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# Neural Mechanisms of Spatial Selective Attention in Areas V1, V2, and V4 of Macaque Visual Cortex

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<sup>1</sup>Department of Psychology, University of Iowa, Iowa City, Iowa 52242-1407; <sup>2</sup>Laboratory of Neuropsychology, National Institute of Mental Health, Bethesda, Maryland 20892; <sup>3</sup>Department of Neurological and Visual Sciences, University of Verona, Verona I-37134 Italy; and <sup>4</sup>Department of Neurosciences, University of California, San Diego, La Jolla, California 92093-0608

**Luck, Steven J., Leonardo Chelazzi, Steven A. Hillyard, and Robert Desimone.** Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *J. Neurophysiol.* 77: 24–42, 1997. Many neurons in extrastriate visual cortex have large receptive fields, and this may lead to significant computational problems whenever multiple stimuli fall within a single field. Previous studies have suggested that when multiple stimuli fall within a cell's receptive field, they compete for the cell's response in a manner that can be biased in favor of attended stimuli. In the present study we examined this role of attention in areas V1, V2, and V4 of macaque monkeys with the use of a behavioral paradigm in which attention was directed to one of two stimulus locations. When two stimuli were presented simultaneously inside the cell's receptive field (which could be accomplished only in areas V2 and V4), we found that the cell's response was strongly influenced by which of the two stimuli was attended. The size of this attention effect was reduced when the attended and ignored stimuli were presented sequentially rather than simultaneously. In addition, the effects became very weak and inconsistent in these areas when only one of the two stimuli was located inside the receptive field. Attention thus modulated sensory responses primarily when two or more simultaneous stimuli competed for access to a neuron's receptive field. As in areas V2 and V4, attention did not modulate sensory responses in area V1 when only a single stimulus was inside the receptive field. In addition, the small receptive fields in this area precluded the simultaneous presentation of attended and ignored stimuli inside the receptive field, making it impossible to determine whether attention effects would be observed under the conditions that led to consistent attention effects in areas V2 and V4. Spontaneous firing rates in areas V2 and V4 were found to be 30–40% higher when attention was directed inside rather than outside the receptive field, even when no stimulus was present in the receptive field. Spontaneous firing rates also varied according to the particular location within the receptive field that was attended. These shifts in spontaneous activity may reflect a top-down signal that biases responses in favor of stimuli at the attended location.

## INTRODUCTION

Neurons at the higher stages of the primate visual system typically have very large receptive fields (RFs), and this may be important for identifying objects in a position-independent manner (Gross and Mishkin 1977; Ito et al. 1995; Lueschow et al. 1994). However, large RFs frequently contain several objects, and the information communicated by a cell about each object is presumably degraded as the number of objects is increased (Miller et al. 1993a; Wise and Desimone 1988). A possible solution to this problem was

reported by Moran and Desimone (1985), who found that neurons in area V4 and inferotemporal (IT) cortex were influenced by attention such that their responses primarily reflected the features of attended stimuli. Specifically, when two stimuli were presented inside the RF of the neuron being recorded and the monkey was instructed to attend to one of the stimuli, the neuron's response to the attended stimulus appeared to be of normal magnitude whereas its response to the ignored stimulus was suppressed. However, no attentional modulation was observed in V4 when only one stimulus was located inside the RF, presumably because this eliminated the ambiguities that arise when multiple stimuli fall within a cell's RF (RFs in IT cortex were too large to test the effects of placing 1 stimulus outside the RF).

The finding that attentional modulations occur only when multiple stimuli compete for access to a cell's RF appears to conflict with numerous behavioral and electrophysiological studies of attention in humans, in which attention effects have been observed under conditions that presumably did not lead to the simultaneous presence of attended and ignored stimuli inside a single RF in prestriate cortex (e.g., Luck 1995; Posner 1980; Prinzmetal et al. 1986). Recent single-unit studies have also indicated that spatial attention can modulate V4 responses when only one stimulus is located inside the RF (Connor et al. 1996; Motter 1993). The primary purpose of the present study was to address some of these discrepancies by recording single-unit responses in areas V1, V2, and V4 with a behavioral paradigm that was derived from human event-related potential (ERP) studies.

In this paradigm, attention was directed to one of two locations for each trial block, and sequences of stimuli were presented at the attended and ignored locations. The direction of attention was alternated between trial blocks, which allowed the response elicited by a given stimulus to be measured when it was attended and when it was actively ignored. The to-be-attended location was indicated to the monkey by means of instruction trials at the beginning of each block, and the monkey was required to remember which location was to be attended without the aid of any visible cues. This procedure avoids the stimulus-stimulus interactions that may occur when the to-be-attended location is indicated by the presentation of a cue stimulus at that location at the beginning of each trial.

In several previous studies, attending to a nonspatial feature was found to influence spontaneous (baseline) firing rates in addition to modulating stimulus-evoked responses

(e.g., Ferrera et al. 1994; Haenny et al. 1988). In a study by Chelazzi et al. (1993), for example, inferior temporal cells that were selective for a given stimulus exhibited elevated baseline firing rates when that stimulus was the to-be-detected target in a visual search task. Changes in baseline activity such as this may reflect top-down bias signals that provide attended stimuli with an advantage over ignored stimuli, and these signals may play an important role in selective attention. However, effects of this nature have not been reported in prestriate cortex in studies of spatial selective attention. A secondary goal of the present study was therefore to determine whether baseline firing rates are influenced when attention is directed to spatial locations just as they are when attention is directed to nonspatial features.

## METHODS

### *Subjects and surgical techniques*

Many of the details of the recording techniques have been described previously (Miller et al. 1993b). Briefly, two adult male rhesus monkeys (*Macaca mulatta*) were surgically implanted with a headpost, a scleral eye coil, and recording chambers. These monkeys will be denoted *monkey A* and *monkey B*. Surgery was conducted under aseptic conditions with isoflurane anesthesia, and antibiotics and analgesics were administered postoperatively. The V4 recording chamber was placed over the prelunate gyrus (left hemisphere of *monkey A* and right hemisphere of *monkey B*), which was located in stereotaxic coordinates on the basis of a preoperative magnetic resonance imaging (MRI) scan. An additional recording chamber was used for V1 and V2 recordings, centered 15 mm lateral and 15 mm dorsal to the occipital pole in the right hemisphere; V1 and V2 recordings were obtained only from *monkey B*. However, recordings that were obtained from area V2 of a second monkey after the present study was completed have confirmed the major findings from *monkey B* (Reynolds et al. 1994). The skull remained intact during the initial surgery, and small holes (~3 mm diam) were later drilled within the recording chambers under ketamine anesthesia to expose the dura for electrode penetrations.

### *Confirmation of recording sites*

Before the main study, several penetrations were made in each chamber to ensure that the electrode was in the appropriate visual area. This was determined by assessing RF sizes, topographic organization, and feature preferences at each site. Neurons in area V2 were recorded by passing the electrode through V1 on the opercular surface, through the underlying white matter, and into the portion of V2 that lies on the posterior bank of the lunate sulcus.

*Monkey B* had originally been implanted with plastic recording chambers, titanium screws, and a brass headpost. In this monkey, tungsten electrodes were inserted into the centers of the V1/V2 and V4 recording sites at the conclusion of the study, and a new MRI scan was obtained to verify the electrode placements. The electrodes were clearly visible in the scans. *Monkey A* was originally implanted with a stainless steel chamber and screws, which were removed at the conclusion of the study. This monkey was then rescanned with MRI to confirm the location of the recording hole in the bone over the prelunate gyrus.

### *Recording techniques*

Recordings were obtained from a tungsten microelectrode that was controlled by a hydraulic microdrive. In most cases, two neurons could be recorded simultaneously and differentiated on the basis of the size and shape of the spike waveform, and an online spike-sorting computer was used to classify these spikes by means

of a template-matching procedure. Although this system allowed the concurrent recording of two neurons, spikes arising from both neurons simultaneously (within a 1-ms interval) could not be detected. Over all conditions, 86% of the recordings were from two simultaneous cells that were both usable (i.e., significantly responsive and appropriately selective for the condition being run) and the remaining 14% were from a single usable cell.

Cells were isolated while the monkey performed the standard attention task (described below) with the use of stimuli presented in the same RF location that was measured in previous recordings at the same site. After one or two responsive neurons were isolated, we determined the RF borders (minimum response field method) and stimulus preferences of the neurons by moving and flashing colored bars on the screen under manual control while the monkey performed a fixation task. The RF borders were used to help place the stimuli in appropriate locations for the attentional manipulations but were not quantified. Depending on which experimental conditions were to be tested in a given session, we sometimes required that a cell be selective for orientation or color to proceed with the attentional manipulations.

### *Stimuli and task*

The basic attention task is diagrammed in Fig. 1. Stimuli were presented at two locations, and the monkey had to attend to one of the locations and ignore the other to detect a target stimulus at the attended location. Attention was directed to one location in some trial blocks and to the other location in other blocks. This was achieved by the use of "instruction" trials at the beginning of each block, as detailed below. There were no visible cues indicating the attended location during each trial, and the monkey was therefore required to remember which location was to be attended.

The monkey initiated a trial by grasping and maintaining contact with a response bar. A fixation spot then appeared on the screen, and the monkey was required to fixate this spot (within a window of  $0.5^\circ$ ) for the remainder of the trial. Location markers, consisting of white outline boxes ( $1.4 \times 1.4^\circ$ ), appeared at both the attended and ignored locations 300 ms after fixation was achieved and remained visible throughout the trial (see Fig. 1). The sequence of task-relevant stimuli began 500 ms after the onset of the marker boxes. The sequences began with a series of nontarget stimuli (rectangles, typically  $0.3 \times 1.2^\circ$ ), which were presented at both attended and ignored locations. Each sequence ended with a target stimulus (a square, typically  $1 \times 1^\circ$ ) presented at the attended location. The monkey was required to respond by releasing the response bar when the target square appeared. Any loss of fixation or release of the response bar before the presentation of the target led to immediate termination of the trial, and data from such trials were excluded from all neural response analyses.

In one variant of this task, pairs of nontarget stimuli were presented simultaneously at the attended and ignored locations. On these "simultaneous" trials, each sequence consisted of between zero and five pairs of nontargets, followed by the simultaneous presentation of a target at the attended location and a nontarget at the ignored location. In another variant of the task, the stimuli were presented asynchronously at the two locations. On these "sequential" trials, the sequence began with between zero and five individual nontargets, presented in a randomized sequence at the two locations, followed by the presentation of the target at the attended location (see Fig. 1). For example, a typical sequential trial might consist of an attended-location nontarget, two ignored-location nontargets, and finally an attended-location target. The monkey was rewarded with a drop of orange juice for releasing the response bar within 500 ms of the onset of the attended-location target (which was always presented as the final item in the stimulus sequence). Each of the six sequence lengths (1–6 total stimuli) was equally likely, and all of the possible sequential orders at each sequence length were equiprobable in the sequential presentation

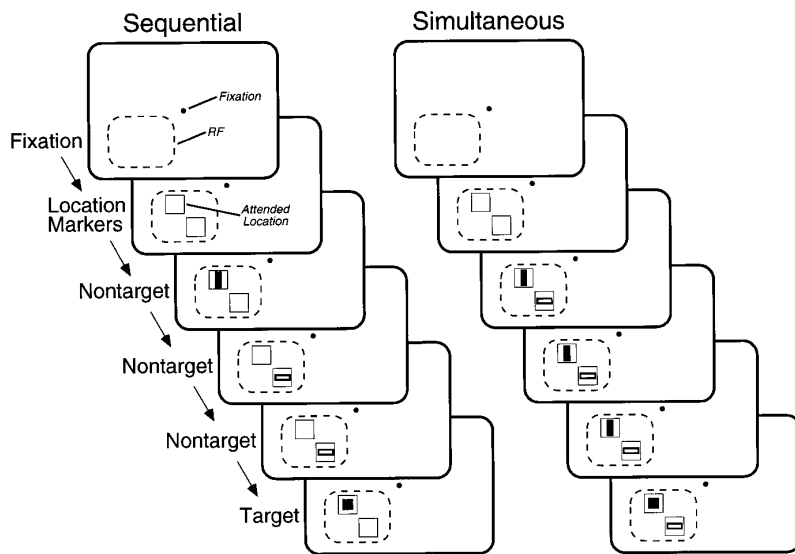


FIG. 1. Example stimulus sequences for sequential and simultaneous trials. The receptive field (RF) of the cell being recorded was mapped before data collection and is represented by the region enclosed by a dashed line. When both sequential and simultaneous trials were used with the inside/inside configuration (as shown here), different orientations and colors were used at the 2 locations, 1 of which was effective at driving the cell and 1 of which was ineffective. For many cells, however, all trials were sequential and the same stimuli were used at both locations. The same stimuli were typically used at both locations in the inside/outside configuration.

conditions. Each stimulus was presented for 50 ms, and the interval between successive stimulus onsets varied randomly between 300 and 450 ms.

In both the sequential and simultaneous conditions, 20% of trials were "catch trials." On a catch trial, a square "pseudotarget" stimulus was presented at the ignored location before the end of the sequence; bar releases to these pseudotargets were considered errors and resulted in a time out. As on normal trials, catch trials ended with a true target presented at the attended location, and responses to this target were rewarded with a drop of juice. The presence of these catch trials was intended to force the monkeys to discriminate both the location and the shape of the target. Bar releases for squares presented at the to-be-ignored location were used as an indication that the monkey was not restricting attention to the appropriate location. The neural activity recorded on catch trials was not included in any of the analyses described below, with the exception of comparisons between attended-location and ignored-location targets.

The first few trials at the start of each block served as instruction trials that indicated which location was to be attended for that block (data from these trials were not included in any of the analyses presented below). On these instruction trials, the to-be-attended location was indicated by a brighter location marker box. After it became clear from the animal's performance that attention was being directed to the appropriate location, the brightened box was returned to the same brightness as the box at the to-be-ignored location. Thus there were no visible cues indicating which location was to be attended, and the monkey therefore had to rely on memory. The monkeys occasionally forgot which location was to be attended and began responding to the square stimulus at the to-be-ignored location on the catch trials. When this occurred, the block was interrupted and another sequence of instruction trials was initiated. Each block consisted of ~150 correctly completed trials. The attended and ignored locations alternated between blocks, and in most cases 6–10 blocks of data were obtained from each neuron under a given set of stimulus parameters. Neurons were not included in the analyses below unless data were obtained from at least two blocks of trials for each direction of attention (3–4 blocks per direction of attention was typical).

### Stimulus conditions

We tested several different stimulus configurations to determine the effects of the spatial positions of the attended and ignored locations with respect to the RF borders, as summarized in Ta-

ble 1. For some neurons, both locations were placed inside the classical excitatory RF, and this was termed the "inside/inside" configuration. For other neurons, an "inside/outside" configuration was used in which one location was inside the RF and the other was at one of three possible locations outside the RF: 1) just outside the RF, in the same visual quadrant as the inside-RF location; 2) in a symmetrical position across the vertical meridian from the inside-RF location; or 3) in a symmetrical position across the horizontal meridian from the inside-RF location. Most neurons were tested with only one of these spatial configurations, but some neurons were tested in two conditions.

For many neurons, only sequential or only simultaneous trials were presented. For other neurons, sequential and simultaneous trials were randomly intermixed, although sequential or simultaneous stimuli were never mixed within a trial. In other words, the sequence of one to six stimuli presented on a given trial consisted entirely of stimulus pairs on simultaneous trials or individual stimuli on sequential trials (see Fig. 1). In some cases, the stimuli at the two locations were identical, and the color and orientation of the stimuli were chosen to be the most effective features for driving the neuron. In other cases, the stimuli at one location were chosen to be the most effective for driving the cell and the stimuli at the other location were chosen to be the least effective. For example, if a cell responded well only to red stimuli, we used red stimuli (effective stimuli) at one location and green stimuli (ineffective stimuli) at the other. The nontarget rectangle and target square at a given location always had the same color and orientation. Except as noted below, the relative locations of the effective and ineffective stimuli remained constant across trial blocks, but they were varied randomly across neurons. The conditions in which different features were used were particularly important when stimuli were presented simultaneously at two locations within the RF, because the use of different features provided a means of observing different responses as a function of which stimulus was attended (e.g., the neuron might produce a greater response when attention was directed to the location of the effective stimulus). The various conditions are summarized in Table 1, which indicates 1) the number of cells recorded in each condition; 2) the visual area from which the recordings were obtained; 3) the positions of the stimuli with respect to the RF border; 4) whether the attended and ignored stimuli were presented sequentially, simultaneously, or both; and 5) whether the same or different stimulus features were used at the two locations.

*Monkey A* was slightly strabismic. Behavioral testing indicated that this monkey could perform the task equally well with either



TABLE 1. Summary of experimental conditions

Condition	Number of Cells, A/B	Visual Area	Second Stimulus Position	Simultaneous or Sequential	Same or Different Features
A <sub>1</sub>	11/23	V4	Inside	Both	Different
A <sub>2</sub>	51/24	V4	Inside	Sequential	Same
B <sub>1</sub>	36/0	V4	Outside (far)*	Sequential	Same
B <sub>2</sub>	0/38	V4	Outside (far)	Both	Same
B <sub>3</sub>	24/6	V4	Outside (near)†	Sequential	Same
B <sub>4</sub>	3/26	V4	Outside (near)	Both	Same
B <sub>5</sub>	26/0	V4	Outside (far)	Sequential	Same‡
C	0/15	V4	Outside§	Simultaneous	Same
D	8/0	V4	Outside (far)	Simultaneous	Different
E <sub>1</sub>	0/23	V2	Outside (far)	Both	Same
E <sub>2</sub>	0/42	V2	Outside (near)	Both	Same
E <sub>3</sub>	0/8	V2	Inside	Both	Different
F <sub>1</sub>	0/19	V1	Outside (near)	Sequential	Same
F <sub>2</sub>	0/60	V1	Outside (near)	Both	Same

At least 1 stimulus was inside the receptive field (RF), and the other was in the location indicated under Second Stimulus Position, given relative to the location of the receptive field. Number of cells is given separately for *monkey A (left)* and *monkey B (right)*, and includes only cells that were appropriately responsive and selective (note that a few neurons were recorded in >1 condition). \* Second position in this condition was in a mirror-symmetrical position across either the horizontal or vertical meridian. † Second position in this condition was just outside the RF, in the same quadrant as the inside-RF stimulus. ‡ This condition was run without location markers. § This condition was run with either 2 or 5 locations, as diagrammed in Fig. 10A.

eye, and its left eye was occluded during all recordings (recordings were obtained only from area V4 in the left hemisphere in this monkey). Binocular presentation was used for the V1, V2, and V4 recordings in *monkey B*.

### Data analysis

Baseline activity was measured as the firing rate during the 100-ms period preceding stimulus onset, and the sensory response was measured as the average firing rate from 50 to 175 ms poststimulus for V4 cells and from 30 to 130 ms poststimulus for V1 and V2 cells. The baseline activity that preceded a stimulus was subtracted from the stimulus-evoked response for that stimulus in all analyses, except as noted below. Because nontarget stimuli greatly outnumbered target stimuli, especially at the ignored location, the nontarget responses could be measured more reliably than the target responses and were therefore the focus of most analyses. Similarly, many more stimuli were presented at the early sequential positions than at the later sequential positions, and our analyses therefore focused on the first three nontarget stimuli in each sequence to avoid the statistical problems that can arise with widely varying sample sizes.

The effects of attention on neural activity were assessed by comparing the activity elicited by a particular stimulus when it was attended versus when it was ignored (i.e., when attention was directed to the other location). Statistical analyses were conducted on each neuron individually by means of an analysis of variance (ANOVA) on the population of single-trial firing rate measurements from that neuron. Each ANOVA had two factors: attention (whether the stimulus was attended or ignored) and sequential position (1st, 2nd, or 3rd position in the sequence). Any variance due to the order of trial blocks was ignored in these ANOVAs. In most cases, each single-cell ANOVA was based on data from  $\geq 150$  trials. We also measured the mean firing rate across trials for each neuron and computed statistics on the population of neurons to assess the presence of consistent attention effects across neurons. A criterion level of  $P < 0.05$  was used in all statistical analyses.

Some of the neurons produced larger responses at early positions in the stimulus sequence and others produced larger responses at late positions in the sequence. However, no consistent pattern was observed across cells, and the effects of attention did not vary across sequential positions. As a result, all of the data presented below were averaged across sequential position.

To quantify the size of the attention effects, we computed an attentional modulation index (AMI) in which the size of the attention effect was scaled by the size of the sensory response. Specifically, the firing rate during the prestimulus baseline period was subtracted from the mean firing rate during the sensory response (with the use of the time intervals described above), and the AMI was then computed as:  $AMI = (\text{attended} - \text{ignored}) \div (\text{attended} + \text{ignored})$ . The AMI can range between  $-1.0$  (complete suppression of response to the attended stimulus) and  $+1.0$  (complete suppression of the response to the ignored stimulus), with a value of 0 indicating no effect of attention. The AMI values can be transformed into a percent change measurement, in which the difference between attended and ignored responses is scaled by the size of the ignored response by the following formula:  $\text{percent change} = 100 \times 2AMI \div (1 - AMI)$ .

We also examined the effects of attention across populations of cells by computing poststimulus histograms for each cell for every combination of stimulus type and direction of attention and then creating averaged poststimulus histograms across the population of cells within a given experimental condition. Several of these averaged histograms are displayed in the figures below. Although these averaged histograms provide a good measure of the central tendency in a population, they may, in principle, differ considerably from the histograms obtained for any of the individual cells. We therefore present histograms of this type only when the averaged histogram is qualitatively similar to the histograms obtained for a large number of individual cells.<sup>1</sup>

### RESULTS

We begin this section by summarizing the behavioral performance of the monkeys and the recording sites, and then describe the responses of the neurons during task perfor-

<sup>1</sup> Across-cell averages can be particularly misleading when individual cells differ greatly in the magnitude of the sensory response. To assess the effects of magnitude differences, we computed averaged histograms in which we first normalized the firing rate of each cell to a constant peak response magnitude before averaging across cells. The resulting averaged histograms were virtually indistinguishable from the histograms created without normalization, which indicates that variability in response magnitude did not produce substantial distortion in the averaged histograms presented here.

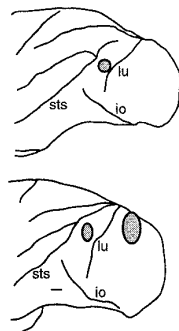


FIG. 2. Locations of recording sites (shaded ovals) in *monkey A* (top) and *monkey B* (bottom) as determined from magnetic resonance imaging (MRI) scans. The recordings were obtained from the right hemisphere in *monkey B*, but the drawing has been reflected horizontally to facilitate comparison with *monkey A*. The V4 recording sites in both animals were located on the prelunate gyrus, between the lunate and superior temporal sulci. In the bottom drawing, the oval on the right indicates the location of both the V1 recording sites on the cortical surface and the sites of entry for the V2 recordings, which were located in the immediately underlying posterior bank of the lunate sulcus. io, Inferior occipital sulcus; lu, lunate sulcus; sts, superior temporal sulcus.

mance. The description of the neural responses begins with area V4 and then proceeds to area V2 and finally to area V1. Within each area, we describe the effects of attention on both sensory responses and baseline firing rates for the inside/inside and inside/outside conditions (where appropriate).

### Behavioral performance

Trials were terminated because of eye movements on 5.7% of standard trials and 8.8% of catch trials. Excluding these trials, the monkeys responded correctly on 93.8% of standard trials and 87.1% of catch trials, with mean reaction times of 323 and 304 ms, respectively. The behavioral errors consisted mostly of false alarms (responses to 1 of the non-targets preceding the target) rather than misses (lack of any response). False alarms were more frequent on catch trials (11.8%) than on standard trials (4.3%), which almost certainly reflects occasional errors in focusing attention onto the correct location. Misses occurred relatively infrequently on both catch trials (1.1%) and standard trials (1.9%). Overall, the monkeys performed the task with a high level of speed and accuracy and exhibited selective processing of attended-location stimuli. There were no obvious differences in performance as a function of the different stimulus conditions except for the differences between standard and catch trials.

### Number and locations of neurons

We collected complete data sets from 253 neurons in V4, 73 neurons in V2, and 79 neurons in V1; these numbers exclude neurons that lacked a significant excitatory response or appropriate stimulus selectivity. The recording sites are illustrated in Fig. 2. Neurons in all three areas had RFs centered in the lower quadrant of the contralateral field. The mean RF eccentricities in V4, V2, and V1 were  $\sim 4.5$ , 6, and  $5^\circ$ , respectively.

### Area V4, inside/inside configuration (condition A)

SIMULTANEOUS VERSUS SEQUENTIAL STIMULI (CONDITION A<sub>1</sub>). In the first set of recordings, we attempted to replicate the results of Moran and Desimone (1985) by measuring the effects of attention on sensory responses in area V4 when the attended and ignored stimuli were presented simultaneously inside the RF. In addition, we also compared sequential and simultaneous stimulus presentation conditions to determine whether the effects of attention depend on the simultaneous presentation of attended and ignored stimuli. To measure the effects of attention on simultaneous trials, different colors and orientations were used at the two locations, as shown in Fig. 1. The stimuli were chosen so that one stimulus would be effective in driving the cell when presented by itself and the other would be ineffective (this configuration was used for both sequential and simultaneous trials). When effective and ineffective stimuli were presented simultaneously, the effects of attention were assessed by determining whether the cell's response was determined primarily by the features of the attended stimulus and not by the features of the ignored stimulus. This would yield a larger response when the effective stimulus was attended and a smaller response when the ineffective stimulus was attended.

We obtained data for both sequential and simultaneous trials from 34 feature-selective cells in this condition (condition A<sub>1</sub> in Table 1). In each case, the cell's response was at least twice as large for the effective stimulus presented alone as it was for the ineffective stimulus presented alone (on average, the response elicited by the effective stimulus was  $\sim 10$  times greater than the response elicited by the ineffective stimulus).

Consistent with the findings of Moran and Desimone (1985), attention had a large and consistent effect on simultaneous trials, with 85% of cells (29 of 34) showing a significantly larger response when attention was directed to the effective stimulus compared with when attention was directed to the ineffective stimulus (see METHODS for description of statistical tests). This can be seen in Fig. 3A, which shows poststimulus histograms averaged across all of the cells that showed a significant attention effect. It is important to note that the sensory stimulus was identical no matter which location was attended: the only difference was the monkey's internal attentional state.

We also found an effect of attention on the sequential trials, as shown in Fig. 3, B and C. For both the effective and ineffective stimuli, the response tended to be larger when the stimulus was attended than when it was ignored. This effect was statistically significant for the effective stimulus in 41% of the cells (14 of 34) and for the ineffective stimulus in 35% of the cells (12 of 34; primarily in cells with some excitatory response to the ineffective stimulus). Only 9% of the cells (3 of 34) showed significant attention effects for both the effective and ineffective stimuli, but all except 2 of the cells with significant effects for sequential stimuli—whether effective or ineffective—were among the 29 cells that showed significant effects for simultaneous stimuli. Effects in the opposite direction (i.e., larger responses for the ignored stimulus) were significant in only two cells for the effective stimuli and in none of the cells for the ineffective stimuli or for the simultaneous stimuli. Example results from an individual cell in this condition are shown in Fig. 4.

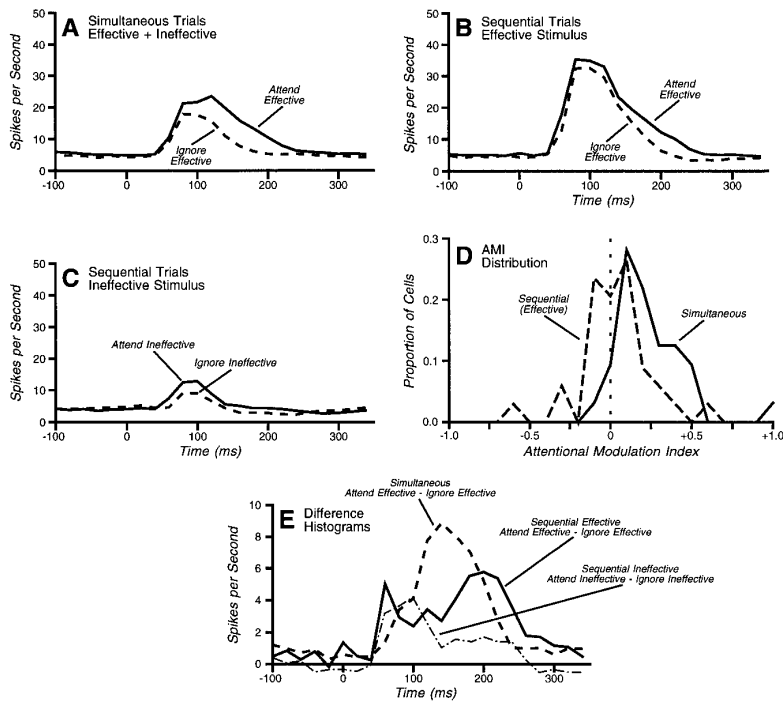


FIG. 3. A: poststimulus histograms for nontarget stimuli on simultaneous trials in condition A<sub>1</sub>, averaged over the 29 V4 neurons that showed a significant attention effect for these trials. Solid line: trials on which attention was directed to the effective stimulus. Dashed line: trials on which attention was directed to the ineffective stimulus. The responses shown here and in all figures below were collapsed across all sequential positions of the stimuli in the sequence, weighted by the total number of stimuli that occurred at each position. The histograms were calculated with 20-ms bins centered at 0, 20, 40 ms, etc. B: poststimulus histograms for the effective stimuli on sequential trials in the same condition, averaged over the 14 cells that showed a significant attention effect for these stimuli. C: poststimulus histograms for the ineffective stimuli on sequential trials, averaged over the 12 cells that showed a significant attention effect for these stimuli. D: probability distribution of the attentional modulation index (AMI) for sequential trials (effective stimuli) and simultaneous trials (effective + ineffective) over all 34 cells run in this condition. E: difference between the attended and ignored histograms shown in A–C.

There were several notable differences between the results for the sequential and simultaneous trials. First, the overall response to the simultaneous presentation of an effective stimulus and an ineffective stimulus inside the RF (simultaneous trials) was smaller than the response to the effective stimulus when presented alone (sequential trials). On average, the response was 77% larger for the effective stimulus presented alone than for the effective and ineffective stimuli

presented together, and a difference in this direction was observed in 33 of the 34 cells that were recorded under these conditions.

A second important difference was that the effects of attention were considerably larger for simultaneous trials than for sequential trials. The difference in the magnitude of the attention effects for cells with significant effects can be seen by comparing Fig. 3, A and B. The size of the effect over the entire population can be seen in Fig. 3D, which shows the probability distribution of the AMI for simultaneous and sequential trials. Almost all of the AMI values were positive for simultaneous trials, and the mean AMI across the population for these trials was 0.24, which corresponds to a 63% increase in the response when the effective stimulus was attended compared with when it was ignored. In contrast, the AMI was frequently negative for the effective stimuli on sequential trials, and the population average was only 0.03, which corresponds to a 6% average increase in response when the stimulus was attended compared with when it was ignored (the AMI was an inappropriate measure for the ineffective stimuli because many cells produced no response to these stimuli, leading to a denominator of 0 in the AMI calculation). In addition, significant attention effects were found in approximately twice as many cells for simultaneous trials as for sequential trials. Thus the effect of attention on the sensory response was both stronger and more consistent when the attended and ignored stimuli were presented simultaneously rather than sequentially.

It should be noted that this pattern of small attention effects on sequential trials and larger attention effects on simultaneous trials was observed in both monkeys, with no obvious differences between monkeys in the size of the effects or the probability of obtaining a significant effect. It should also be noted that, although we have used a criterion of  $P < 0.05$  for classifying attention effects as significant,

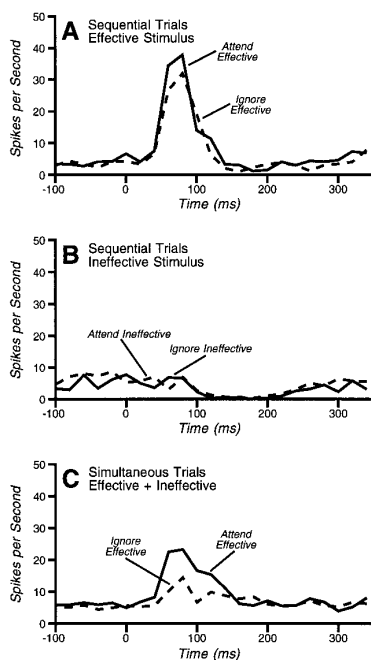


FIG. 4. Data from a single V4 neuron in condition A<sub>1</sub>. A: poststimulus histograms for the effective stimulus on sequential trials. B: poststimulus histograms for the ineffective stimulus on sequential trials. C: poststimulus histograms for the effective-ineffective pair on simultaneous trials.

many of the single-neuron attention effects described above were significant at the  $P < 0.001$  level ( $\sim 45\%$  of the cells with significant effects on sequential trials and  $\sim 75\%$  of the cells on simultaneous trials).

The time course of the attentional modulation also appeared to differ between simultaneous and sequential trials. This can be seen in Fig. 3E, which shows the difference between the attended and ignored histograms. On sequential trials, the attention effect began sharply at the onset of the sensory response for both the effective and ineffective stimuli ( $\sim 60$  ms poststimulus), with a second peak at  $\sim 200$  ms after stimulus onset for the effective stimuli. In contrast, the attention effect for the simultaneous trials rose gradually from 60 ms poststimulus to a peak at  $\sim 150$  ms. It should be noted that part of the late portion of the attention effect fell outside the 50- to 175-ms measurement window used in the analyses described above, but extending the end of the measurement window to 250 ms had only a minor effect on the outcome of these analyses (and led to difficulties in the analysis of the data from the inside/outside configuration because of shifts in baseline firing rates, as described below).

The poststimulus histograms shown in Fig. 3 were created with a binwidth of 20 ms, which makes it difficult to use them in determining the exact time at which attention began to modulate the response. A more precise analysis of the time course was therefore conducted on the basis of a statistical analysis that examined the entire population of 34 cells (similar results were obtained when only the cells with significant attention effects were examined). In this analysis, the average firing rate was measured for each cell in successive 5-ms time bins following stimulus onset and a series of ANOVAs was then conducted that compared the mean firing rate across cells during a given time bin with the baseline firing rate. The onset latency of the sensory response was then assessed by finding the first time bin at which the mean firing rate across cells was significantly greater than the mean baseline firing rate. Similarly, the onset of the attention effect was assessed in a second set of ANOVAs, which was used to determine the first time bin at which the mean firing rate across cells was significantly greater when attention was directed to the effective stimulus than when attention was directed to the ineffective stimulus. Separate analyses were conducted for the simultaneous trials and for the effective stimuli on sequential trials (the ineffective stimuli were not analyzed in this manner). On sequential trials, both the sensory response and the attentional modulation of the response first reached the  $P < 0.05$  criterion level at the time bin centered at 60 ms poststimulus, which corresponds well with the time course shown in the histograms in Fig. 3. The sensory response also began at 60 ms poststimulus on simultaneous trials, but the attention effect on those trials did not become significant until 75 ms poststimulus. Thus attention influenced responses from the very beginning of the sensory response on sequential trials, but there was a short delay in the onset of the attentional modulation on simultaneous trials.<sup>2</sup>

<sup>2</sup> The onset times derived from these population analyses do not necessarily reflect the average onset times. Rather, they reflect the earliest time at which a substantial proportion of cells deviated from 0 (i.e., enough cells such that the mean across the population was significantly different from 0). This does not, however, change any of our conclusions regarding the time course of activity across the population of V4 cells.

SAME FEATURES CONDITION (CONDITION A<sub>2</sub>). The data described above were obtained with different stimulus features at the attended and ignored locations. This differs from the procedure of most ERP studies of attention, which have typically used identical stimuli at both locations, and makes it possible that the attention effects described above were not purely due to spatial attention. We therefore tested 75 additional cells with the same stimulus features at both locations (condition A<sub>2</sub> in Table 1). We again used the inside/inside spatial configuration, with an average spatial separation of  $3.1^\circ$  between the stimuli (center to center). Because there would be no straightforward way to measure the effects of attention for identical stimuli presented simultaneously inside the RF, all trials in this condition were sequential.

As in the experiments described above, many cells exhibited a larger response to a stimulus when it was attended than when it was ignored. ANOVAs calculated for each individual neuron indicated that attended stimuli produced significantly larger overall responses than ignored stimuli in approximately half of the cells (37 of 75). Only two cells showed a significantly smaller response for attended stimuli in this condition, which is approximately the number expected by chance. Figure 5A displays average poststimulus histograms for the 37 cells that exhibited significantly larger responses for attended stimuli, and histograms from a representative individual cell are shown in Fig. 5B.

The size of the attentional modulation was quantified with the AMI, as shown in Fig. 5D. Although the majority of cells exhibited positive AMI values, indicating a larger response for attended stimuli than for ignored stimuli, the effects tended to be rather weak. The average effect across the entire population was only 0.04 (corresponding to an 8% modulation), and only three cells exhibited an AMI of  $>0.15$  (i.e., an increase of  $\geq 35\%$ ). This was approximately the same magnitude as observed for sequential trials in the previous condition (condition A<sub>1</sub>).

As shown in Fig. 5C, the time course of the attention effect in this condition was very similar to the time course observed for effective stimuli on sequential trials in condition A<sub>1</sub>. Specifically, the attention effect began sharply at  $\sim 60$  ms after stimulus onset, with a second peak at  $\sim 200$  ms poststimulus. A statistical analysis of the time course of the sensory response and the attentional modulation was conducted with 5-ms time bins, as described above for condition A<sub>1</sub>, and this analysis indicated that both the sensory response and the attentional modulation first became significant at the time bin centered at 60 ms poststimulus. Thus both the magnitude of the attention effect and its time course in this condition were highly similar to the sequential-trial results from the previous condition, which suggests that these effects reflect spatial attention rather than feature-based selective processing.

The data discussed above were obtained from nontarget stimuli, but similar results were also obtained for the target stimuli. Figure 6 shows poststimulus histograms for target stimuli, averaged across the same set of cells shown in Fig. 5A. As was observed for nontargets, target stimuli elicited larger responses when presented at the attended location than when presented at the ignored location (which occurred only on catch trials). Moreover, the magnitude of this effect was comparable with the effects observed for nontarget stimuli. Thus the effects of spatial attention in this condition ap-



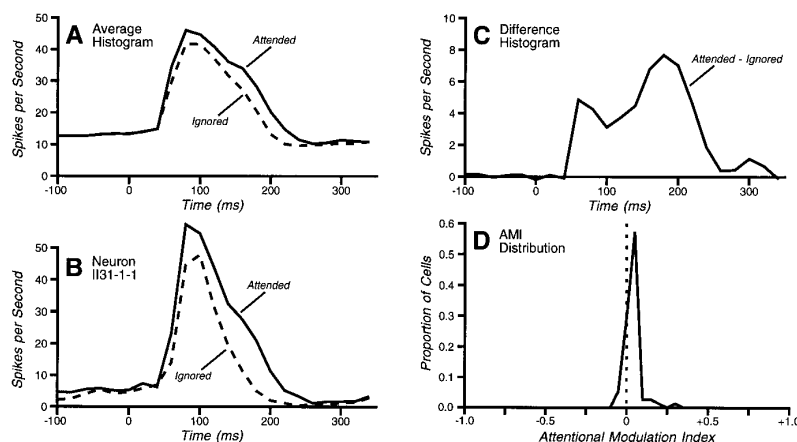


FIG. 5. *A*: average poststimulus histograms from the 37 V4 cells that showed a significant attention effect with the inside/inside configuration and identical stimuli at the attended and ignored locations (condition  $A_2$ ). Solid line: response of the neurons to a nontarget stimulus when it was attended. Dashed line: response of the neurons to the same stimulus when the other location was attended. *B*: poststimulus histograms from an individual neuron in this condition. *C*: difference between the attended and ignored histograms shown in *A*. *D*: probability distribution of the AMI over all 75 cells run in this condition.

peared to be independent of the form of the stimulus and its meaning within the behavioral task.

#### Area V4, inside/outside configuration (condition $B$ )

EFFECT OF ATTENTION ON SENSORY RESPONSES (CONDITIONS  $B_1$  AND  $B_2$ ). To test the hypothesis that spatial attention influences V4 responses primarily when both the attended and ignored locations are inside the RF, 74 V4 cells were tested with the inside/outside configuration (conditions  $B_1$  and  $B_2$ ). In these cells, one location was centered inside the RF and the other location was placed at a mirror-image location across either the horizontal meridian or the vertical meridian; the average interlocation distance was  $9.6^\circ$ . No consistent differences in attention effects were observed between these two inside/outside configurations. Thirty-six cells were run only with sequential trials (condition  $B_1$ , monkey *A* only), and 38 were run with both simultaneous and sequential trials (condition  $B_2$ , monkey *B* only). In general, the effects of attention on the sensory response in these conditions were small and inconsistent in comparison with the inside/inside conditions, and the effects that were observed were complicated by substantial attention-related shifts in baseline firing rates.

We consider the sequential data first. As can be seen in the population-average poststimulus histograms shown in Fig. 7A, there was no consistent effect of attention on the peak stimulus-evoked response. Of the 74 cells tested in conditions  $B_1$  and  $B_2$ , 7 gave a significantly larger response to attended stimuli than to ignored stimuli (positive attention effect) and 3 gave a significantly smaller response to attended stimuli (negative attention effect). This is a far smaller proportion of cells with significant attention effects

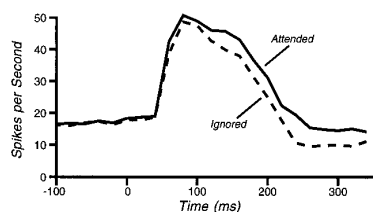


FIG. 6. Average poststimulus histograms from the same 37 V4 cells shown in Fig. 5 (condition  $A_2$ ), but showing the responses elicited by targets rather than nontargets. Note that targets were presented at the ignored location only on catch trials.

than was found in the inside/inside conditions. There was, however, a clear effect of attention on the baseline firing rate: higher baseline firing rates were observed when attention was directed inside rather than outside the RF (see Fig. 7A). These baseline effects are described in more detail in the next section; here we only consider their possible influence on the measurements of firing rates in the poststimulus period.

Inspection of the single-cell histograms suggested that the sustained shift in baseline firing rate when attention was directed inside the RF may have carried over into the time interval of the stimulus-evoked response in some cells, and this may have artificially elevated firing rates during the sensory response period. If so, this might account for the few cells with significant positive attention effects in this condition. To compensate for any effects of differential baseline activity on the responses, an additional analysis was conducted in which the firing rate preceding a stimulus was subtracted from the firing rate measured during the stimulus-evoked response. When the single-neuron ANOVAs were recalculated with these adjusted firing rates, the number of cells with significant positive attention effects dropped from seven to two.

However, subtracting the baseline activity from the sensory response increased the number of cells with significant negative attention effects (i.e., smaller responses to a stimulus when it was attended compared with when it was ignored) from 3 to 14, because a higher baseline firing rate was subtracted from the responses when attention was directed inside the RF. This bias in favor of negative attention effects is ambiguous, however, because it is not clear whether these effects were due to a real decrease in the sensory response for attended stimuli or to an inappropriate subtraction of the baseline activity from the sensory responses of some cells. To ensure that none of the significant effects were caused by the baseline shift, it is possible to accept positive attention effects as valid only when they are significant with the baseline subtracted away and to accept negative attention effects as valid only when they are significant without the baseline subtracted away. With this criterion, there were two cells with significant positive effects of attention in V4 not accounted for by baseline shifts and three cells with negative effects, which is not significantly different from the number expected by chance (binomial

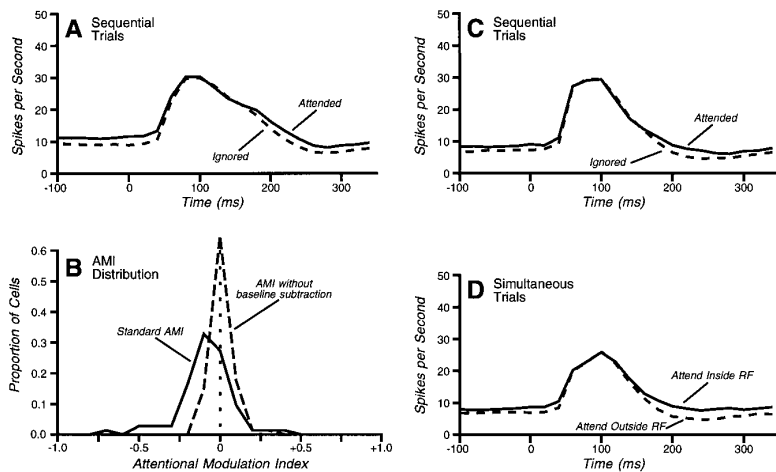


FIG. 7. *A*: poststimulus histograms for nontarget stimuli presented inside the RF on sequential stimulus presentation trials, averaged over all 74 V4 cells in the inside/outside configuration with the same features at both locations (conditions  $B_1$  and  $B_2$  combined). One location was inside the RF and the other was at a mirror-symmetrical position across either the horizontal or vertical meridian. *B*: probability distribution of the standard AMI and the AMI computed without baseline subtraction for the cells shown in *A*. *C*: poststimulus histograms for sequential trials, averaged over 38 cells in which data were obtained for both sequential and simultaneous stimulus presentation trials (condition  $B_2$  alone). *D*: poststimulus histograms for simultaneous trials, averaged over the same cells shown in *C*.

theorem,  $P = 0.165$ ). However, this conservative criterion probably underestimates the true number of cells with real effects of attention on the sensory response.

The difference in baseline activity when attention was directed inside versus outside the RF also affected the AMI values in the same way. Because the baseline firing rate was subtracted from the sensory response when the AMI was computed, the higher baseline firing rate on trials in which attention was directed inside the RF caused a negative shift in the AMI values for this condition (Fig. 7*B*, solid line). The mean AMI value was  $-0.10$ , which corresponds to a 22% decrease in the response when the stimulus inside the RF was attended compared with when it was ignored. To reduce the effect of the baseline activity changes, we computed an alternative AMI value without subtracting the baseline (Fig. 7*B*, dashed line). The AMI without baseline subtraction had a mean of  $0.01$ , which is consistent with the lack of an attention effect on the peak stimulus-evoked response that can be seen in the poststimulus histograms for this condition (Fig. 7*A*). In sum, there was relatively little overall effect of attention on the stimulus-evoked response in the inside/outside configuration, and the modest effects that were observed could be interpreted as either positive or negative depending on how the baseline firing rate was treated.

Of the 74 total cells tested with the inside/outside configuration, 38 were tested with both simultaneous and sequential trials, and poststimulus histograms are shown for this subset of cells in Fig. 7, *C* (sequential trials) and *D* (simultaneous trials). Although simultaneous presentation greatly increased the size of the attention effect in the inside/inside configuration (condition  $A_1$  above), the effects of attention were virtually identical for simultaneous and sequential trials in the inside/outside configuration.

**EFFECTS OF ATTENTION ON BASELINE FIRING RATES (CONDITIONS  $B_1$  AND  $B_2$ ).** As indicated above, attention had a consistent effect on the baseline firing rate of the cells in the inside/outside configuration even though there was little or no effect on the peak stimulus-evoked response. Specifically, individual ANOVAs computed on the data from each cell on sequential trials indicated that 40 of the 74 cells in conditions  $B_1$  and  $B_2$  had a significantly higher firing rate during the prestimulus interval when attention was directed inside

the RF compared with when attention was directed outside the RF (similar results were obtained on simultaneous trials). Only two cells showed a significant effect in the opposite direction. For those cells showing a significant positive effect of attention in the baseline period, the baseline firing rate was 42% higher when attention was directed inside rather than outside the RF (14.4 vs. 10.1 spikes/s, respectively).

As shown in Fig. 8*A*, this shift in the baseline firing rate began at the start of the trial,  $\sim 175$  ms after the onset of

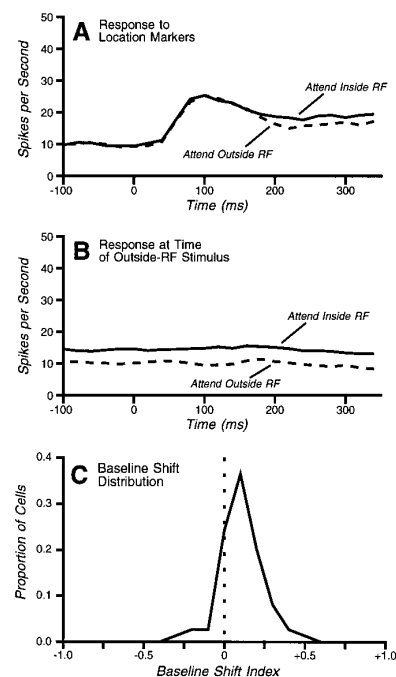


FIG. 8. *A*: activity at the beginning of the trial for the 40 V4 cells that showed a significant attention effect in the baseline period in conditions  $B_1$  and  $B_2$ . Time 0: onset of the location markers that appeared 500 ms before the start of the task-relevant stimulus sequence. Note that the increase in firing that can be seen between 50 and 100 ms poststimulus reflects the onset of the location marker boxes. *B*: activity for the same cells shown in *A* during the time periods in which a nontarget stimulus was presented outside the RF. Time 0: onset of the outside-RF stimulus. *C*: probability distribution of the baseline shift index for all 74 cells in the inside/outside configuration with the same features at both locations (conditions  $B_1$  and  $B_2$  combined).

the location markers that appeared at the beginning of each trial (*time 0* on the abscissa). This effect was also present in the time period during which a stimulus was presented outside the RF, as shown in Fig. 8*B*. The increase in baseline firing therefore began before the first task-relevant stimulus was presented and appeared to continue throughout the entire trial, but was not present at the very beginning of the trial.

To quantify the magnitude of this baseline shift across the entire population of cells, a baseline shift index (BSI) was computed in a manner similar to the AMI:  $BSI = (\text{baseline when attending inside the RF} - \text{baseline when attending outside the RF}) \div (\text{baseline when attending inside the RF} + \text{baseline when attending outside the RF})$ . Baseline activity was quantified as the mean firing rate in the 100 ms preceding stimulus onset. The distribution of the BSI over the population is shown in Fig. 8*C*. This index was  $>0$  for 80% of the 74 cells in this population, and the mean value was 0.13, which corresponds to a 30% higher firing rate when attention was directed inside the RF compared with outside the RF. Thus, although the baseline shift effect consists of an increase of only a few spikes per second in a given cell, it represents a substantial effect when the entire population is considered. Additional experiments concerning this effect are described in a later section.

**CONTROL FOR STIMULUS SEPARATION (CONDITIONS  $B_3$  AND  $B_4$ ).** Although the effects of attention on sensory responses in the inside/inside and inside/outside configurations appeared to be very different, the spatial separation between the attended and ignored stimuli was larger in the inside/outside configuration; if attention effects simply decrease as the distance increases, this might explain the difference in results between the two configurations. We therefore tested an additional 59 V4 cells with the use of one location inside the RF and one location that was just outside the classical excitatory RF (conditions  $B_3$  and  $B_4$ ). All 59 cells were tested with sequential trials, and 29 were also tested with simultaneous trials. The outside location was often in the inhibitory surround of the RF, as indicated by an inhibition of the cell's baseline firing rate when a stimulus was presented alone at this location (significant inhibitory responses were observed in 17 of the 59 cells). The average separation between the two locations was  $3.6^\circ$ , which was approximately equal to the separation used in the inside/inside configuration.

As is evident in the population-average poststimulus histograms shown in Fig. 9*A*, bringing the two locations closer together did not lead to an increase in positive attention effects. Indeed, the average peak response was slightly smaller for attended stimuli than for ignored stimuli (i.e., a negative attention effect). An increase in baseline activity was observed when attention was directed to the location inside the RF, just as in the cells tested with a greater separation between the attended and ignored locations (conditions  $B_1$  and  $B_2$ ). The mean BSI across the population of cells in the present condition was 0.17, corresponding to a 41% change in baseline firing rates. Similar effects were observed on both simultaneous and sequential trials (see Fig. 9, *C* and *D*).

To assess these effects quantitatively, we first computed the firing rates in the poststimulus period, without subtracting baseline activity, for the stimuli presented inside the

RF on sequential trials. Of the 59 cells tested, 5 showed significantly larger responses when the stimulus was attended compared with when it was ignored (positive attention effects) and 6 showed significant effects in the opposite direction (negative attention effects). As was the case with larger stimulus separations, the proportion of cells with significant attention effects was substantially smaller than it was when both stimuli were inside the RF. When the baseline activity was subtracted away to compensate for the shift in baseline, the number of cells with positive attention effects dropped to 1 and the number of cells with apparently negative attention effects increased to 25. Thus, if any possible effects of the baseline are eliminated by counting positive effects with the baseline subtracted and negative effects with the baseline included, there were seven cells with significant effects of attention; this is somewhat more than would be expected by chance (binomial theorem,  $P = 0.009$ ).

The shift toward negative effects caused by subtracting the baseline activity can also be seen in the AMI population histogram (see Fig. 9*B*), which was computed with the baseline activity subtracted. The majority of cells had a negative AMI, and the mean AMI across the population was  $-0.14$ , which corresponds to a 33% decrease in the response to a stimulus when it was attended compared with when it was ignored. However, the average AMI was 0.00 when the AMI was computed without subtracting the baseline activity. Thus, depending on how the baseline was treated, the effects of attention on the sensory response in this condition were either small or predominantly negative.

#### *Area V4, multiple-item displays (condition C)*

A recent study by Motter (1993) suggested that cells in V4 may show attention effects with a single stimulus inside the RF, but only when many stimuli are presented simultaneously outside the RF. It is therefore possible that the absence of large attention effects in the inside/outside conditions described above was due to the use of only one stimulus outside of the RF. To examine this possibility, we conducted an experiment in which stimuli were presented at one location inside the RF and either one or four additional locations outside the RF, positioned as shown in Fig. 10*A* (condition C, *monkey B* only). Although this is fewer stimuli than used by Motter, they were positioned to create a relatively high density within the same hemifield as the RF, without actually encroaching on the RF. The two or five stimuli were always presented simultaneously and were presented in the same color and orientation. Trials with two stimuli were run in separate blocks from trials with five stimuli. Except for these differences, the conditions were unchanged from the recordings described above (e.g., condition  $A_1$ ).

In general, the effects of attention were not strongly influenced by increases in the number of stimuli. Figure 10 shows average poststimulus histograms for the 15 cells studied under these conditions. When the responses were measured without subtracting the baseline, five cells showed significantly larger responses when attention was directed to the stimulus inside the RF on two-item trials, and six cells showed such effects on five-item trials (4 of these cells showed significant effects on both 2- and 5-item trials). One cell showed significantly smaller responses when attention was directed to the stimulus inside the RF for both two-item

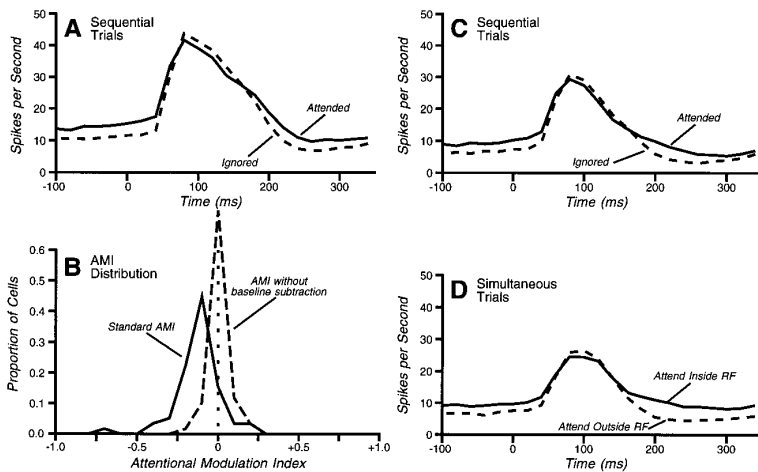


FIG. 9. A: poststimulus histograms for nontarget stimuli on sequential trials, averaged over all 59 V4 cells recorded with 1 location inside the RF and the other location in the same quadrant, just outside the RF (conditions B<sub>3</sub> and B<sub>4</sub> combined). B: probability distribution of the standard AMI and the AMI without baseline subtraction for the cells shown in A. C: poststimulus histograms for sequential trials, averaged over 28 cells in which data were obtained for both sequential and simultaneous trials (condition B<sub>4</sub> alone). D: poststimulus histograms for simultaneous trials, averaged over the same cells shown in C.

and five-item trials. As was the case for the inside/outside data in conditions B<sub>1</sub>–B<sub>4</sub>, there was a substantial shift in baseline activity when attention was directed inside the RF for both the two- and five-item trials in condition C. When we subtracted this baseline difference from the sensory responses, there was a decrease in the number of positive attention effects (3 significant cells for each array size), accompanied by an increase in the number of significant negative attention effects (2 significant cells for each array size).

To test whether the attention effects were significantly different for the two-item compared with the five-item trials, we measured the mean sensory response across trials for each cell (with the baseline firing rate subtracted away) and entered these values into a single two-factor ANOVA with direction of attention and number of stimuli as within-subjects factors. Although there was a tendency for the attention effects to be larger on the five-item trials, the interaction between the attention effect and the number of stimuli did not approach statistical significance [ $F(1,14) = 2.35$ ,  $P =$

0.15]. This analysis was also repeated with a longer measurement window of 50–250 ms to include the offset of the sensory response, but the interaction again failed to reach significance [ $F(1,14) = 2.83$ ,  $P = 0.11$ ]. Thus increasing the number of stimuli in the display did not substantially influence the attention effects under the present task and stimulus conditions.

#### Explorations of the baseline shift effect in area V4 (conditions B<sub>5</sub> and D)

ROLE OF THE LOCATION MARKER BOXES (CONDITION B<sub>5</sub>). There are many potential explanations for the increase in baseline activity that was observed when attention was directed inside the RF, and we explored several of these possibilities. We first tested the hypothesis that this shift reflected a change in the sustained sensory response elicited by the location marker boxes, which were present continuously throughout the entire trial. Specifically, if the sustained sensory response to the location marker box located inside the

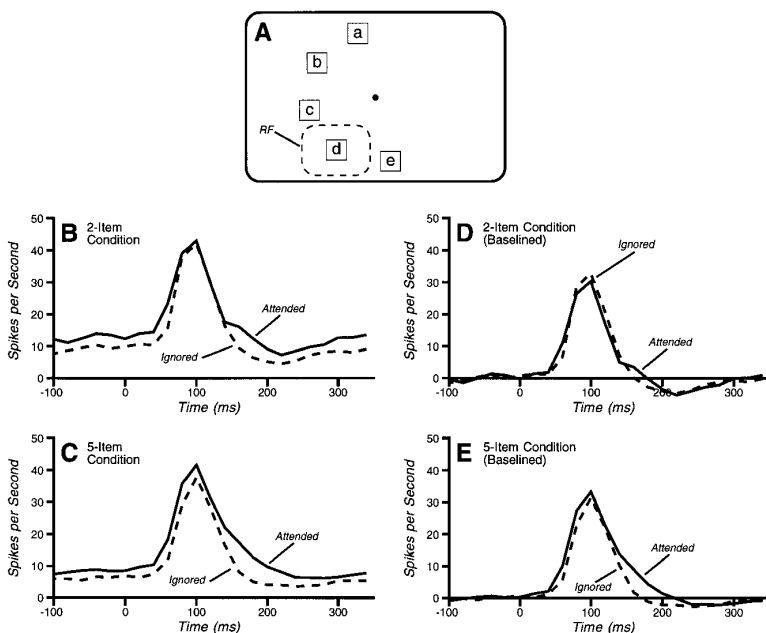


FIG. 10. A: stimulus configuration used to test the effects of the number of stimuli in area V4 (condition C). All 5 locations were used on 5-item trials, whereas only the locations labeled b and d were used on 2-item trials. For both trials types, however, attention was always directed toward either location b or location d, thus equating the spatial demands of the task across configurations. The stimuli were always presented simultaneously, and the same stimulus features were used at all locations. B: poststimulus histograms for nontarget stimuli on 2-item trials, averaged over 5 cells showing a significant attention effect. C: poststimulus histograms for nontarget stimuli on 5-item trials, averaged over 6 cells showing a significant attention effect. D: same as B, except that the average firing rate in the 100-ms prestimulus interval was subtracted away from the histograms to eliminate any effects of baseline differences. E: same as C, except that the average firing rate in the 100-ms prestimulus interval was subtracted away from the histograms to eliminate any effects of baseline differences.



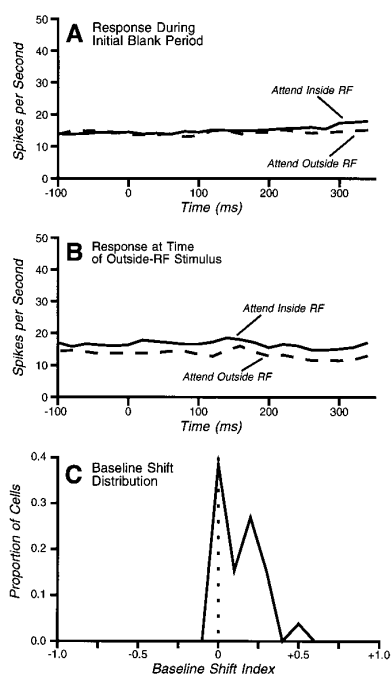


FIG. 11. *A*: poststimulus histograms averaged over all 26 V4 cells tested in the inside/outside configuration with no location markers (condition B<sub>5</sub>). These histograms show activity at the beginning of the trial, and *time 0* represents the time point at which the location markers normally appeared, 500 ms before the start of the task-relevant stimulus sequence. This is analogous to Fig. 8*A*, except no location markers were present. *B*: poststimulus histograms for the same cells shown in *A*, but showing activity during the periods in which nontarget stimuli were presented outside the RF. *C*: probability distribution of the baseline shift index for the cells shown in *A*.

RF was larger when attention was directed inside the RF, then this would have produced an apparent increase in the baseline firing rate.

To test this hypothesis, we eliminated the location marker boxes in recordings from 26 V4 cells, with the use of the inside/outside configuration and sequential stimulus presentation (condition B<sub>5</sub>, *monkey A* only). One location was centered inside the RF and the other was in the mirror-symmetrical position across the vertical meridian. At the beginning of each trial, a 500-ms blank delay period replaced the 500-ms period during which the location markers were normally presented before the onset of the task-relevant stimulus sequence. The task-relevant stimuli were then presented on a screen that was entirely blank except for the fixation point (which was always located outside the RF). The to-be-attended location was indicated to the monkey by means of instruction trials at the beginning of each trial block in which a location marker box was presented only at the to-be-attended location; once the monkey began responding selectively to targets at this location, the location marker was eliminated and the recording for that block began.

As shown in Fig. 11, the baseline shift effect was indeed present under these conditions, beginning in the blank period that preceded the onset of the task-relevant stimuli and continuing throughout the entire course of the trial. Of the 26 cells, 18 showed significantly greater firing rates in the prestimulus interval when attention was directed inside the RF compared with when attention was directed outside the RF, and none of the cells showed a significant effect in the opposite direction. The distribution of the BSI across the

population of cells in this condition was similar to the distribution observed when location markers were present (compare Figs. 8*C* and 11*C*), and the mean BSI value of 0.13 in the present condition was similar to the mean value of 0.12 that was obtained when location markers were present. Thus the baseline shift effect can occur in the absence of continuous stimulus presentation and presumably reflects a top-down input to the cells rather than a modulation of sensory processing.

**ROLE OF TARGET FEATURES (CONDITION D).** A second possible explanation for the baseline shift effect is that it reflects an internal memory or template of the target stimulus, achieved by means of activating the cells that would normally respond to the target when it is actually presented. For example, a target consisting of a green square in the lower left quadrant of the display might be represented in short-term memory by an increased spontaneous firing rate in cells that are responsive to green squares and have RFs that include the lower left quadrant. If so, this would lead to the increase in baseline activity that was observed when attention was directed inside the RF, because all of the cells described above were responsive to the target stimulus when presented inside the RF. We tested this hypothesis by recording baseline activity in trial blocks in which the target stimulus was an effective sensory stimulus for the cell being recorded and comparing this with the baseline activity recorded in trial blocks in which the target stimulus features were ineffective in driving the cell (condition D, *monkey A* only). We predicted that, if the baseline shift effect reflects activation of cells that code the expected target stimulus features, then this activity would be found primarily in those neurons that would normally respond well to the target.

In this condition, stimuli were presented simultaneously at two locations, one centered inside the RF and the other at the mirror-symmetrical position across the vertical meridian. The stimuli were selected so that both the nontarget and target stimuli at one location were effective at driving the cell (when presented alone inside the RF), whereas both the nontarget and target stimuli at the other location were ineffective. As in the previous conditions, the nontarget and target stimuli at a given location shared the same color and orientation. The positions of the effective and ineffective stimuli remained fixed during each 3-min trial block, and each block was preceded by instruction trials to indicate the color, orientation, and location of the target for that block. The positions of the effective and ineffective stimuli were switched between blocks, and all combinations of stimulus location and attended location were tested in each cell.

We were able to test only eight highly selective cells from a single monkey in this condition, but the results were very clear in these cells, as summarized in Fig. 12. Specifically, the baseline shift was approximately equal in magnitude whether the target was an effective or ineffective stimulus, and no statistically significant differences were observed between these cases. In addition, significant baseline shift effects were observed equally often when the target was effective and when it was ineffective. Thus directing attention inside the RF leads to an increase in baseline activity even when the cell does not respond to the target stimulus presented inside the RF. This finding casts doubt on the hypothesis that the baseline shift effect reflects the activation of a

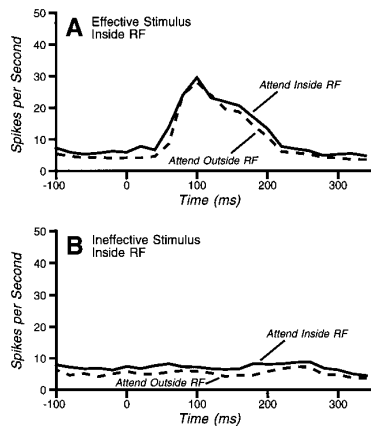


FIG. 12. Poststimulus histograms averaged over 8 highly selective V4 cells (condition D), tested with an effective stimulus inside the RF (A) or with an ineffective stimulus inside the RF (B). These histograms show the average of the nontarget trials, because these were the most numerous and therefore had the highest signal-to-noise ratio. The cells were selected on the basis of showing a large response for the effective target stimulus and little or no response for the ineffective target stimulus ( $<3$  spikes/s on average), but these cells were also typically highly selective for the corresponding nontarget stimuli, as shown here.

template or memory that includes the color and orientation of the target stimulus, although it could reflect a memory that specifies only the location of the target.

**BASELINE SHIFTS IN THE INSIDE/INSIDE CONFIGURATION (CONDITION A<sub>2</sub>).** Although the baseline shift effect was observed with several different spatial configurations in the inside/outside configuration, this effect cannot ordinarily be observed in the inside/inside configuration because attention is always directed inside the RF in this configuration. However, we noticed that even when both stimulus locations were inside the RF, stimuli at one location elicited larger responses than stimuli at the other location for many cells, presumably because one location was closer to the center of the RF. This suggested that the baseline shift might actually be observable in the inside/inside configuration and that we could measure it if we compared the baseline activity when attention was directed to the more responsive versus the less responsive location.

To test this possibility, a regression analysis was conducted that quantified the relationship between a measure of location preference and the BSI across the 75 cells tested in the inside/inside sequential condition with the same features at both locations (condition A<sub>2</sub>). In this analysis, the two stimulus locations were arbitrarily labeled location 1 and location 2, and a location preference index (LPI) was computed by measuring the response to a stimulus at each location, irrespective of the direction of attention, with the baseline firing rate subtracted. The difference between the responses at the two locations was then scaled by the sum of the responses, and the LPI was computed as the scaled difference in response size:  $LPI = (\text{location 1 response} - \text{location 2 response}) \div (\text{location 1 response} + \text{location 2 response})$ . This index ranges between +1.0 for complete location 1 preference and -1.0 for complete location 2 preference. The BSI also ranged between +1.0 for greater baseline activity when location 1 was attended and -1.0 for greater baseline activity when location 2 was attended, and was computed for this condition as follows:  $BSI = (\text{baseline}$

when attending to location 1 - baseline when attending to location 2)  $\div$  (baseline when attending to location 1 + baseline when attending to location 2).

Figure 13A displays the results of this analysis and shows that directing attention to the more effective location led to a higher baseline firing rate than directing attention to the less effective location. The correlation between the LPI and BSI was strong and highly significant ( $r = 0.51$ ,  $P < 0.001$ ), and the slope of the regression line was fairly steep (0.68).

To examine this effect in another way, average poststimulus histograms were constructed from the 16 cells that had the largest location preferences (LPI less than -0.15 or LPI greater than +0.15, which corresponds to a difference of at least 38%). These histograms were then used to compare the baseline activity when attention was directed to the more effective or the less effective location. Figure 13B shows the responses of these cells following the onset of the location markers at the onset of the trial, before the beginning of the task-relevant stimulus sequence. A baseline shift can clearly be seen in these histograms, even though both locations were inside the RF. Thus an attention-related shift in baseline firing may occur in both the inside/inside and inside/outside configurations. It should be noted, however, that attentional modulation of the sensory response was not dependent on the presence of a higher level of baseline activity in the recorded cell: significant positive attention effects were frequently observed for stimuli at the less effective location (in the sequential stimulus conditions), even though the baseline firing rate was lower when attention was directed to this location.

#### Recordings from area V2 (condition E)

Recordings were obtained from 73 cells in area V2 with the same basic task used for the initial inside/inside recordings from area V4 (condition A). Of these 73 cells, 65 had RFs that were too small for both stimulus locations to be placed within the RF. Therefore for these cells we placed one location at the center of the RF and one location outside the RF. The outside-RF location was in the mirror-symmetrical position across the horizontal or vertical meridian for 23 cells (condition E<sub>1</sub>) and within the same quadrant as the RF in 42 cells, at a distance comparable with the distances between locations used in the inside/inside recordings in area V4 (condition E<sub>2</sub>). Because no clear differences were observed as a function of the location of the outside-RF stimulus, the data presented below have been collapsed across these spatial configurations. The same stimulus features were used at both locations, and sequential and simultaneous trials were randomly intermixed.

The results from these recordings, which are summarized in Fig. 14, were highly similar to the inside/outside results obtained in area V4 (see Fig. 7). Specifically, baseline firing rates were typically greater when attention was directed inside the RF, but there was no consistent effect of attention on the stimulus-evoked response. The effect of attention on baseline activity was somewhat more consistent in area V2 than in area V4, and was statistically significant in almost 75% of the neurons (48 of 65). For cells showing a significant effect, the baseline was 44% higher when attention was directed inside versus outside the RF (11.69 vs. 8.14 spikes/s, respectively). The mean BSI across the entire population

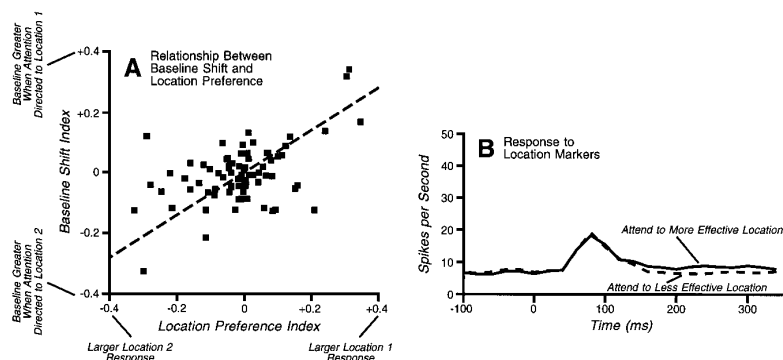


FIG. 13. A: scatterplot of the relationship between the baseline shift index and the location preference index (LPI), based on all 75 V4 cells from the original inside/inside configuration (condition A<sub>2</sub>). For these cells, all trials were sequential and the same features were used at both locations. B: activity at the beginning of the trial, averaged over 16 cells that showed substantial preference for 1 of the 2 locations (LPI less than  $-0.15$  or LPI greater than  $+0.15$ ). Time 0: onset of the location markers that appeared 500 ms before the start of the task-relevant stimulus sequence.

of cells was 0.18, which corresponds to a 43% change in baseline firing rates. No cells showed significant baseline shifts in the opposite direction.

When the stimulus-evoked responses were analyzed, 4 of the 65 cells were found to have a significant negative attention effect (i.e., a smaller response when the stimulus was attended than when it was ignored). Significant positive attention effects for the stimulus-evoked response were observed in 12 cells, although some of these effects appear to have been a result of a continuation of the baseline shift into the time period of the sensory response. As in the V4 analysis, we compensated for any contribution of elevated baseline activity to the attention effects by subtracting the baseline activity from the stimulus-evoked responses and repeating the analysis. Significant positive attention effects remained in five cells in this analysis, which is slightly more

than would be expected by chance. As was true in the V4 data, subtracting the baseline activity caused an increase in the number of cells with significant negative attention effects (from 4 to 22 cells). If the possible effects of baseline shifts are discounted, a total of 14% of the cells showed a significant attentional modulation of the sensory response (5 cells with significant positive effects after baseline subtraction and 4 cells with significant negative effects without baseline subtraction).

Data were also obtained from eight cells that were selective for orientation or color and had RFs that were large enough to fit both the attended and ignored locations ( $2 \times 2^\circ$  or larger), allowing recordings to be obtained with the inside/inside configuration (condition E<sub>3</sub>). As can be seen in the single-cell examples displayed in Fig. 15, the sensory responses were modulated by attention, just as in area V4. However, although these cells began to respond  $\sim 40$  ms after stimulus onset, the effects of attention did not typically begin until after 100 ms poststimulus. As a result, only one of the eight cells showed a significant effect of attention in the 30- to 130-ms latency range. We therefore conducted a second analysis based on the firing rate in the 130- to 230-ms latency range, and many more significant effects were observed in this analysis. On sequential trials, six of the eight cells exhibited significantly larger responses to the effective stimulus when it was attended than when the ineffective stimulus was attended. On simultaneous trials, seven of the eight cells showed a significantly larger response to the effective-ineffective pair when the effective stimulus was attended. Thus attention had consistent effects on V2 sensory responses when both the attended and ignored stimuli were located within the RF, just as in area V4. However, the number of cells recorded with the inside/inside configuration in area V2 was too small to assess the time course of the attention effects or to determine whether the effects were larger on simultaneous trials than on sequential trials.

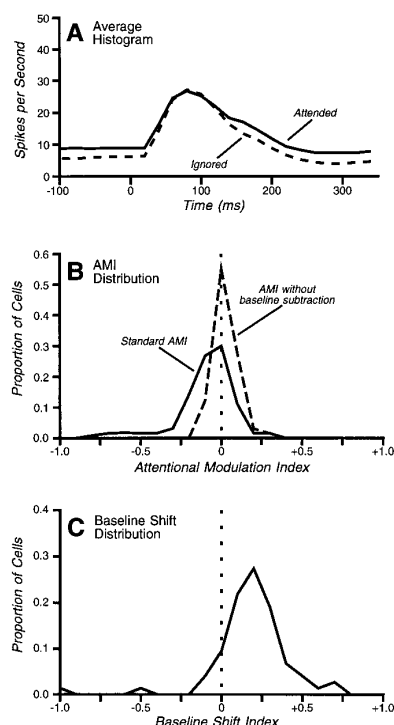


FIG. 14. A: poststimulus histograms for nontarget stimuli on sequential trials, averaged over all 65 V2 neurons in the inside/outside configuration with the same features at both locations (conditions E<sub>1</sub> and E<sub>2</sub> combined). B: probability distribution of the standard AMI and the AMI without baseline subtraction for the cells shown in A. C: probability distribution of the baseline shift index for the cells shown in A.

#### Recordings from area V1 (condition F)

We recorded from 79 cells in area V1 with the same basic task used in areas V2 and V4. Because of the small RF sizes in V1, only one stimulus location could be placed inside the RF. The other was placed outside the RF, but was located nearby in the same quadrant such that both locations could fall within a typical RF in area V4. In addition, the stimuli were decreased in size (typically  $0.2 \times 1.0^\circ$ ) to achieve a maximal response. Some of the cells were recorded with

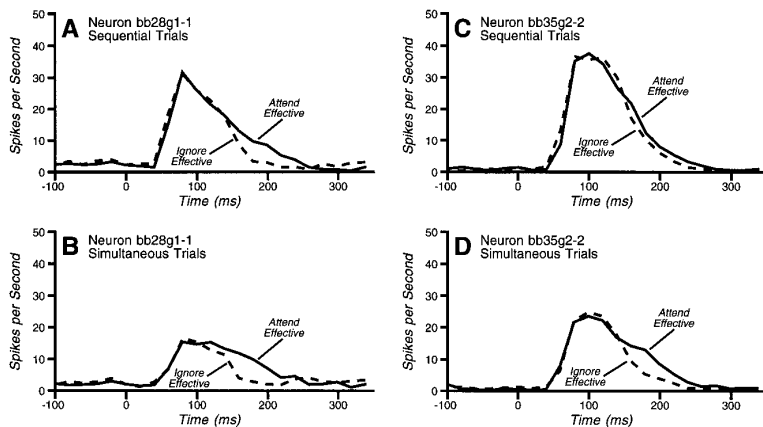


FIG. 15. Poststimulus histograms for 2 representative V2 cells from the inside/inside configuration with different features at the 2 locations (condition  $E_3$ ). Solid line: trials on which attention was directed to the effective feature. Dashed line: trials on which attention was directed to the ineffective feature. A: effective stimulus on sequential trials for neuron *bb28g1-1*. B: effective and ineffective stimuli presented together on simultaneous trials for neuron *bb28g1-1*. C: effective stimulus on sequential trials for neuron *bb35g2-2*. D: effective and ineffective stimuli presented together on simultaneous trials for neuron *bb35g2-2*.

sequential trials only (condition  $F_1$ ), and others were recorded with both sequential and simultaneous trials (condition  $F_2$ ).

Figure 16A displays poststimulus histograms averaged across the entire population of V1 cells. These histograms indicate that there was no consistent effect of attention on the stimulus-evoked response in these cells. This can also be seen in Fig. 16B, which shows that the AMI values for these cells were typically near 0, with a mean of  $-0.02$ . For 60 of the 79 cells, the attended and ignored stimuli were presented simultaneously instead of sequentially on a subset of trials, and comparable results were obtained for both sequential and simultaneous trials.

When the individual cells were examined statistically, three showed significantly larger responses to attended stimuli and four showed significantly larger responses to ignored stimuli, which is only slightly larger than the number expected by chance (binomial theorem,  $P = 0.044$ ). It is important to note, however, that the small size of the V1 RFs precluded us from testing cells with the inside/inside configuration, and it is possible that attention more clearly affects V1 activity when both attended and ignored items fall within a given cell's RF.

In contrast to areas V2 and V4, where attention influenced

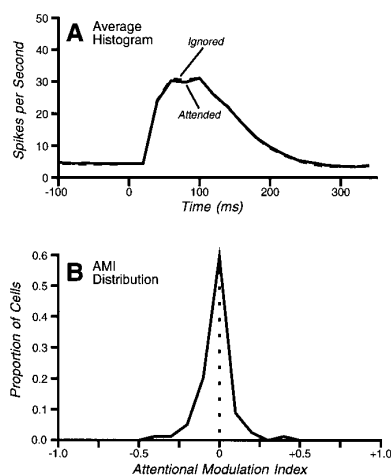


FIG. 16. A: poststimulus histograms for nontarget stimuli on sequential trials, averaged over all 79 V1 cells in the inside/outside configuration with the same features at both locations (conditions  $F_1$  and  $F_2$  combined). B: probability distribution of the AMI for the cells shown in A.

baseline firing rates across a variety of stimulus configurations, there was no consistent increase in the baseline firing rate in area V1 when attention was directed inside the RF (see Fig. 16A). Of the 79 cells, 3 showed a significant increase and 3 showed a significant decrease in baseline activity when attention was directed inside rather than outside the RF, and even the significant effects were quite weak. Thus the baseline shift effect appears to arise subsequent to area V1.

#### Eye movements

Because RFs in areas V1 and V2 are typically quite small, fixation shifts of only a few minutes of arc may significantly influence responses in these areas. However, the possibility of small but systematic differences in fixation location has not been tested in most electrophysiological studies of spatial selective attention in these areas. To assess the possibility that small shifts in fixation may have influenced the attention effects described above, we conducted a series of statistical analyses ( $t$ -tests) in which we compared the average eye position when the monkey attended to one location versus the other location. Trials that were terminated because of response errors or eye movements beyond the  $0.5^\circ$  fixation window were excluded from this analysis. Despite the use of this small window, statistically significant differences in eye position were found in  $\sim 85\%$  of the inside/outside recordings. These eye position differences were quite small, averaging  $\sim 0.03^\circ$  and never exceeding  $0.08^\circ$ . However, given the small RF sizes in V1 and V2, even these small differences in eye position might have been enough to produce statistically significant differences in the sensory response for some of the neurons. In addition, small shifts in eye position would be expected to move the stimulus closer toward the center of the RF in some cases and farther away in others, sometimes leading to positive effects and sometimes leading to negative effects. This is exactly the pattern observed in areas V1 and V2 in the inside/outside conditions. We therefore cannot rule out the possibility that some of the significant attention effects obtained with the inside/outside configuration in V1 and V2 were artifacts of small shifts in eye position. It is unlikely that shifts in eye position could account for the few significant attention effects found with the inside/outside configuration in area V4, however, because the V4 RFs were typically several degrees wide,  $\geq 2$



orders of magnitude larger than the average  $0.03^\circ$  difference in eye position.

We also examined eye position differences in the inside/inside conditions, in which the attended and ignored stimuli were closer together than in some of the inside/outside conditions. As expected, the average difference in eye position was smaller than in the inside/outside conditions (40% smaller, or  $0.02^\circ$ ). Thus several factors argue against the possibility that fixation differences were responsible for the attention effects observed in the inside/inside conditions: 1) the fixation differences were smaller in the inside/inside conditions, but the attention effects were larger; 2) compared with the size of the fixation differences, RF sizes were large in both V2 and V4 in the inside/inside conditions (at least  $2 \times 2^\circ$ ); and 3) attention effects in the inside/inside conditions were consistently positive rather than a mixture of positive and negative.

### *Correlations and oscillations*

It has been suggested that oscillatory neuronal responses or synchronized activity across several cells may play a role in selective attention (e.g., Eckhorn et al. 1988; Niebur et al. 1993; Singer and Gray 1995). If so, the baseline shifts observed in the present experiment might reflect an increase in such oscillatory or synchronized activity. To assess this possibility, we conducted time series analyses on the inside/outside data from area V4 (conditions B<sub>1</sub>–B<sub>5</sub>, 154 cells) and area V2 (conditions E<sub>1</sub> and E<sub>2</sub>, 62 cells). Autocorrelations were computed for each individual cell and cross-correlations were computed for pairs of cells that were recorded simultaneously from the same electrode. These analyses were applied to the 800-ms period that began at the onset of the location markers at the beginning of each trial and ended 300 ms after the onset of the first task-relevant stimulus. This interval was chosen because it was available on all trials, regardless of sequence length. Correlations were assessed with time lags ranging from  $-200$  to  $+200$  ms. Correlations between two neurons are normally affected by the presentation of stimuli to which both neurons respond, and this source of correlation was subtracted away with the use of a procedure described by Gochin et al. (1991).

About 5% of the cells showed some evidence of oscillations in their autocorrelograms, but only one cell showed a strong and unambiguous oscillation. In addition, many pairs of cells had peaks in their cross-correlograms, typically centered at 0 ms. However, the oscillations and correlations were not affected in any consistent manner by the direction of attention. Specifically, the correlations and oscillations were not consistently larger when attention was directed inside the RF, nor were substantial effects of attention observed in any individual autocorrelograms or cross-correlograms. Thus, although we cannot conclusively rule out the possibility of attention-related changes in oscillations or correlations, any such effects were too small to be readily observed in the present recordings.

### DISCUSSION

Several years ago, Moran and Desimone (1985) reported that when a monkey attended to one of two stimuli that were placed within the RF of a neuron in V4 or IT cortex, the

neuron's response was determined primarily by the features of the attended stimulus. There was no effect of attention, however, when one stimulus was located inside the RF and the other was outside. A number of models have been proposed to explain these and related results (e.g., Crick and Koch 1990; Desimone 1992; Niebur et al. 1993; Olshausen et al. 1993; Tsotsos 1995), including the proposal that attention serves to bias competitive interactions between stimuli. Specifically, competition may result from mutual inhibition between extrastriate cells or between the inputs to these cells, and these bottom-up interactions may be influenced by top-down signals from systems that control attention and working memory (Desimone and Duncan 1995; Desimone et al. 1990).

According to this view, attentional modulation of sensory processing is accomplished by a two-stage mechanism. In the first stage, top-down signals bias activity in favor of cells representing the relevant object or location. In the second stage, these selected cells gain an advantage in their competitive interactions with other neurons and ultimately suppress the responses of these cells. Because these competitive interactions are likely to be strongest for nearby cells sharing the same RF, this would explain why attention effects are largest when two stimuli are present within the same RF. We assume that the same mechanism operates in both area V4 and IT cortex, but that the spatial range of the competitive interactions is much larger in IT cortex because of the larger RFs in this area. This view of the role of attention in V4 and IT cortex contrasts markedly with the common assumption that attention simply enhances the processing of stimuli at the attended location at the expense of all other locations in the visual field, which may be a more appropriate description of the operation of attention in other structures, such as posterior parietal cortex (see Colby 1991).

In the present study we examined this competition-based model and the conclusions of Moran and Desimone (1985) with a different behavioral paradigm and a variety of stimulus manipulations. We have confirmed that, when effective and ineffective stimuli are presented simultaneously within the RF of a V4 neuron, the sensory response is larger when attention is directed to the effective stimulus than when attention is directed to the ineffective stimulus. In other words, the response of the cell was determined primarily by the attended stimulus when attended and ignored stimuli were presented simultaneously. We also found that attentional modulations occurred under conditions of both simultaneous and sequential stimulus presentation, although the attention effects were considerably larger with simultaneous presentation. This difference between simultaneous and sequential presentation is consistent with the competition idea, because competition between two stimuli is likely to be reduced when they are presented at different times.

We have also confirmed the finding of Moran and Desimone that attentional modulations of the sensory response are greatly diminished when the attended and ignored stimuli are moved apart so that they are not located within the same RF (i.e., in the inside/outside configuration). Although some cells exhibited significant effects of attention with this stimulus configuration, these cells were relatively infrequent, and the attention effects were almost as likely to consist of smaller responses to the attended stimulus as they were to consist of larger responses.

The comparison of the inside/inside and inside/outside configurations in the present study was complicated by the presence of shifts in baseline firing rates in the inside/outside configuration. Specifically, the effects of attention on the sensory response in the inside/outside condition depended on whether the sensory response was measured as an absolute firing rate or as a change in firing relative to the prestimulus firing rate. It is not clear which of these measurements best reflects the information used by the visual system in this context, and it is therefore prudent to conclude that the effects of attention in the inside/outside configuration might be either minimal or predominantly negative (i.e., depending on how the baseline firing rate is treated). In either case, however, consistently positive attention effects were obtained only when both the attended and ignored stimuli were presented inside the RF.

Although area V2 was not studied by Moran and Desimone (1985), our results indicate that a similar mechanism operates there as well as in V4. Specifically, the sensory responses of V2 cells were consistently modulated by attention when both the attended and ignored stimuli were presented inside the RF. In addition, similar to Moran and Desimone, we found no consistent attention effects in area V1, where the RFs were too small to contain both stimuli. Given that consistent attentional modulations were observed in area V2 in the inside/inside condition, it is quite possible that such effects could also be observed in area V1 if both attended and ignored stimuli could somehow be placed inside a single RF. However, it should be noted that no attention-related shifts in baseline activity were observed in area V1, even though these shifts were present under comparable conditions in areas V2 and V4.

The present findings of differences between the inside/inside and inside/outside conditions in areas V2 and V4 should not be taken to imply that RFs have sharply defined and permanently fixed borders or that there is a sudden shift in the effects of attention at the RF border (De Weerd et al. 1995; Gilbert and Wiesel 1992). In general, the stimuli used in the present study were either well inside or well outside of the excitatory portion of the RF, and it was not possible to examine how the effects of attention changed in the transitional zone between the excitatory and inhibitory areas. If attention depends on competition, however, then we would expect that the effects of attention on a stimulus located near the RF center would gradually decline if the second stimulus were moved toward the periphery of the excitatory region.

#### *Effects of attention on baseline firing rates*

In addition to attentional modulations of stimulus-evoked responses, we also found that the spontaneous activity of cells in V2 and V4 was increased when the animal attended to a location within the RF, resulting in a shift in prestimulus baseline firing rates. This effect was observed even when both stimuli were presented inside the RF, with higher baseline activity present when the monkey attended to the more effective of the two locations, which was presumably closer to the RF center. Although this 30–40% increase in baseline activity added only a few spikes per second to the output of a given cell, it presumably represented a substantial effect across the entire population of V4 cells. Studies in other visual, motor, and prefrontal regions have found comparable

shifts in maintained activity when animals attend to nonspatial features or hold information in memory (for a review, see Fuster 1994).

There are several possible explanations for the baseline shift observed here, but the present results indicate that it does not reflect a change in the sensory response to the location markers or an internal target template. Instead, this effect may reflect a top-down signal that gives a competitive advantage to a stimulus at an attended location. The fact that large shifts were present in the inside/outside condition, in which attention did not strongly modulate sensory responses, would seem to argue against this proposal. However, if the effects of attention on the sensory response are determined by a combination of local competition induced by nearby stimuli and a biasing signal that favors one population of cells over another (reflected by the baseline shift), this would explain why modulations of the sensory response were observed primarily in the inside/inside conditions.

It is important to note that baseline shifts such as this may well lead to changes in blood flow, which might be measured in positron emission tomography (PET) or functional MRI studies of spatial attention. Thus a PET or functional MRI study might find increased “activation” in specific parts of the cortex when attention is directed to some location (e.g., Heinze et al. 1994), but the increased blood flow might be caused by shifts in baseline firing rates rather than changes in the stimulus-evoked activity, especially because the baseline shifts are present throughout the entire period of sustained attention rather than just the sensory response period.

#### *Comparison with previous single-unit studies*

As indicated above, our results qualitatively confirm and extend the conclusions of Moran and Desimone (1985). There was a quantitative difference, however, in that Moran and Desimone found that attention produced a 178% increase in the sensory response in V4 whereas we found only a 63% increase in the most comparable condition (i.e., condition A<sub>1</sub>, with 2 stimuli presented simultaneously within the RF). This difference could be due to differences in the nature of the task (Moran and Desimone used matching to sample), the difficulty of the task (Spitzer et al. 1988), the stimulus presentation times (200 ms in the previous study vs. 50 ms in the present), or the particular stimuli used. Recent studies in our laboratory suggest that all of these variables may make a quantitative difference in the magnitude of the attention effects (Reynolds et al. 1995; unpublished data).

The difference in attention effects observed in the present study between the inside/inside and inside/outside configurations has been confirmed in two recent studies of attention, one in the medial superior temporal area (MST) (Treue and Maunsell 1996) and one in area V4 (Chelazzi and Desimone 1994). In both of these studies, a preferred and a nonpreferred stimulus were placed inside the RF, and the cells gave a substantially larger response when the preferred stimulus was attended than when it was ignored; much smaller effects were found when the nonpreferred stimulus was moved outside the RF. However, although every study in which an inside/inside configuration was compared with an inside/outside configuration has confirmed that attentional modulations of sensory responses are much larger for the inside/inside configuration, the presence or absence of attentional

modulations for the inside/outside configuration varies across studies. For example, Haenny et al. (1988) failed to find any attentional modulation of V4 responses when the animal made a saccade to a stimulus inside the RF versus one of three stimuli outside, which is similar to the findings of the present study. Maunsell et al. (1991) also failed to find any effects of spatial attention in V4 when they compared a condition in which the animal passively fixated a fixation target outside the RF with a condition in which the animal performed a matching-to-sample task with the use of the stimulus inside the RF. Similarly, although Motter (1993) found significant attention effects in areas V1, V2, and V4 with one stimulus inside the RF and several stimuli outside, attended stimuli elicited smaller responses almost as often as larger responses, which is not very different from results obtained with the inside/outside configuration in the present experiment. In contrast, Connor et al. (1996) obtained consistently positive attention effects in V4 with an inside/outside configuration. In this experiment, attention was directed to one of four stimuli that surrounded the RF of the cell being recorded, and enhanced responses were observed for a "probe" stimulus that was presented inside the RF when the probe was near the attended stimulus. However, the close proximity of the four surrounding stimuli to the cell's RF and to the probe stimulus raises the possibility that competitive interactions were present despite the fact that only one stimulus was inside the classical excitatory RF.

Other studies have found positive effects of spatial attention in area V4 even when the competing stimulus was far removed from the RF borders. For example, the study of Spitzer et al. (1988) included a control condition in which one stimulus was inside the RF and another was in the opposite hemifield, and consistently larger responses were observed in area V4 when the monkey attended to the stimulus inside the RF. However, these effects occurred only when the monkey performed a very difficult discrimination on the stimulus inside the RF. Similarly, Reynolds et al. (1996) found that contrast sensitivity for a stimulus presented inside the RF was enhanced in area V4 when the monkey attended to this stimulus compared with when attention was directed to a stimulus located far from the RF border. However, this effect occurred only for low-contrast stimuli. Nicholas et al. (1996) also found consistently positive attention effects with one stimulus inside the RF and another stimulus far from the RF border, but these effects were present only for targets that were difficult to segment from the background. These three studies suggest that attention may modulate sensory responses even in the absence of clear competitive interactions under certain conditions, especially when the stimuli are difficult to discriminate.

There have been several other studies of attention in area V4 in addition to those described above, but these studies did not explicitly manipulate spatial selective attention. Instead, they manipulated nonspatial variables such as whether the stimuli matched the color or orientation of a cue (Ferrera et al. 1994; Haenny et al. 1988; Motter 1994) or whether the monkey was engaged in a specific task (Fischer and Boch 1985; Mountcastle et al. 1981). In these studies, the stimulus-evoked responses and/or baseline firing rates were found to vary as a function of the behavioral condition, but the relationship between such nonspatial attention effects and the findings of the present study is not yet clear.

### *Comparison with ERP and imaging studies*

The behavioral paradigm used in this study was designed, in part, to allow a comparison between monkey single-unit attention effects and human ERP and PET attention effects. The findings of the present study are partially consistent with previous ERP and PET studies of spatial attention in that attention was found to modulate sensory responses in extrastriate areas but not in primary visual cortex (Heinze et al. 1994; Mangun et al. 1993). In contrast with the present results, however, these ERP and PET effects were obtained with attended and ignored stimuli that were located on opposite sides of the vertical meridian, too far apart to fit within a single RF in areas V2 or V4. One possible explanation for this discrepancy might be that the ERP and PET effects arise in some other area, such as the human homologue of macaque inferior temporal cortex; RFs in this area of the macaque are sufficiently large that attention effects could potentially be observed across the vertical meridian. Alternatively, it is possible that the ERP and PET effects are related to the baseline shift effect, which was observed in V2 and V4 even when the two locations were in different hemifields.

### *Locus of attentional modulation*

There has been an ongoing debate in the psychological attention literature for several decades about whether attention operates before or after perceptual processing has been completed (see Duncan 1980; Treisman 1969). Although the finding of attentional modulation in relatively low-level areas such as V2 and V4 appears to provide *prima facie* evidence that attention operates during the course of perceptual processing, these cortical areas might participate in post-perceptual processes such as short-term memory storage as well as perceptual processes. To settle this issue, it is therefore necessary to provide information about the timing of the attentional modulation as well as its neuroanatomic locus. In the present study, we found that the effects of attention in area V4 in the inside/inside conditions began very early, at the onset of the sensory response on sequential trials and very shortly thereafter on simultaneous trials (see Figs. 3E and 5C). In addition, the attentional modulation of the sensory response in the inside/inside conditions was virtually identical for target and nontarget stimuli (see Fig. 6), which is consistent with an attentional mechanism that operates before the stimuli have been identified. Together these results indicate that visual-spatial attention operates, at least in part, by creating a preset sensory bias that modulates the initial volley of sensory information as it passes through area V4 whenever there is competition between stimuli.

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