Binary Mapping of Cortical Spike Trains in Short-Term Memory

MARK BODNER, YONG-DI ZHOU, AND JOAQUÍN M. FUSTER
Department of Psychiatry and Brain Research Institute, School of Medicine, University of California, Los Angeles, California 90024

Bodner, Mark, Yong-Di Zhou, and Joaquín M. Fuster. Binary mapping of cortical spike trains in short-term memory. J. Neurophysiol. 77: 2219–2222, 1997. Microelectrode studies in monkeys performing short-term memory tasks show the sustained elevated discharge of cortical neurons during the retention of recalled sensory information. Cortical cells that are part of memory networks are assumed to receive numerous inputs of excitatory as well as inhibitory nature and local as well as remote. Thus it is reasonable to postulate that the temporal and spatial summation of diverse inputs on any cell in an activated network will result in temporally discrete groups of spikes in its firing. The activation of a network in active memory supposedly increases the magnitude and diversity of those inputs and thus increases the discontinuities and frequency fluctuations in the firing of cells in the network. In this study we use a new method of analysis that allows the quantification of firing discontinuities in a spike train. We apply it to parietal cells recorded from monkeys during the performance of a tactile short-term memory task. In our method, time is divided into bins of equal duration and the measure of discontinuities is the total count of the number of transitions between consecutive time bins with and without spikes. The results of the analysis show that in many of the cells studied, discontinuities (transitions between spiking and nonspiking) reflect memory-related activity obscured in the measures of raw spike frequency over a wide range of frequencies. These cells show more firing transitions in active short-term memory than in baseline (intertrial) conditions.

INTRODUCTION

Memories can be stored in widely distributed and overlapping networks of interconnected cortical neurons (Fuster 1995). Any given neuron or group of neurons representing a particular attribute of associative memory may be part of many different networks. Because adaptive behavior and the cognitive operations that support it commonly require the temporary retention of memories, cerebral mechanisms probably exist that ensure the temporary activation of memory networks (working memory). Microelectrode studies in monkeys performing short-term memory tasks show the sustained elevated discharge of cortical neurons during the retention of recalled sensory information (Funahashi et al. 1989; Fuster 1973; Fuster and Alexander 1971; Fuster and Jervey 1981, 1982; Koch and Fuster 1989; Miyashita and Chang 1988; Niki 1974).

Neurons in the cerebral cortex receive numerous inputs of excitatory as well as inhibitory nature and local as well as remote. Thus it is reasonable to postulate that the temporal and spatial summation of diverse inputs on any cell in an activated network will result in temporally discrete groups of spikes in its firing. Reentrant inputs from the same cell (Sporns et al. 1989; Tononi et al. 1992; Zipser et al. 1993) may also cause transient firing changes. Therefore in short-term memory, the activation of a network can be expected to be accompanied by increased discontinuities in the firing of its cells as they deviate from random "spontaneous" firing and become more subject to extrinsic inputs.

Using a new method of analysis, we have determined that in parietal cells discontinuities (or transitions) reflect memory-related activity obscured in the measures of raw frequency of spike trains. Because the temporal characteristics of spike-rate fluctuations related to memory cannot be predicted from available evidence, our attempt to quantify them required that spike sequences be analyzed over a wide range of temporal resolutions.

METHODS

The spike train records of 43 units of parietal cortex were selected from a database obtained for a study of firing frequency in two monkeys performing a tactile memory task (Zhou and Fuster 1992). The animal performed the task inside a sound-attenuated booth while sitting in a primate chair with its head fixed. The task performed was delayed tactile matching-to-sample with two pairs of cylindrical rods of identical dimensions (19-mm diam) but different features; one pair of rods had vertical versus horizontal parallel ridges on their surface whereas the other had smooth versus rough surface texture. A trial began with a click signaling that a vertical rod (the sample) was accessible to touch, out of sight, directly in front of the animal. The animal’s palpation of the rod’s girth was followed by a delay, during which the animal must memorize the sample rod for subsequent choice at delay’s end; a second sound signaled the accessibility of two rods, one of them identical to the sample. The monkey extended his hand into the object compartment and, after palpating the objects, indicated his choice by pulling one of them. If he correctly chose the sample rod he was rewarded with liquid reinforcement. The sample rod and its relative position at the choice changed randomly from trial to trial. Except for touching the rods, the animal was trained to sit still and to rest its operating hand on a rounded metal ledge. Removing the hand from the ledge, other than for sample or choice, automatically aborted the trial; use of the other hand was restricted by a metal plate. The animal’s movements were monitored by video camera and a transducer motion detector on the primate chair. Similar tasks have been used for neurophysiological study (Maunsell et al. 1991). Most units were from hand representation areas of somatosensory cortex, area S1 (comprising areas 3a, 3b, 1, and 2). The selection criteria for the units used in this study were 1) an electrically isolated and demonstrated stable discharge; 2) a minimum behavioral performance of 70% for each possible combination of stimulus and choice position, with an overall average of ≥75% for all combinations; and 3) a discharge that was not excessively slow.

The spike trains of the selected units were analyzed by mapping them to binary sequences (Fig. 1) with the following procedure. Time is first divided into consecutive bins of equal duration. Then
A binary sequence is generated indicating the presence (1) or absence (0) of spikes in each bin. This procedure can also be viewed as applying a type of low-pass filter in which spiking frequencies that occur over periods shorter than that of a given bin size are eliminated. Single-unit spike trains from baseline and delay periods (each 12-s long) were independently converted to binary sequences by this method. All baseline and delay trains recorded from a cell were then compared according to two different parameters of the binary sequences obtained at a given bin size: 1) the number of transitions between the 1s and 0s in the sequences (fluctuations between periods of activity and nonactivity) and 2) the total number of 1s in the sequences (filtered frequency). In the first type of comparison, all baseline and delay spike trains are ranked from highest to lowest number of transitions occurring in their respective binary sequences (Fig. 2). A nonparametric ranks test (rank sum) (Siegel and Castellan 1988) was used for determining any differences in transition numbers between spike trains recorded from these different periods, with $P < 0.05$ taken as indicating a significant difference between them at a given analyzing bin size. However, the resolution at which memory-related spike activity will be apparent is unknown a priori. Thus we carried out this procedure for each integer bin size over a range from 1 to 140 ms, with 140 ms being the upper range at which the binary curve becomes a flat line for most of the spike trains (see Fig. 1). However, because we used all bin sizes from 1 to 140 ms, it is possible that any one of these bin sizes might inadvertently show a significant difference between baseline and delay trains. Therefore a statistical adjustment was made by randomly reassigning all the original spike trains with regard to their baseline and delay labels, while still keeping the total number of baseline and delay trains equal. Thus a number of baseline trains were redesignated delay trains and vice versa. This reassignment was performed 1,000 times for each cell, and the analysis over the 140 bin sizes was performed for each reassigned set of baseline and delay trains. The statistic computed in each case was the number of bin sizes resulting in significant transition number differences between baseline and delay spike trains as determined by the rank test. This statistic gave at random the number of discriminations to be expected, because any differences seen were not between the actual baseline and delay trains but between trains with arbitrary baseline and delay assignment. Thus we established the distribution of that statistic under the null hypothesis; that is, the spike trains were drawn from a common distribution, regardless of epoch (baseline or delay). The same procedure was also carried out for the second type of comparison, ranking of trains by filtered frequency. In both cases the criterion of significance was $P < 0.05$. In addition to these comparisons an analysis was performed in which the raw spike trains (no binning) were ranked by their average frequency and the ranks test applied.

RESULTS

A total of 26 cells (60%) discriminated between baseline and delay periods by the transition statistic (Table 1); fourteen of them discriminated between the two periods in the absence of differences in average frequency (Fig. 2). Thus the average firing frequency of these cells did not vary from one period to the other, but varied in the number of transient changes of firing frequency. All but 1 of 14 cells exhibited higher numbers of transitions in the delay period trains than the baseline trains.

Among the cells there were 5 (12%) that discriminated baseline from delay by transition number that showed no discrimination by filtered frequency (Table 1). This means that, in the absence of differences in the frequency of spike-
FIG. 2. Raw frequency and transition analysis of spike trains from 2 different cells, one (A) in area 5a and the other (B) in area 2 (position of cells in diagrams of brain sections). Top: average frequency ranking of delay and baseline period spike trains (trains from baseline in white, from delay in black) from left to right in descending order and regardless of trial sequence. Height of each bar corresponds to the total number of spikes recorded over the 12-s period of each train. Bottom: transition number ranking of the binary curves obtained from the same trains with a mapping bin size of 20 ms for cell A and 23 ms for cell B. Numbers of transitions in the binary sequences are ranked in descending order from left to right (baseline white, delay black). Observe in both cells that transition numbers were higher for delay than for baseline ($P < 0.01$) in the absence of significant average frequency differences.

Filled bins, these cells showed differences between the two periods in their firing pattern.

The reliability of the analysis method was tested by generating fictitious cells with the same frequency during the 12-s period as the original spike trains but with randomized spike sequence. In those cells showing discrimination of baseline or delay period by average frequency, the fictitious cells also showed significant differences in average frequency and transition number. When the period assignment was also randomized in these cells, no significant discriminations were observed. For the cells that did not discriminate by average frequency, no significant differences above

<table>
<thead>
<tr>
<th></th>
<th>Different by Average Frequency</th>
<th>Not Different by Average Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different by T and FF</td>
<td>12 cells (28)</td>
<td>9 cells (21)</td>
</tr>
<tr>
<td>Different by T, not FF</td>
<td>0 cell (0)</td>
<td>5 cells (12)</td>
</tr>
<tr>
<td>Different by FF, not T</td>
<td>0 cell (0)</td>
<td>1 cell (2)</td>
</tr>
<tr>
<td>No differences by T or FF</td>
<td>2 cells (5)</td>
<td>14 cells (32)</td>
</tr>
</tbody>
</table>

Total of 43 cells. Numbers in parentheses represent percentage of cells. T, transitions; FF, filtered frequency.
chance were observed in their fictitious counterpart by either measure, frequency or transition.

DISCUSSION

This study indicates that the activation of cortical networks in so-called “working memory” (Fuster 1995) is not only manifested by the well-documented changes in firing frequency (Funahashi et al. 1989; Fuster 1973, 1990; Fuster and Alexander 1971; Fuster and Jervey 1981, 1982; Koch and Fuster 1989; Miyashita and Chang 1988; Niki 1974; Zhou and Fuster 1996) but also by short-term fluctuations of discharge (i.e., transition number) in the spike sequence. Our data show that these changes take place in somatosenory cortex during haptic memorizing. Furthermore, baseline versus delay differences in transition number (temporal distribution of 1s in the binary sequence) and not in filtered frequency (number of 1s) suggest changes in firing pattern related to working memory.

The memory-related changes in transient firing frequency indicate changes in the state of activity of memory networks. The increased frequency of transitions during the memory periods (delay) supports the hypothesis that in those periods the cells are subject to increased inputs from the network(s) to which they belong. These inputs may come, for example, from the sectors of the cortical network representing associated properties of the memorandum (Fuster 1995). Furthermore, the transition increases may result from reentrant reverberatory activity between those sectors of the cortical network. Active short-term memory can be understood as the sustained activation of a recurrent cortical network with fixed synaptic weights, as shown by the behavior of a computational model (Zipser et al. 1993). That model predicts that the activated network will periodically shift between frequencies or “attractors.” These changes in attractor frequency have been observed but not quantified in inferotemporal cells (Fuster 1990; Zipser et al. 1993). The increase in transitions observed here in somatosensory cells during the delay period of the tactile task may be a function of the network’s shifting among its various attractors during short-term active memory of tactile features.

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