other differ in surface texture (smooth versus rough). (*C*) Schematic diagram of events in a trial of the haptic memory task. Two insets below depict the relative positions of the objects and handrest. (*D*) Visuo-haptic variant of the task in *C*. Instead of tactile sample, a visual icon was presented on a small screen: a pattern of vertical or horizontal parallel stripes. The correct choice, at the end of the delay, was the pull on the rod with the same direction of edges as the stripes on the icon.

was graphically displayed and digitally recorded. This record was used for control of all body movements during a session. The fully trained animal performed the task with precise, stereotypical, and economical movements of almost constant duration from one trial to the next, while the test rods were at all times out of sight. Thus the task was a test of short-term memory of the objects' surface features as perceived exclusively by touch.

A cross-modal (visuo-haptic) delayed matching to sample task was also used for some cells as a control task (Fig. 1*D*). This task is similar to the one used by Maunsell *et al.* (12) in a study of V4 cells. Our test is identical to the haptic-haptic task except as follows. Here, instead of the sample object, the monkey is presented with a visual icon (for 3 sec) on a small screen at eye level: a black and white pattern of vertical or horizontal parallel stripes symbolizing the direction of edges in the rod to be chosen haptically at the end of the delay. The icon and the position of its corresponding rod at the choice are changed in random order from trial to trial.

All units were recorded extracellularly. The discharge of any given cell was recorded through a series of haptic-haptic trials with one pair of test objects or—in less than 15% of the cells—with both pairs. Some units were also recorded during the visuo-haptic task. After recording a unit, the attempt was made to identify as precisely as possible its receptive field on the hand of the animal. The changes in the cell's discharge during performance with one pair of objects, as well as the object-related differences in that discharge, were statistically evaluated using a Student's *t*-test for correlated means ($P < 0.05$); intertrial discharge variance served as the error term. Whenever the two pairs of objects were tested, the Bonferroni adjustment was applied.

After the completion of the recording experiments, small electrolytic lesions were made in the cortex and underlying white matter at several locations. These microlesions were used as reference marks for later histological localization of the units recorded in the experiments.

## RESULTS

Five hundred and three neurons were recorded from the hand representation areas of anterior parietal cortex (Brodmann's

Table 1. Unit delay activity in hand areas

| Area | 3a ($n$ = 214) | 3b ($n$ = 49) | 1 ($n$ = 42) | 2 ($n$ = 198) | All ($n$ = 503) |
|---|---|---|---|---|---|
| Excited | 60 (28) | 20 (41) | 15 (36) | 40 (20) | 135 (27) |
| Inhibited | 23 (11) | 7 (14) | 8 (19) | 37 (19) | 75 (15) |
| Unchanged | 131 (61) | 22 (45) | 19 (45) | 121 (61) | 293 (58) |

Percentages in parentheses.

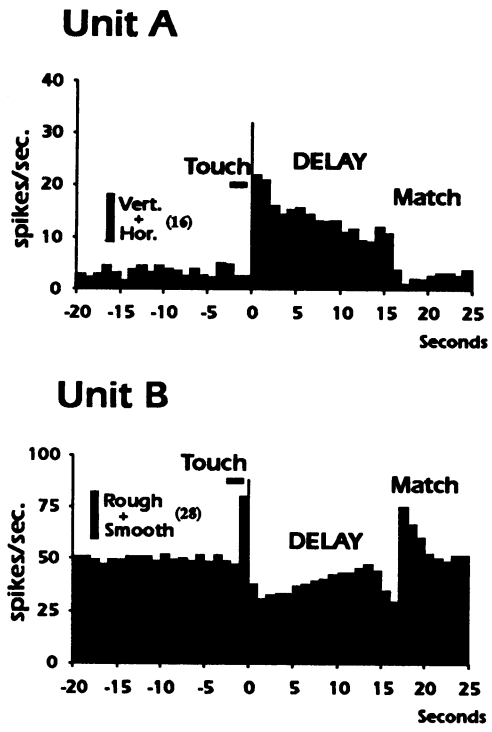


FIG. 2. Average frequency histograms (binsize, 1 sec) from two nondifferential delay-reacting units in area 2 (time-locking event—at 0—is the return of the hand to the handrest after the sample stimulus). The histogram for each unit represents the average of records from *all* trials with one pair of rods (trial number in parentheses). Unit A, tested with edged rods, shows elevated, gradually descending, discharge during the delay period. Note rapid return to baseline firing after the match. Unit B, tested with different textures, is excited by touch but strongly inhibited throughout the delay. There is no inhibition following the match.

areas 3a, 3b, 1, and 2) while the fully trained animals performed the task. As expected, many cells showed excitatory or inhibitory reactions temporally related to hand projection and/or the touch of the test objects. Some of the touch reactions differed depending on the sample object.

Judging from eye-movement, hand-movement, and body-movement records, no clear evidence was found to indicate that the animal adopted any given posture or performed any given movement as a device to retain information during the delay period that followed presentation of the sample. About 42% of all the cells (Table 1) showed changes in firing frequency through all or much of that delay period; their discharge was persistently higher or lower than intertrial baseline (Fig. 2). The time course of elevated delay discharge varied considerably from cell to cell. In some cells, firing frequency reached a peak at or immediately after the sample, gradually diminishing thereafter in the course of the delay (Fig. 2, Unit A). Ten percent (21 cells) of the delay-reacting cells showed differential delay activity (11 cells, $P < 0.05$; 10 cells, $P < 0.01$) that depended on which sample object had been palpated during the sample period (Fig. 3). In other words, during the delay, the firing frequency of these differential delay cells was higher after one sample object than after another. The object-differential delay discharge of five out of the 21 delay-differential cells was preceded by also object-differential reactions at the sample (Fig. 3, Unit B). The delay-selective discharge was not necessarily the continuation of the sample-selective reaction (Fig. 3, Unit B). About one half of the delay-excited or -inhibited units showed similar excitatory or inhibitory firing changes during the premovement period (about 1.5 sec) before reaching for the sample, that is, the period between the click (the start of a trial) and the hand-off (the start of the hand movement toward the sample object). Premovement activity change, either excitation or inhibition (Fig. 4 *Top* and *Middle*), tended to increase in anticipation of the hand movement. The other half of delay-

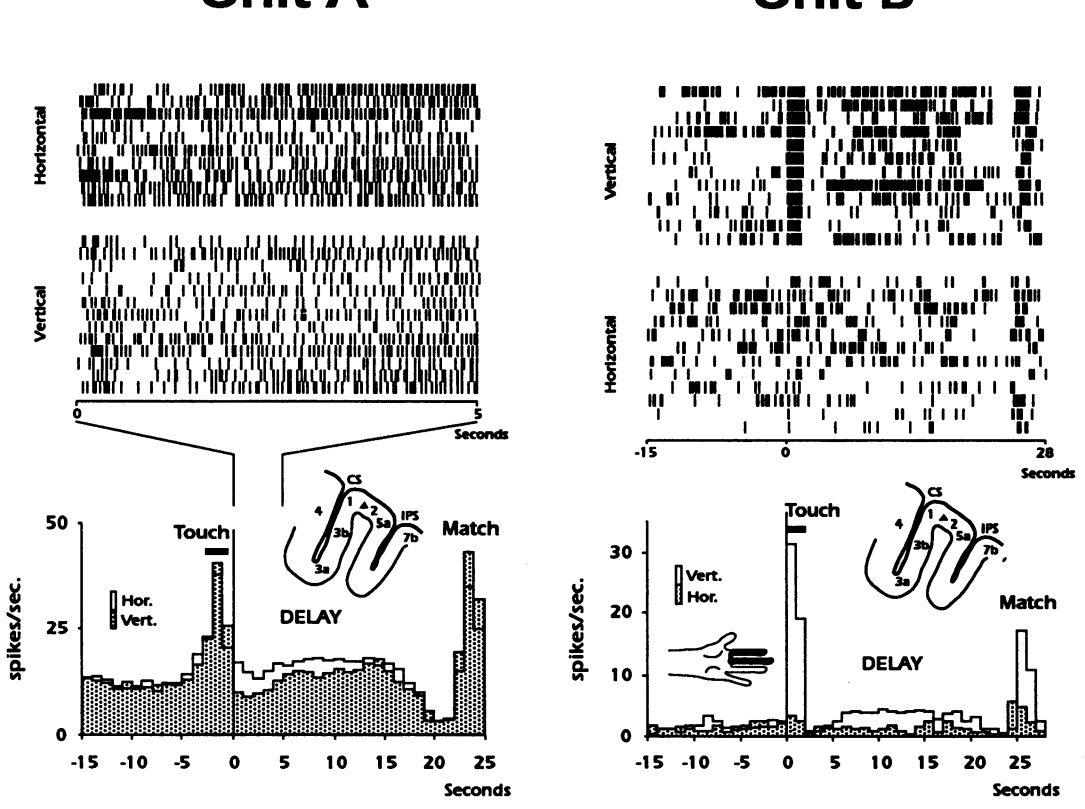


FIG. 3. Rasters and average frequency histograms (binsize, 1 sec) from two units, their location marked by a triangle in brain section diagrams. Two superimposed histograms, one for each sample object, average the discharge of each unit. (The time-locking event for the histograms of unit A is the return of the hand to the handrest and, for unit B, the first contact with the sample stimulus.) In unit A, delay activity favors the horizontal edges (raster for first 5 sec of delay). In unit B (receptive field indicated—in black—in a diagram of the monkey's hand), the unit is activated differentially by touch and retention of the vertical edges; note the absence of differential activity in the first 3 sec of the delay.

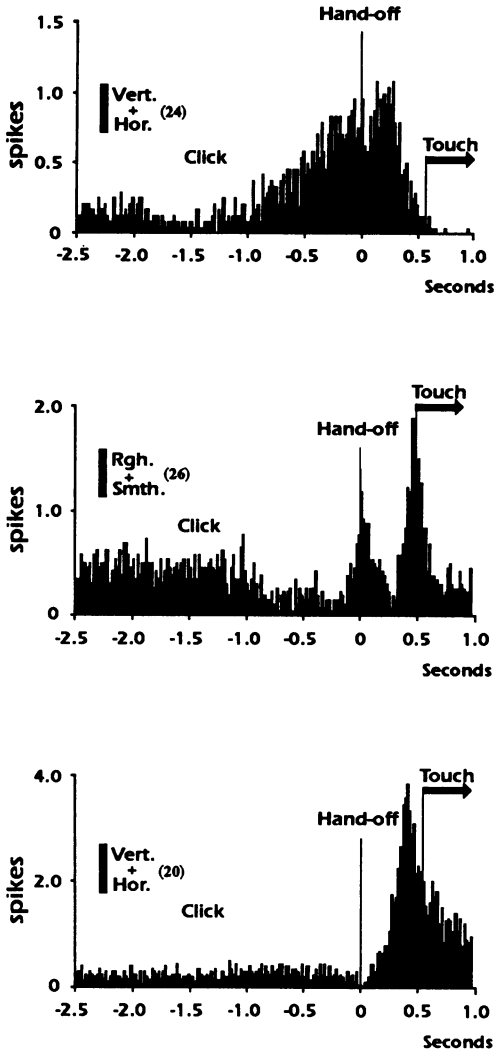


FIG. 4. Average spike-frequency histograms (binsize, 20 msec) from three cells showing their activity during the time span between the click and the hand movement for sample touch. (The time-locking event is hand-off, when the animal's operating hand breaks contact with the handrest.) The upper cell shows accelerating premovement activity beginning about 1 sec prior to the hand movement (hand-off). The cell in the middle shows decreasing premovement activity. The cell below shows no premovement activity.

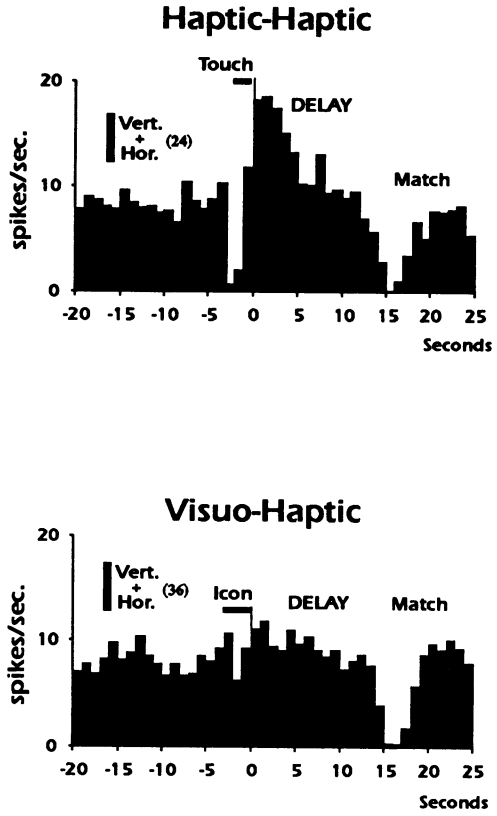


FIG. 5. Average frequency histograms (binsize, 1 sec) from a unit in area 3a during performance of the haptic-to-haptic task (above, all trials with both objects, number in parenthesis) and the visual-to-haptic task (below, all trials with both icons, number in parenthesis). The time-locking event for the histogram above is the return of the hand to the handrest and, for the histogram below, the end of the visual stimulus (icon). In the first task, the cell is inhibited during haptic sampling and choice (match) and is strongly excited during the intervening delay. In the second task, the cell is also inhibited at the haptic choice, but shows no clear change during the delay. Note, in both cases, rapid return to baseline firing after the match.

modulated units did not show premovement activity changes (Fig. 2).

Thirty cells were recorded in both the haptic-haptic and the visuo-haptic (cross-modal) task. The levels of the monkey's behavioral performance on the two tasks were comparable. Fourteen out of the 30 cells showed prominent nondifferential delay activity in the haptic-haptic task, but not in the visuo-haptic task (Fig. 5). Two other cells showed similar delay activity in both tasks. Two others reacted differentially in the delay of the haptic-haptic task but not the visuo-haptic task. The remaining 12 cells showed no delay activity either in the haptic-haptic or the visuo-haptic task.

## DISCUSSION

The principal finding of this research is the presence in anterior parietal cortex of cells that undergo sustained changes of firing frequency during the delay period of a tactile memory task. These changes are reminiscent of those previously observed in association cortex during retention of visual or tactile stimuli (2–9). Although the areas explored in this study are structurally and functionally different (13–15), the interareal differences observed in the incidence of memory-related cells may be due to uneven or insufficient sampling. Further work is needed to clarify this issue.

Both the delay-activated and delay-inhibited cells encountered here are probably involved in the retention of tactile information for the short term. However, even though they constitute a minority, the cells most clearly involved in this process are those that, during the delay, are selectively activated by one of the sample objects. It is unlikely that the delay-differential discharge of these cells is due to factors other than the active memory of the object. For example, since the task was nonspatial (the position of the correct choice was randomly assigned in each trial and could not be predicted by the animal), delay discharge could not be attributed to spatial location. The relatively low number of object-selective "memory cells," even though higher than chance level, is most likely due to the restricted sample of object-stimuli used in the task. Probably most cells were simply not tested with their optimal stimuli.

Cells that were nondifferentially activated or inhibited during the delay cannot be excluded from the memory process. Such cells may participate in the retention of tactile features that were common to both objects (e.g., shape, size). Other factors, such as arousal or preparation for motor response, can be ruled out in at least some of these cells. Briefly, the reasons for inferring that nondifferential delay reaction reflects mem-

ory, and not those factors, lie in the results of using two control procedures: (*i*) the visuo-haptic task, and (*ii*) the analysis of correlation between premovement activity and delay activity.

The visuo-haptic task was identical to the main, haptic-haptic, task with regard to requirements of attention during the delay and motor response at the end of it; yet, one half of the cells tested in both tasks showed either excitation or inhibition during the delay in the haptic-haptic task but not in the visuo-haptic one. Thus, both arousal and motor set can be excluded as significant factors in determining delay activity.

Premovement activity of somatosensory neurons may be related to preparation for movement (16–22). In the present study, the animal was trained not to move the hand away from the handrest for about 1.5 sec after the click that started the trial (see *Methods*). Therefore, if the delay activity of a cell were due to the preparation for movement, similar activity should be expected during the premovement period before the sample. However, one half of the delay-reacting cells did not show premovement activity.

The evidence that cells in somatosensory cortex are involved in haptic short-term memory contradicts the general notion that sensory cortex is exclusively devoted to the analysis of sensory features. In this respect, present data are in accord with recent work suggesting that the primary visual cortex may play a role in cognitive function (23–25). There is mounting evidence that the somatosensory cortex is susceptible to functional plasticity (26–29) and is involved in higher cognitive functions related to haptic perception (30). The short-term retention of the tactile features of an object in the context of a haptic memory task is a cognitive operation contingent on the prior learning of the task, and thus on plastic neural changes at the time of learning. Our data do not address those changes but indicate that, in the fully trained monkey, certain cells—which presumably underwent those changes with the learning of the task—are protractedly activated during the temporary retention of tactile stimuli, the task's memoranda.

The mechanisms of active short-term memory are unknown but appear to depend on the reentry of impulses through reverberating circuits in sensory or associative cortex (1, 31). In the case of haptic memory, those circuits may not only involve parietal—notably somatosensory—neurons but also, through long connective loops, neurons in the cortex of the frontal lobe. When active memory serves the temporal integration of behavior and the mediation of cross-temporal contingencies, as is the case in haptic memory tasks, those loops most likely involve the dorsolateral prefrontal cortex (32–35).

We thank William Bergerson and Bradford A. Lubell for technical assistance. This work was supported by National Science Foundation Grant IBN-9308905 and National Institute of Mental Health Grants MH-25082 and MH-51697 to J.M.F.

1. Fuster, J. M. (1995) *Memory in the Cerebral Cortex* (MIT Press, Cambridge, MA), pp. 237–281.
2. Fuster, J. M. & Alexander, G. E. (1971) *Science* **173,** 652–654.
3. Fuster, J. M. (1973) *J. Neurophysiol.* **36,** 61–78.
4. Niki, H. (1974) *Brain Res.* **70,** 346–349.
5. Funahashi, S., Bruce, C. J. & Goldman-Rakic, P. S. (1989) *J. Neurophysiol.* **61,** 331–349.
6. Fuster, J. M. & Jervey, J. P. (1981) *Science* **212,** 952–955.
7. Fuster, J. M. & Jervey, J. P. (1982) *J. Neurosci.* **2,** 361–375.
8. Miyashita, Y. & Chang, H. S. (1988) *Nature (London)* **331,** 68–70.
9. Koch, K. W. & Fuster, J. M. (1989) *Exp. Brain Res.* **76,** 292–306.
10. Fuster, J. M. (1990) *J. Neurophysiol.* **64,** 681–697.
11. Gibson, J. J. (1966) *The Senses Considered as Perceptural Systems* (Houghton Mifflin, Boston), pp. 97–135.
12. Maunsell, J. H., Sclar, G., Nealey, T. A. & DePriest, D. D. (1991) *Visual Neurosci.* **7,** 561–573.
13. Kaas, J. H. (1983) *Physiol. Rev.* **63,** 206–231.
14. Kaas, J. H. & Pons, T. P. (1988) in *Comparative Primate Biology, Vol. 4: Neurosciences,* ed. Steklis, H. P. (Alan R. Liss, New York), pp. 421–468.
15. Kaas, J. H. (1995) *Brain Behav. Evol.* **46,** 187–196.
16. Miles, F. A. & Evarts, E. V. (1979) *Annu. Rev. Psychol.* **30,** 327–362.
17. Matthews, P. B. C. (1988) *Can. J. Physiol. Pharmacol.* **66,** 430–438.
18. Nelson, R. J. (1988) *Brain Res. Bull.* **21,** 411–424.
19. Nelson, R. J. & Douglas, V. D. (1989) *Brain Res.* **484,** 43–56.
20. Jiang, W., Chapman, C. E. & Lamarre, Y. (1991) *Exp. Brain Res.* **84,** 342–354.
21. Nelson, R. J., Smith, B. N. & Douglas, V. D. (1991) *Exp. Brain Res.* **84,** 75–90.
22. Lebedev, M. A., Denton, J. M. & Nelson, R. J. (1994) *J. Neurophysiol.* **72,** 1654–1673.
23. Kosslyn, S. M., Alpert, N. M., Thompson, W. L., Maljkovic, V., Weise, S. B., Chabris, C. F., Hamilton, S. E., Rauch, S. L. & Buonanno, F. S. (1993) *J. Cogn. Neurosci.* **5,** 263–287.
24. Le Bihan, D., Turner, R., Zeffiro, T. A., Cuénod, C. A., Jezzard, P. & Bonnerot, V. (1993) *Proc. Natl. Acad. Sci. USA* **90,** 11802–11805.
25. Kosslyn, S. M., Thompson, W. L., Kim, I. J. & Alpert, N. M. (1995) *Nature (London)* **378,** 496–498.
26. Kaas, J. H., Merzenich, M. M. & Killackey, H. P. (1983) *Annu. Rev. Neurosci.* **6,** 325–356.
27. Kaas, J. H. (1991) *Annu. Rev. Neurosci.* **14,** 137–167.
28. Pons, T. P., Garraghty, P. E., Ommaya, A. K., Kaas, J. H., Tuab, E. & Mishkin, M. (1991) *Science* **252,** 1857–1860.
29. Garraghty, P. E. & Kaas, J. H. (1992) *Curr. Opin. Neurobiol.* **2,** 522–527.
30. Roland, P. E. (1981) *J. Neurophysiol.* **46,** 744–754.
31. Zipser, D., Kehoe, B., Littlewort, G. & Fuster, J. M. (1993) *J. Neurosci.* **13,** 3406–3420.
32. Barbas, H. & Mesulam, M. M. (1985) *Neuroscience* **15,** 619–637.
33. Fuster, J. M. (1989) *The Prefrontal Cortex* (Raven, New York), 2nd Ed.
34. Barbas, H. (1992) in *Advances in Neurology,* eds. Chauvel, P., Delgado-Escueta, A. V., Halgren, E. & Bancaud, J. (Raven, New York), Vol. 57, pp. 91–115.
35. Shindy, W. W., Posley, K. A. & Fuster, J. M. (1994) *Cereb. Cortex* **4,** 443–450.