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Synchrony: A Neural Correlate of Somatosensory Attention

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Roy A, Steinmetz PN, Hsiao SS, Johnson KO, Niebur E. Synchrony: a neural correlate of somatosensory attention. *J Neurophysiol* 98: 1645–1661, 2007. First published June 27, 2007; doi:10.1152/jn.00522.2006. We investigated whether synchrony between neuronal spike trains is affected by the animal's attentional state. Cross-correlation functions between pairs of spike trains in the second somatosensory cortex (SII) of three macaque monkeys trained to switch attention between a visual task and a tactile task were computed. We previously showed that the majority of recorded neuron pairs (66%) in SII cortex fire synchronously while the animals performed either task and that in a subset of neuron pairs (17%), the degree of synchrony was affected by the animal's attentional state. Of the neuron pairs that showed changes in synchrony with attention, about 80% showed increased synchrony when the animal attended to the tactile stimulus. Here, we show that peak correlation typically occurred at a delay <25 ms; most commonly the delay was close to zero. Half-widths of the correlation peaks were distributed between a few milliseconds and hundreds of milliseconds, with the majority lying <100 ms and the mode of the distribution around 20–30 ms. Maximal change in synchrony occurred mainly during the periods when the stimulus was present, and synchrony usually increased when attention was on the tactile stimulus. If periods of elevated firing rates around the motor response times were removed from the analysis, the percentage of pairs that changed the degree of synchrony with attention more than doubled (from 35 to 72%). The observed effects did not depend on details of the statistical criteria or of the time window used in the analysis.

INTRODUCTION

The amount of information available at the sensory surfaces vastly surpasses that which can be processed in detail by the CNS (Parasuraman 1998; Pashler 1996). The selection of relevant information and the rejection of irrelevant input is therefore of utmost importance for any complex organism. Herein we address the question of the neuronal implementation of selective attention in the brain—i.e., how attention modifies the neural representation of stimuli. Although most studies of attention focus on changes in firing rate with attentional state (e.g., Burton et al. 1997; Hsiao et al. 1993; Hyvarinen et al. 1980; Luck et al. 1997; Moran and Desimone 1985; Motter 1994a,b; Poranen and Hyvarinen 1982; Reynolds and Desimone 1999; Treue and Maunsell 1996), substantial experimental evidence indicates that the temporal structure of neuronal activity may be involved in the neuronal mechanisms of selective attention (Bouyer et al. 1981; Desmedt and Tomberg 1994; Fries et al. 2001; Hatsopoulos et al. 1998; Maynard et al. 1999; Murthy and Fetz 1992, 1996a; Niebur et al. 2002; Sokolov et al. 2000; Steinmetz et al. 2000; Tiitinen et al. 1993; Womelsdorf et al. 2006).

Both theoretical analyses (Crick and Koch 1990) and computational modeling studies (Niebur and Koch 1994; Niebur et al. 1993; Tass and Haken 1996) suggest that selective attention may manifest itself by a "temporal tagging" mechanism that distinguishes attended from unattended stimuli. We have previously tested this hypothesis in an electrophysiological study (Steinmetz et al. 2000) and found that, indeed, neuronal synchrony is correlated with the attentional state. The idea that synchrony is a neural correlate of attentional selection is based on the fact that increasing synchrony between neurons representing an object or location increases the efficacy of that neural representation at the next synaptic stage in the brain.[1] Specifically, Niebur and Koch (1994) assumed that the temporal tag involves synchronous firing among multiple neurons in an ensemble and that attentional modulation influences the timing of spikes so that neurons within the focus of attention tend to fire together (within a few milliseconds) more frequently than neurons outside the focus of attention. The model posits that the degree of synchrony between neurons represents whether a stimulus is attended and predicts that the degree of synchrony changes depending on the subject's focus of attention.

In the Steinmetz et al. (2000) study, we reported that shifting the focus of attention from a visual to a tactile task alters synchronous firing in SII cortex. Area SII was chosen because previous studies indicate that a large fraction (80%) of the neurons is affected by the animal's focus of attention (Burton et al. 1997; Hsiao et al. 1993, 2002; Jiang et al. 1997; Meftah et al. 2002; Poranen and Hyvarinen 1982). Our working hypothesis was that if synchronized firing between neurons plays a role in perception, then the degree of synchrony between neurons representing a tactile stimulus should change when the animal's focus of attention is directed toward versus away from the stimulus. Spike trains of 648 neuron pairs, from 436 neurons in SII cortex in four hemispheres of three monkeys, were analyzed and tested for synchrony in a 50-ms window ($\pm$25 ms around zero delay). Seventy-eight percent (339/436) of these neurons showed a significant change in firing rate when the animal switched between the tactile and visual tasks (Hsiao et al. 1993; and unpublished data). Sixty-six percent (427/648) of the neuron pairs had significant cross-correlogram peaks ($P < 0.05$) during the visual task, the tactile task, or both. These previous results, which are summarized in the first

[1] This is somewhat simplified; it is well-known that synchrony does not always increase the firing rate in postsynaptic neurons (Bernander et al. 1994; Mikula and Niebur 2003). However, the parameter space in which synchrony does increase postsynaptic firing rate is usually large and in or close to what is assumed to be the physiological range.

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three columns of Table 1, show that although the percentages varied between 53 and 78% for the three monkeys, a high degree of synchronous firing between neurons in SII cortex was observed in all cases. Seventeen percent (74/427) of the neuron pairs with significant cross-correlogram peaks also showed significant changes in synchrony between the visual and tactile tasks. On average 80% (59/74) responded with increased and 20% responded with decreased synchrony when the monkey performed the tactile task (Table 1). The fractions of all neuron pairs with significant synchrony that also had significant changes in synchrony ($P < 0.05$) between the tactile and visual tasks (Table 1) were 16.0, 35.3, and 9.5% for M1, M2, and M3, respectively. When the criterion for significance was set at $P < 0.01$, the percentages were 8.6, 28.0, and 6.6 with an average percentage of 13.2. When stated in terms of neurons rather than pairs, assuming that our electrodes recorded from a random sample of the population, the percentages were larger: of all the neurons involved in synchronous firing, 26, 53, and 18% in M1, M2, and M3, respectively, were involved in one or more pairings in which synchrony changed significantly ($P < 0.05$).

In the present report, we will extend the analyses performed in the prior study in several ways, as subsequently explained. We will begin with a brief description of the behavioral tasks and recording techniques used in both studies, and the computational and statistical methods used in the present report. We then show that the previously reported results do not depend on details of the statistical methods used and that they are robust when narrower time windows are chosen to define synchronous firing (i.e., sharper synchrony). We will also show how synchrony develops over time during an attention task, how attention affects the features of the cross-correlograms, and we will provide further evidence that the effects cannot be explained by changes in firing rate. In particular, we show that the effects of attention on synchrony are unlikely to be due to long-term covariation of neuronal firing rates, latency covariations, or to movement-related synchrony resulting from the animal's motor response. In fact, removal of data recorded during the motor response substantially increases the fraction of neuron pairs whose correlation is influenced by changes in the attentional state.

METHODS

Behavioral tasks

Three macaque monkeys were trained to perform a tactile form-discrimination task and a visual light-discrimination task (Fig. 1*A*). The animals were trained to perform the same visual task but three separate tactile tasks that varied in difficulty. Animals were comfortably seated in a chair in front of a computer monitor with their heads, arms, hands, and fingers restrained. The hands were oriented with the glabrous skin facing upward and positioned so that the cutaneous stimuli could be presented to the distal pads of their index, middle, or ring fingers. Throughout the experiment the animal's focus of attention was switched back and forth in blocks between attending to either the stimulus pattern on the finger pad or to visual stimuli presented on the video monitor. The aim was to keep all aspects of the experiment constant except for the animal's focus of attention.

In the visual task, three white squares, approximately 2° on each side and aligned horizontally, appeared on the monitor. After a random interval that lasted from 1 to 3 s, either the left or right square, selected at random, dimmed slightly. The monkey's task was to indicate which square dimmed by turning a switch to the left or right with its hand (M1) or pulling or pushing a switch with its foot (M3). Monkey M2 started by using the hand switch (as M1) and was then retrained to use the foot switch (as M3). We switched from having the animal respond with its hand to its foot because we realized after completing our studies with the first animal that many neurons in SII cortex have receptive fields that span both hands. If the animal responded correctly, it was rewarded with a small liquid reward. The screen then went blank and, after a period of about 1–3 s, the three white squares reappeared. If the animal responded incorrectly or responded before the squares dimmed, the screen went black immediately and the trial was restarted after a brief time-out period. For all three animals, the tactile stimuli (subsequently described) were presented during the visual task and continued unabated while the animal performed the visual task. Tactile stimuli occurred asynchronously with the visual stimuli. All three animals easily learned to perform this task and once trained performed at about 95% correct.

The aim was to train animals to discriminate the spatial form of cutaneous stimuli. Because of the difficulty in training animals to perform multiple tasks we trained three animals to perform three separate tasks. The easiest discrimination task was performed by monkey M3 who simply had to discriminate the orientation of a 6.0-mm-long bar (Fig. 1*Ac*). The bar was made of Ultem, a kind of hard light plastic (McMaster-Carr, Atlanta, GA), and was wedge shaped with sides that had a 60° taper onto the finger. The ends of the bar were slightly rounded to minimize the end effects of the bar. In the task, the bar was

TABLE 1. *Fractions and percentages for shift-predictor corrected cross-correlograms (SCCCs)*

	SCCC (±25 ms)			SCCC (±5 ms)		
Monkey	Synchrony	Change	Increase	Synchrony	Change	Increase
M1	50/95 (52.6)	8/50 (16.0)	7/8 (87.5)	49/95 (51.6)	10/49 (20.4)	8/10 (80.0)
M2	116/145 (77.9)	41/116 (35.3)	35/41 (85.4)	101/145 (69.7)	40/101 (39.6)	36/40 (90.0)
M3	264/408 (64.7)	25/264 (9.5)	17/25 (68.0)	203/408 (49.8)	29/203 (14.3)	17/29 (58.6)
Average	427/648 (65.9)	74/427 (17.3)	59/74 (79.7)	353/648 (54.5)	79/353 (22.4)	61/79 (77.2)

Columns 2, 3, and 4: ±25 ms (Steinmetz et al. 2000); columns 5, 6, and 7: ±5 ms. The first column lists monkeys (M1: letter discrimination, constant target; M2: letter discrimination, varied target; M3: bar orientation discrimination). Columns 2 and 5 show the fraction of cell pairs with significant synchronous firing ($P < 0.05$) for the SCCCs. Columns 3 and 6 show the fraction of neuron pairs in columns 2 and 5 in which the synchrony changed between the visual and tactile tasks ($P < 0.05$). Columns 4 and 7 show the fraction of neuron pairs in columns 3 and 6 in which synchrony increased during the tactile task.

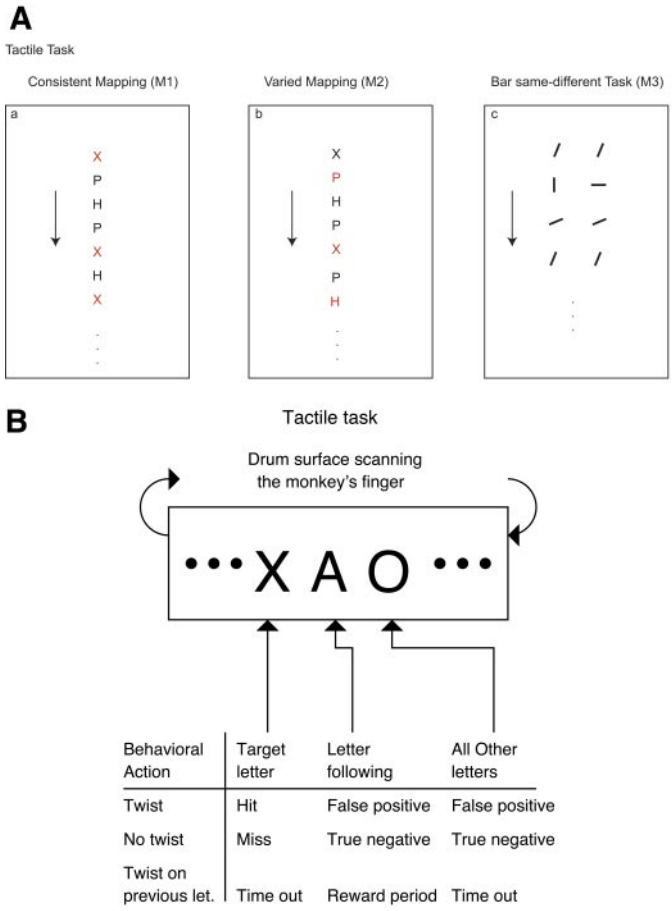


FIG. 1. *A*: tactile tasks. *a*: tactile pattern-matching task used for monkey M1. A typical pattern sequence (XPHPXHX. . .) is illustrated. Raised letters were scanned from a proximal-to-distal direction across a distal finger pad that was within the receptive fields of the neurons being recorded from. Pattern colored red in the figure (X in this example) was displayed on a computer screen in front of the monkey and the monkey was rewarded for pressing a key when the pattern scanning across its finger matched the pattern displayed on the computer screen. In this task, the target letter remained constant during an entire recording session from one set of neurons; the target letter changed between sessions (Consistent Mapping design). *b*: tactile pattern matching task used for monkey M2. Target letter changed randomly after each correct recognition for monkey M2 (Varied Mapping design). *c*: orientation-discrimination task used for monkey M3. Each trial consisted of 2 applications of a stimulus bar to a distal finger pad. First was applied at one of 8 random orientations; after a delay, the bar was presented again at either the same orientation (as illustrated in trials 1, 3, and 4) or at the orthogonal orientation (as illustrated in trial 2). Monkey turned a switch in one direction when the orientations matched and in the other direction when they did not. *B*: behavioral design for pattern-matching task. In this example X was the target letter. Matrix below the drum surface shows how each trial was classified for the purposes of analysis and how that classification depended on the animal's behavior.

indented into the distal finger pad at one of eight orientations (separated by 22.5°) for 500 ms, removed from the finger for 1 s, and then indented into the skin at either the same orientation or at the orthogonal orientation. The animal was required to push a foot switch if the two orientations were the same and to pull the switch with its foot if they were different. We chose a match-to-sample task because orientation discrimination is relatively easy and we wanted to have a period (presentation of the sample) when the animal was not required to perform a motor task. Humans performing this task find that discriminating the orientation of the bar is fairly easy and the matching task mildly demanding.

The first and second animals (M1 and M2) were trained to perform a form-discrimination task. In this task the animals were required to discriminate the form of a raised capital letter (6.0 mm high) embossed on a rotating drum (Johnson and Phillips 1988) that scanned the pattern (15 mm/s) across the distal pad of a single finger pad. The animals were required to respond within 500 ms after the letter left the finger depending on whether the letter matched the target letter that was displayed on the video monitor in front of the animal. If the letter matched, the animal turned a switch with the hand or foot ipsilateral to the recording hemisphere. In the majority of the experiments the animal responded with its foot; for a few experiments in M2 the animal was allowed to respond with its hand. The animals were given a liquid reward for correctly identifying the target letters. The target and nontarget letters for both animals were chosen from a subset of the letters (AHLOPX) chosen because they have approximately the same intensity (total length of edges), have distinct features, and in human and monkey psychophysical experiments (Hsiao et al. 1993; Vega-Bermudez et al. 1991) have been shown to be easily discriminated from each other (mean recognition of >85%). For both animals across one set of trials only a subset of three of the letters was used. These three letters were randomly arranged around the circumference of the drum with eight total letters spaced 30 mm apart. The target letter, which was chosen from one of the three letters that was on the drum, was displayed on the screen (>3° high). Performance of the task for both M1 and M2 required that the animal attend to all of the letters that scanned across its finger and to respond only when there was a match. Evidence that animals attended to all of the relevant letters is shown in Hsiao et al. (1993).

Although the tactile stimuli were the same for the two animals, the task that the animal had to perform was slightly different. This task difference appears to have resulted in significant differences in the results. For monkey M1 the target letter remained the same for the entire period of time that a single set of neurons was studied (~45 min, i.e., for many rotations of the drum; Fig. 1*Aa*). Because we required the animal to discriminate only the same letter for an extended period of time it allowed the animal to concentrate on identifying a subset of features that were unique to the target letter and to ignore other features. For monkey M2, the target letter on the screen changed after each correct response [this occurred every third or fourth letter on average; i.e., approximately every 7.5–10 s (Fig. 1*Ab*)]. This task was quite demanding because it required not only that the animal switch its focus of attention to the video monitor after each correct response ("Hit") but also the animal was required to switch its attentional set to concentrate on a different set of features. Humans performing this task find it to be very challenging and report that it requires substantial effort to perform.

The level of arousal of the monkeys was controlled by adjusting the mean intertrial interval of the visual task so that the rate of reward during the visual task corresponded to the reward rate during the tactile task. For example, because for all three animals the tactile stimulus was presented to the finger pad every 3–5 s, the mean time between visual stimuli was adjusted to about 5 s.

All three animals were trained until they achieved about 90% correct responses in each task. That is, M1 and M2 correctly identified the target letter about 85% of the time (performance was slightly better for M1 than for M2) or M3 correctly matched the orientation of the bar (95%). The recognition performance of 85% for M1 and M2 was higher than human letter recognition performance of 66% that Vega-Bermudez et al. (1991) reported over the same letter sets. This was most likely because the animals were trained for several months to perform the task with just this subset of letters and previous studies have shown that performance improves with training (Vega-Bermudez et al. 1991) and during each set of trials the animal needed to identify only three letters. The animal's performance was similar across all of the six letters used. For all three animals, the focus of attention was switched every 7–8 min between the visual and tactile tasks by changing the video screen from a set of three squares (visual task) to either a letter of the alphabet (M1 and M2) or an oriented bar (M3).

Animals and animal training

All three animals were male *Macaca mulatta* and weighed between 3 and 5 kg. All surgical and experimental procedures and treatments were approved by the Animal Care and Use Committee at the Johns Hopkins University and described in more detail by Hsiao et al. (1993). Briefly, animals were placed on a restricted water diet and were brought into the laboratory 6 days/wk for 4–5 months for training. Animals were first taught to perform the visual task and subsequently the tactile task. In both tasks the animals were initially taught to respond to a correct stimulus (a dimmed square for the visual task or embossed letter or oriented bar for the tactile task). Then, delay periods and nontarget letters were included in the stimulus sequence with the monkeys given a brief time-out period during which they could not receive a reward if they responded incorrectly.

Recordings

Neural activity was recorded using up to seven separate extracellular microelectrodes driven by a Reitboeck microdrive (Mountcastle et al. 1991). The end of the microdrive was modified so that the seven electrodes were linearly aligned; in some experiments they were spaced 400 μm apart and in other experiments 600 μm apart. Electrode locations in monkey M1 were marked by electrolytic lesions at the ends of some electrode tracks. All track locations in M2 and M3 were marked with fluorescent dyes (Dye-I or Dye-IC5; see Di Carlo et al. 1996). Individual spikes were isolated using both a window-amplitude discriminator and a template-based discriminator (Alpha Omega). Only spikes that were determined to be well isolated from both background noise and from other spikes and were stable over the entire recording session were included in the analysis. We analyzed neuron pairs in which only the spikes were collected on separate electrodes (therefore with a 400-μm minimal spacing) to ensure that the neurons were distinct. The mean distance between recording sites of neuronal pairs that showed synchronous responses (see following text) exceeded 1,000 μm. Standard histological techniques were used after sacrificing the animal to confirm that the neurons were located in SII cortex (for details see Di Carlo et al. 1996).

Computation of correlograms

A tactile trial in the current analysis consisted of the presentation of one letter in the letter-discrimination task or a pair of bars in the bar-orientation task (Fig. 1*A*). Spike train data related to each trial were first sorted (categorized) into "analysis blocks" according to the particular stimulus (specific letter or bar orientation), task (tactile or visual), and behavioral outcome (hit, miss, false positive, true negative). Figure 1*B* illustrates a categorization matrix for each trial (passage of a raised letter across the finger pad) for the letter-matching task (monkeys M1 and M2). For instance, one particular analysis block for M1 could consist of all trials in which the target letter "X" was applied to the monkey's finger pad, the monkey attended to the tactile stimulus, and it responded correctly. This is labeled as a "Hit" in the categorization matrix in Fig. 1*B*. Spike trains were binned with a binwidth of 2.4 ms (M1 and M2) or 4.4 ms (M3), which was small enough to ensure that bins rarely contained more than one spike. Therefore a spike train is represented by a sequence of zeros (if the bin contains no spike) or a nonzero number corresponding to the numbers of spikes in each bin.

Let two such sequences—$S^n_{\alpha sm}(t)$ and $S^n_{\beta sm}(t)$—represent the spike trains for the two members of a simultaneously recorded neuron pair α and β, where $n = 1 \ldots N_{sm}$ indexes the trial number and $m = 1, 2$ the attentional state (corresponding to whether the animal was performing the tactile or visual task, respectively). The subscript $s = 1 \ldots S_m$ indicates the identity of the presented stimulus (which embossed letter was presented for M1 and M2 or the orientation of the stimulus bar for M3). Note that each combination of s and m specifies an analysis block and that the analysis block labeled by s and m contains N_{sm} trials. The index $t = 1 \ldots \Theta/b$ is the bin number, where Θ is the length of the spike train in question and b is the analysis bin width.

Two cross-correlograms were computed for each block—a raw correlogram between simultaneously recorded pairs of responses and a so-called shift predictor. The latter, which more descriptively could be called an "exhaustive shuffle corrector," consists of the average of the correlograms between all nonsimultaneous pairs. It thus provides an estimate of the synchrony expected by chance. The raw cross-correlogram $P^n_{\alpha\beta sm}(\tau)$ averaged over N_{sm} trials was defined as

$$C_{\alpha\beta sm}(\tau) = \frac{1}{N_{sm}} \sum_n \sum_t S^n_{\alpha sm}(t+\tau) S^n_{\beta sm}(t) \qquad (1)$$

The contribution of stimulus-locked effects (including changes in the mean rate) to the raw cross-correlogram was estimated by computing the shift predictor $P_{\alpha\beta \mathrm{sm}}(\tau)$ over the same block of N_{sm} trials

$$P_{\alpha\beta sm}(\tau) = \frac{1}{N_{sm}(N_{sm}-1)} \sum_{i \neq j} \sum_t S^i_{\alpha sm}(t+\tau) S^j_{\beta sm}(t) \qquad (2)$$

Note that all permutations are always performed over the trial number and that time stamps of individual action potentials are never changed. The shift predictor was then subtracted from the raw cross-correlogram to obtain an estimate of the syn-

chrony above or below that expected by chance, which we call the corrected correlogram.

Finally, the corrected correlogram was averaged over all correct trials for all stimulus conditions for each attentional state to obtain the shift-predictor corrected cross-correlogram (SCCC)

$$SCCC = \frac{1}{S_m} \sum_{s=1}^{S_m} [C_{\alpha\beta sm}(\tau) - P_{\alpha\beta sm}(\tau)] \quad (3)$$

More details about the analysis procedure are provided by Roy et al. (2000a).

Trial duration was 2.5 s (for the letter-recognition tasks performed by M1 and M2) or 4.5 s (for the match-to-sample task performed by M3) and each analysis was based on at least four alternations between blocks of trials in which the animal was performing either the visual or the tactile task (Hsiao et al. 1993). Each trial was divided into 1,024 bins, which yielded bin widths of 2.4 ms (M1 and M2) or 4.4 ms (M3). Only tactile trials with correct responses were included in the analyses.

Statistical methods

The first question that we addressed is whether the synchrony exhibited in the SCCC is significantly different from that expected from the null hypothesis—that the two neurons fired independently on each trial. The measure of synchrony we adopted (i.e., deviation of the SCCC from chance level) was the sum of squared SCCC bin values within ±25 ms around zero lag; we refer to this measure as T (see Fig. 2). A measure based on the sum of absolute SCCC values, rather than their squares, yielded very similar results, which will also be subsequently reported. We quantified the statistical significance of our results by repeating all of the analyses that lead to the SCCC 500 times with the Fisher permutation test (Efron and Tibshirani 1993). In each replication, the responses of one neuron of a pair were paired with responses of the other neuron in such a way that all responses from the second neuron were used (a permutation) but the responses of the first and second neurons were never from the same trial. The significance of the deviation of the observed T value from what is expected from

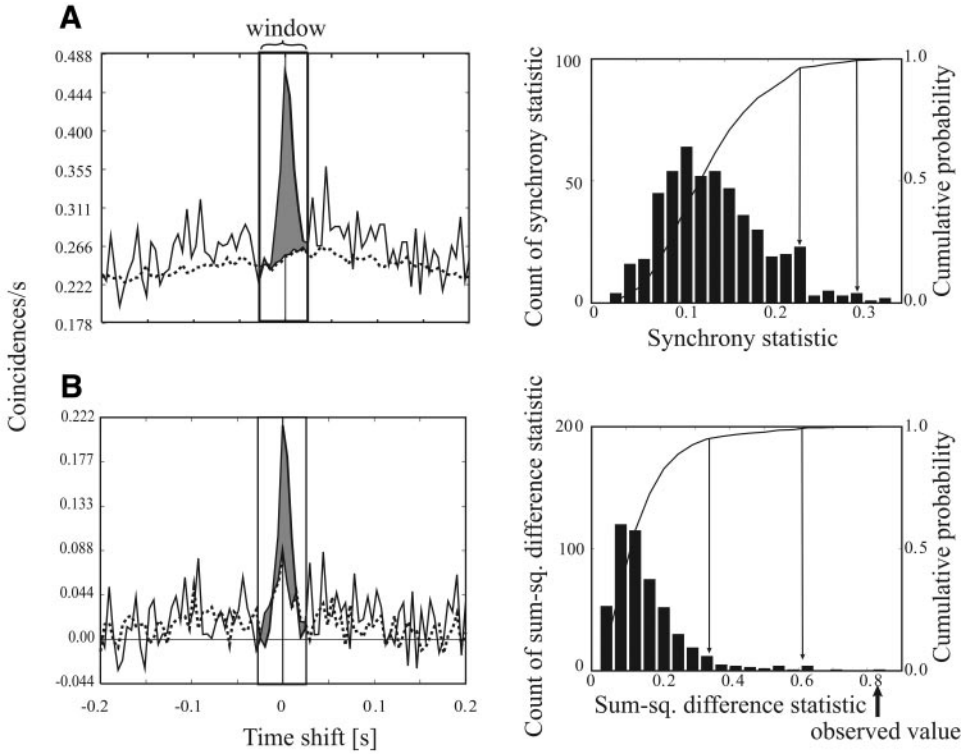


FIG. 2. Basic analysis methods. *A*, *left*: typical raw correlogram (solid line) and shift predictor (dashed line). Abscissa is the time shift between spikes in one spike train relative to spikes in the other. Ordinate is the frequency with which spikes in one spike train occur at the specified time shift relative to spikes in the other spike train. A *coincidence* is defined as the coincident occurrence of spikes in a window 2.5 ms wide centered at the specified time shift. Measure of synchrony over and above that expected by chance (T) is the sum of squared deviations of the raw correlogram from the shift predictor within a ±25-ms time shift window. *A*, *right*: distribution of the synchrony statistic (T), expected from the null hypothesis—that there is no more or less coincidence between 2 spike trains than that expected by chance from their respective rate profiles. Shaded histogram represents the T statistics for 500 permutations in which the spikes evoked within each trial (letter passing over the receptive field) from one neuron were paired with spikes evoked within different trials from another neuron. *Left ordinate* represents the count in each histogram bin. Solid line represents the cumulative probability that the test statistic T, based on the null hypothesis, will be $\leq T$ on the abscissa. *Right ordinate* represents cumulative probability. Values at the 95th and the 99th percentiles are marked with dropped arrows. Raw correlogram, illustrated on the *left*, had a value 0.8 (not shown). *B*, *left*: shift-predictor corrected cross-correlograms (SCCCs) for responses during the tactile (solid line) and the visual tasks (dotted line). Neuron pair is the same as in *A*. SCCC for the tactile task is the difference between raw correlogram (solid line) and shift predictor (dashed line) shown in *A*, *left*. Difference between the tactile and visual SCCCs was measured as the sum of squared differences between them measured over the same ±25-ms window (shaded region) as used to calculate the synchrony statistic T. *B*, *right*: distribution of the sum-squared difference measure expected from the null hypothesis—that there is no change in synchrony as the animal switches between the tactile and visual tasks. Shaded histogram represents this difference statistic for 500 pairs of visual SCCCs constructed from the same pair of neurons by a bootstrap method. Solid line represents the cumulative probability and the 95th and the 99th percentiles as in *A*, *right*. Sum squared difference between the tactile and visual SCCCs, 0.8, which was greater than any of the 500 values generated under the null hypothesis, is illustrated on the abscissa.

the null hypothesis was computed as the fraction of T values from the distribution of permuted SCCCs that exceeded the observed T. Neuron pairs with significance levels $P < 0.05$ were selected for further analysis. The analysis was also repeated with a more stringent significance value ($P < 0.01$) to determine the robustness of the results.

The second question was to determine whether synchrony differed significantly between the tactile and the visual task (the baseline condition). Our measure of the change in synchrony was the sum of squared differences D between the SCCC for the tactile task and the SCCC for the visual task within ±25 ms around zero lag. The null hypothesis is that the change in synchrony D is unaffected by the task being performed. Stated more rigorously, the null hypothesis is that tactile and visual SCCCs may both display statistically significant synchrony but that they differ from one another by no more than a pair of visual SCCCs drawn at random (or a pair of tactile SCCCs drawn at random). Random samples of visual SCCCs were constructed using a bootstrap procedure (Efron and Tibshirani 1993), where visual SCCCs were constructed by averaging over a set of single-trial cross-correlograms drawn randomly and with replacement from the original visual single-trial correlograms. The distribution of differences that would occur by chance if there was no difference between the visual and tactile SCCCs was determined by the sum of squared differences between pairs of these visual SCCCs (i.e., D) to yield a distribution based on 500 random samples. The significance of the sum of squared differences D, between the tactile and visual SCCCs, was computed as the fraction of the random sample that was $>D$. The significance level was first set at $P = 0.05$ and the analysis then again repeated at $P = 0.01$. The results did not depend on whether the visual or tactile trials were used in the bootstrap procedure.

Other bootstrap tests based on tactile SCCCs and a bootstrap version of the t-test (Efron and Tibshirani 1993) were also applied to the same spike train data set to determine the robustness of our results (see DISCUSSION). To obtain the direction of change in synchrony (i.e., whether synchrony increased or decreased when the monkey switched attention to the tactile task), we computed the signed difference (i.e., not absolute values or squares) between the SCCCs over the same ±25-ms time window for all pairs that showed a significant attentional effect.

Tests for statistical significance

Statistical significance was tested with bootstrap procedures because they are supported by solid statistical theory and they make no assumptions about the distributions of the data. When used in these studies, bootstrap procedures provide a model-free test of the degree of synchrony and change in synchrony (Roy et al. 2000a) and do not impose a priori assumptions on underlying stochastic mechanisms of neural firing (e.g., Poisson statistics). Likewise, no assumption of independence of firing in neighboring time analysis bins or the distribution of the test statistics (e.g., normality) is required (Roy et al. 2000b).

Fitting procedure

To analyze the properties of neuronal synchrony, SCCCs that exhibited statistically significant synchrony were fitted with Gaussian functions that were then used to estimate the spread and magnitude of the half-width and peak delay values of the correlograms. These Gaussian functions were not used to decide whether neurons fired synchronously or whether change in synchrony status was correlated with changes in the attentional state; those decisions were determined by the resampling methods described in the previous section.

The Gaussian-fit functions were of the form $A + \langle B \times \exp\{-[(x - C)^2/\sigma^2]\}\rangle$, where the parameters A, B, C, and σ represent estimates of the average baseline value, the amplitude, the peak delay, and the SD of the Gaussian that best fits the SCCC, respectively. The fits were done using a nonlinear least-squares Levenberg–Marquardt algorithm.

Control for movement effects

Although animals respond at approximately the same rate when performing the two tasks, in the tactile task all of the motor responses occur at about the same time in the trial (by definition, one motor response is guaranteed to occur in each "hit" trial). This is not necessarily the case during the visual task because the visual task was performed asynchronously with the tactile stimuli. We were therefore concerned that the movement related responses might contribute to the observed synchrony effects.

To control for movement-related synchrony due to the throwing of the switch, we compute movement-triggered peristimulus time histograms (PSTHs) for all monkeys (for both tactile and visual tasks). That is, spike times are entered in these PSTHs relative to the throwing of the switch and not relative to the beginning of the trial. Figure 3 shows the three

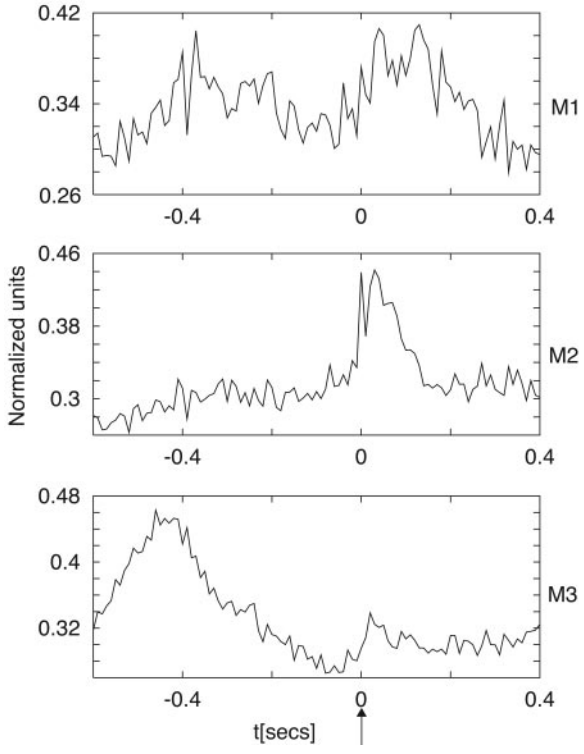


FIG. 3. Averaged peristimulus time histograms (PSTHs, over all neurons) shown for each monkey, of spike times relative to the throwing of the switch on each trial (*time point 0*, shown by black arrow). Spike rates have been normalized to correct for neurons with widely varying rates. Notice the abrupt change in rate in monkey M2 locked to the throwing of the switch.

movement-triggered PSTHs that are averaged over all correct tactile trials in all neurons (results are similar for the visual task). Of the three monkeys, only M2 showed a substantial rate increase after the throwing of the switch. We controlled for movement effects in two ways. First, we deleted the 100-ms spike train segment immediately after each switch throw, thus eliminating the rate changes that could correlate with any events related to the throwing of the switch, and repeated the entire analysis using this modified data set (including all the bootstrapped tests). Second, the analyses were repeated with trials classified as *true negatives* (see Fig. 1*B*). No motor response occurs in these trials but the monkey needed to pay attention to the scanned letters to respond correctly in the true negative trials, that is, not to throw the switch (Hsiao et al. 1993).

RESULTS

Synchronous neuronal pairs

In the INTRODUCTION (in particular, Table 1), we have already listed the percentages of neuron pairs that were found synchronous in our previous study (Steinmetz et al. 2000). Here we report that these results do not depend on the details of the test statistics. The percentages of the neuron pairs having significant cross-correlogram peaks ($P < 0.05$) during the visual task, the tactile task, or both using the absolute area (rather than the square) measure of synchrony were 42.0, 77.0, and 54.0 for M1, M2, and M3, respectively. The percentages of pairs whose level of synchrony differed between the two attentional states (again using the absolute value of the difference between correlation functions rather than the square as the test statistic), were 12.5, 31.5, and 8.2 with an average percentage of 15.7.

Our results are also extremely unlikely to be obtained by chance alone. Because we adopted 5% significance as our threshold for classifying a neuron pair as having exhibited a significant change in synchrony, on average 5% of pairs would appear to do so by chance. Under the assumption of an underlying binomial distribution, the probability of obtaining eight (16%) or more significant results in 50 cases (M1; see Table 1) when chance alone yields 2.5 cases (5%) is 0.0032. The corresponding probabilities for M2 and M3 were 4.378×10^{-24} and 0.0018, respectively.

At a narrower window (±5 ms; sharper synchrony), the percentages were similar and are summarized in the final three columns of Table 1. Overall 55% (353/648) of the neuron pairs had significant cross-correlogram peaks ($P < 0.05$) during the visual task, the tactile task, or both. This drop in percentage relative to the results obtained with the wider window is expected for the narrower window chosen in this analysis. Using this measure, 22% (79/353) of the neuron pairs with significant cross-correlogram peaks also showed significant changes in synchrony between the visual and tactile tasks. On average 77% (61/79) responded with increased synchrony when monkeys performed the tactile task (Table 1).

Figure 4, *A–D* shows examples of raster plots (*a*, *b*) for four different neuron pairs recorded from monkey M1 (*A*), M2 (*B* and *C*), and M3 (*D*), in which attention to the tactile stimulus produced a significant increase in synchrony. Synchronous events (spikes from two neurons within 2.5 ms of each other for M1 and M2, and within 4.5 ms for M3) are represented as large blue diamonds. For the coincidence histograms, the trial duration was subdivided into 1,000 bins. The rate of synchronous events (*c*; red) reaches a maximum of between 2/s (*D*) and 7/s (*B*) as the stimulus letter passes (Fig. 4, *A*, *B*, and *C*) or during the period just before the oriented bar is pressed into the finger pad during the tactile task (Fig. 4*D*). During the visual task, the rate of synchronous spikes within 2.5 ms (*c*; green) rarely exceeds 1/s in any of the neuron pairs shown. A certain rise in synchrony is expected because the impulse rates in both neurons rise due to the presentation of the tactile stimulus (letter or oriented bar) (*c*, *d*) but that rate (the rate of synchronous events expected by chance) also never rises above 1/s, as shown in *e* (blue curve).

Shape of the cross-correlograms

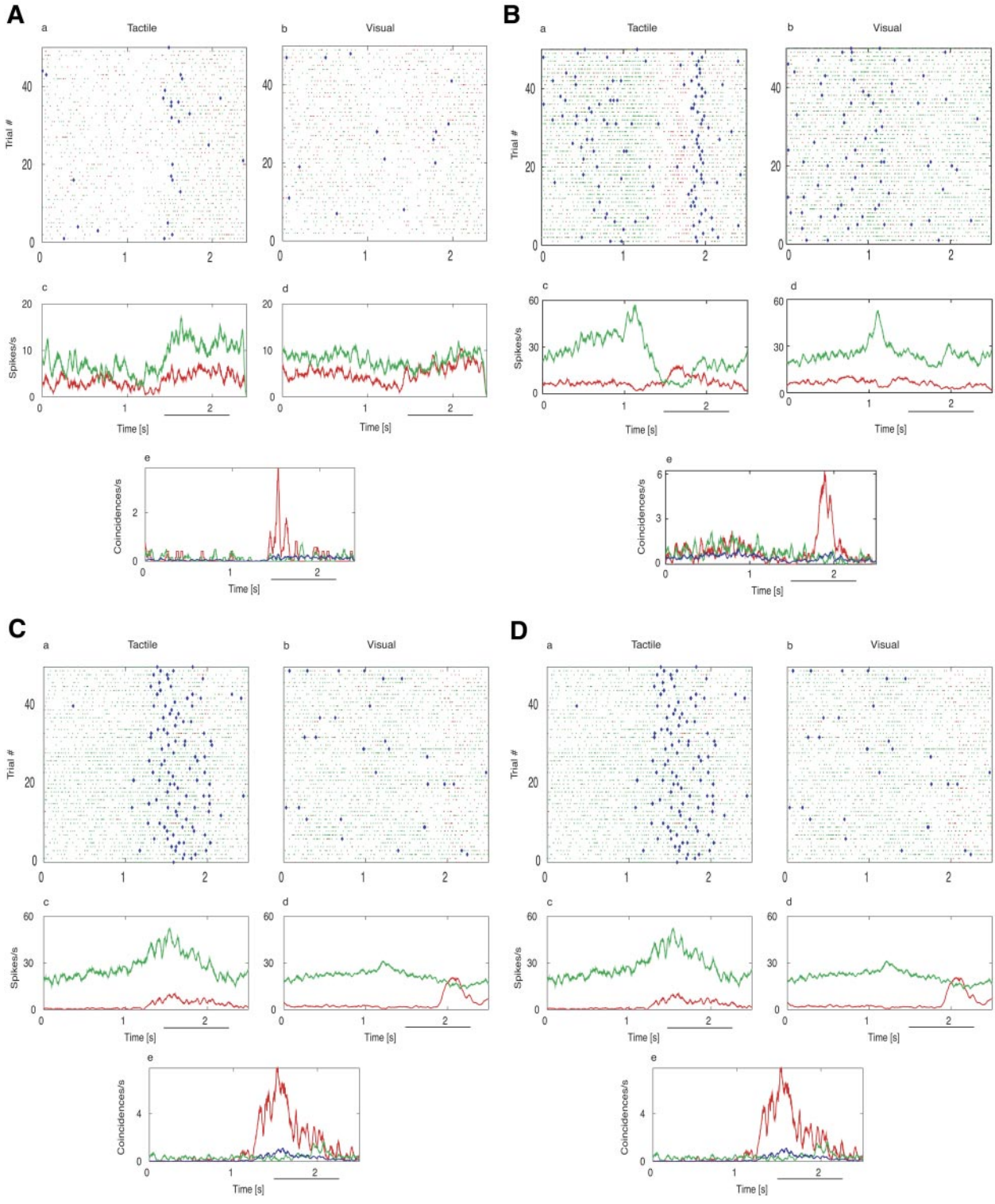
Figure 5, *A* and *B* shows the scatter distributions of the half-width and peak delay (plotted against each other; *right*) of all the SCCCs from all neurons possessing significant synchrony (at $P < 0.05$) that could be fitted with a Gaussian function (tactile: 77%; visual: 76%; the other SCCCs were not fit sufficiently well by Gaussians to meet our quality criteria). The two parameters (half-width and peak delay) were computed from the fitted Gaussian functions as described in METHODS. The *left panels* of Fig. 5*A* (tactile task) and Fig. 5*B* (visual task) show examples of superimposed raw and fitted SCCCs for various combinations of half-widths and peak delays, ranging from SCCCs with sharp peaks centered around zero lag to very broad peaks with nonzero lags. The majority of neuron pairs had half-widths <100 ms (58%; tactile, 61%; and visual, 55%) and peak delays within 20 ms (63%; tactile, 65%; visual, 62%). A majority of neuron pairs that showed a significant change in synchrony ($P < 0.05$) also had half-widths <100 ms (55%) and peak delays within 20 ms (73%) of zero lag. Figure 6, *A* and *B* shows the histograms of peak delay and half-width of all the SCCCs from Fig. 5, *A* and *B* separately for the tactile and the visual tasks. No significant differences arising from changes in the attentional focus between the visual and tactile tasks were observed between the distributions of peak-delay times nor half-widths of the SCCC peaks (Kolmogorov–Smirnov test, peak delay: $P = 0.065$; half-width: $P = 0.138$).

Four relatively narrow SCCCs (tactile: solid lines; visual: dashed lines) are shown in Fig. 7. Figure 7, *A–C* illustrates pairs that show more synchrony when the animal switched to the tactile task, whereas Fig. 7*D* illustrates a neuron pair with less synchrony when the animal switched to the tactile task. Figure 7, *A* and *C* shows a typical example, with significant synchrony during both the tactile and visual tasks, but much more during the tactile state. The majority of the pairs that show a significant change in synchrony with attentional state are of the type illustrated in Fig. 7, *A* and *C*. Figure 8 illustrates a histogram of the mean change in coincidence rate over the entire trial for all neuron pairs (all monkeys) with a significant attentional effect. Changing the focus of attention between the visual and tactile tasks resulted in an average change of about one to two synchronous spikes per second (median value of the change: 1.6 synchronous spikes/s) in each trial. Although the number might seem low, it is neurobiologically significant, given that the mean background coincidence rate (both tasks combined) for all neurons showing an attentional effect was eight coincidences/s (tactile: 9.5; visual: 6.7), which translates to about a 25% change in the number of synchronous events.

Furthermore, we show in the next section that the likely neuronal effect is significantly larger than this average when the time course of the effect is taken into consideration.

Temporal development of synchrony

Figure 9 shows examples of peristimulus coincidence rate histograms for nine cell pairs [two from M1 (Fig. 9, *A* and *B*), four from M2 (Fig. 9, *C–F*), and three from M3 (Fig. 9, *G–I*)]. All of these neuron pairs showed a significant change in synchrony with attention. Four curves are shown for each pair. The red and green curves represent the coincidence PSTHs during the tactile and visual tasks, respectively, whereas the blue and yellow curves show the coincidences expected by chance (i.e., coincidences that are expected due to simultaneous covariation of stimulus induced responses on a trial-by-



trial basis). The expected coincidence PSTHs were computed from the same random ordering of spike train data used to estimate the shift predictors. In the four examples in monkey M2 (which had the highest percentage of neuron pairs showing an attentional effect) shown in Fig. 9, *C–F*, a maximum increase in the coincidence rate is observed in the tactile task relative to the visual task during the period when the raised letter was scanned over the monkey's distal finger pad (1.5–2.25 s). Coincidence rate changes during the period just before the arrival of the stimulus were smaller.

The location of maximum coincidence rate change was less clearly localized in the other two monkeys. In monkey M1 (Fig. 9, *A* and *B*), an increase in coincidence rate was also observed during the application of the letter stimulus, although the effect was weaker than that in M2. In monkey M3 (Fig. 9, *G–I*), changes in coincidence rates were distributed around and between the times when the stimulus was applied (Fig. 9*G*), and during the presentation of the first and second stimulus (Fig. 9*H*) and during the presentation of the second stimulus only (Fig. 9*I*). Figure 9*I* shows an example in which coincidence rates were greatest during the visual task (i.e., decrease in synchrony during the tactile task). These results should be contrasted with those found by de Oliveira et al. (1997), who described a higher concentration of synchronous events among neurons in extrastriate visual cortex during the expectation phase of an animal performing a motion-detection task.

To characterize the population behavior, we investigated the temporal location of the maximum difference in coincidence rate between the two tasks (coincidences defined as two spikes within 2.5 ms of one another for M1 and M2, 4.5 ms for M3) and we computed a quantitative measure of the magnitude of that change. Figure 10 (*left*) shows histograms of the magnitude of the maximum change in the nonaccidental coincidence rate between the tactile and the visual tasks over the whole trial period for the three monkeys. In this figure positive numbers signify more synchrony during the tactile task than during the visual task. The maximum change in synchrony occurs predominantly in the direction of the tactile task in all three monkeys (Fig. 10, *left*). Figure 10 (*right*) illustrates the distribution of times during a trial where the maxima occurred. In monkeys M1 and M2 (the scanned letter tasks) the maxima coincided with periods when the letter stimulus scanned across the distal finger pad of the monkey (black bars under abscissas). Locations of the maxima are more uniformly distributed in M3. In all three monkeys, the instantaneous change of the excess coincidence rate during the response is larger than the mean value displayed on the abscissa in Fig. 8 because the response to the stimulus is confined to a fraction of the trial duration and the values in Fig. 8 are averaged over the whole trial duration.

Other sources of synchrony

Care must be taken when using correlation functions to avoid introducing spurious short-term correlations. These might be of two forms. The first consists of long-term covariations in some feature of the neural responses, e.g., firing rates (excitability covariation; Brody 1998) or common onset at different latencies (latency covariation; ibid). Second, spurious correlations could be attributed to movement-related events. We will discuss these different sources of correlations in turn, together with the controls that we used to correct for them.

Brody (1998) demonstrated that spurious peaks may appear in cross-correlograms due to long-term covariations in firing rate between pairs of neurons. This may happen if, for instance, the firing rates of the neurons decrease together, or because of slow conjoint variations of the membrane potentials of the two neurons. To correct for this "excitability covariation," at the beginning of the analysis we eliminated all neurons that had obvious long-term trends in firing rates across the trials. This resulted in 10 (of 658) pairs being excluded (<2% of all pairs).

The contribution of the latency covariation was controlled by computing the covariation of the peak response latency during the response period (1.0–2.0 s for M1 and M2, 1.5–2.0 s for M3) with the observed spike–spike correlation. The peak response latency was computed by sliding a three-point moving-average window across the response period. No systematic correlation between response latency and observed synchrony was observed: The average correlation coefficient between peak latency and synchrony strength over all pairs with significant synchrony was 0.0101 (M1: −0.0183; M2: 0.0354; M3: 0.01319) during the tactile task, and 0.0195 during the visual task (M1: 0.0385; M2: 0.006844; M3: 0.01309). Over all the pairs showing a significant change in synchrony, the average correlation coefficients were as follows for the tactile task: M1: −0.0024; M2: 0.0583; M3: 0.0212; for the visual task: M1: 0.0346; M2: 0.0142; M3: −0.0166. Therefore in all cases the contribution of latency covariation was found to be negligible.

It is possible that there are differences between attention-induced synchrony and synchrony arising from other sources and that such differences, if they exist, are reflected in the widths of the peaks in the correlograms. Determining whether these differences are significant will be addressed in future experiments that investigate whether the width of the correlo-

FIG. 4. Representative neural response pairs from monkeys M1 (*A*), M2 (*B* and *C*), and M3 (*D*). Rasters contains spike times from 50 trials while the animal is performing the tactile (*a*) and the visual (*b*) task. Green and red ticks in each raster represent spikes from the 2 neurons. Large blue diamonds represent coincidences, which are defined as spikes occurring within 2.5 ms (*A–C*) or 4.5 ms (*D*) of each other. Trials are 2.5 s long for monkeys M1 and M2 (*A–C*) and 4.5 s for M3 (*D*). Note that all synchronous events (blue diamonds) are shown in these rasters, whereas the statistical analyses subtract the estimated profiles of chance synchronous events. *c* and *d*: instantaneous spike rates (smoothed with a Gaussian filter, SD 10 ms) for the rasters above them. Bars under the abscissas denote the approximate times the stimulus was in contact with the skin. *e*: raw synchrony rates during the tactile task (red), during the visual task (green), and the synchrony rate expected by chance alone in the tactile task (blue). Note that all synchronous events (blue diamonds) are shown in these rasters, whereas the statistical analyses subtract the estimated profiles of chance synchronous events. *A*: neural responses during the tactile task are unremarkable except that the spike coincidences are clustered in a narrow time window around the time of stimulus arrival. *B*: discharge rate of one neuron (green ticks) is either rising in anticipation of the next stimulus or is a function of the convolution of the stimulus with the spatiotemporal characteristics of the receptive field of the neuron. When the raised letter enters the finger pad, it is inhibited. Another neuron (red ticks) responds in an excitatory manner when the letter is over the finger pad. *C*: during the early phase of the "red" neuron's response in the tactile task, relatively few "red" ticks are visible because they have mostly been replaced by blue diamonds; that is, almost every "red" action potential is paired with a "green" action potential while the monkey performs the tactile task. At the peak response rate for both neurons (about 10 and 40 impulses/s) the probability that any "red" spike will coincide with a "green" spike is about 0.1. *D*: stimulus consists of 2 oriented bars pressed into the skin. Stimulus bar comes in contact with the skin first from about $t = 1.7$ s to $t = 2.2$ s and then from $t = 3.3$ s to $t = 3.8$ s. Coincidences appear to be clustered during the period leading up to each stimulus.

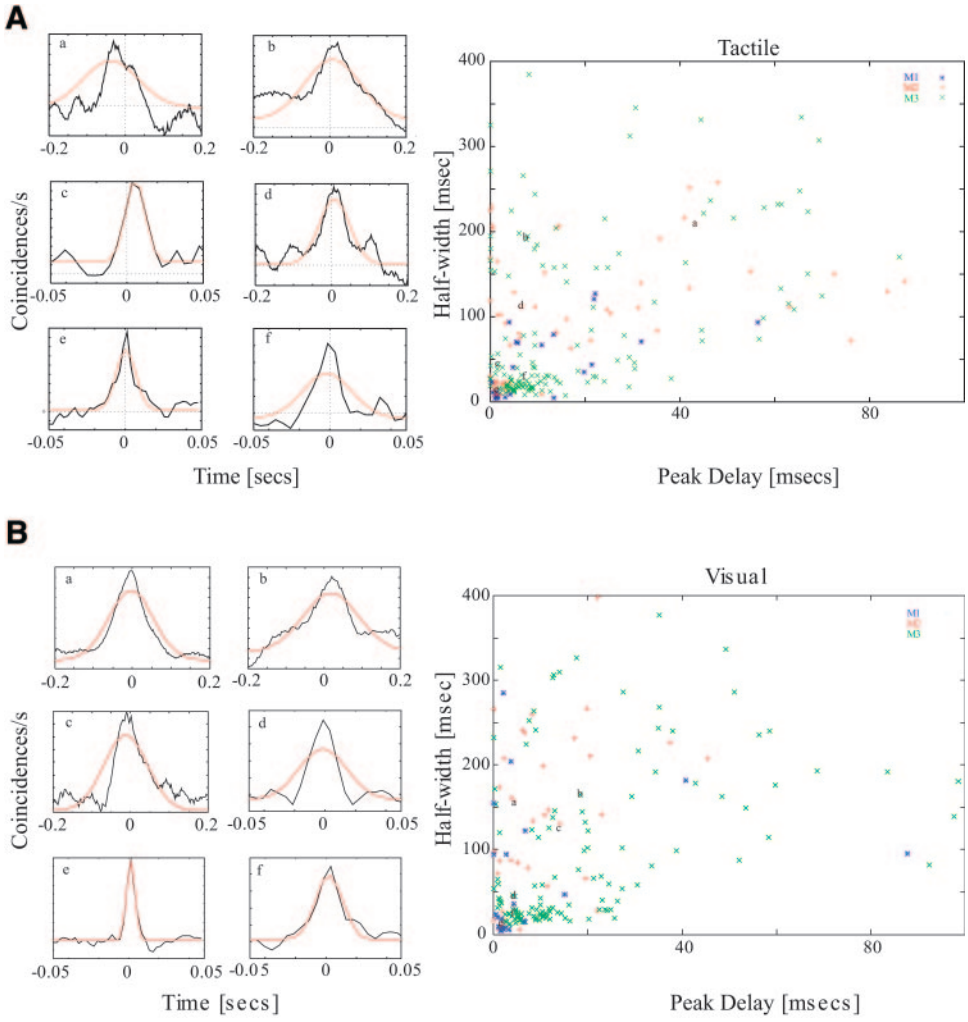


FIG. 5. *A*: synchrony spread and offset for tactile task. Spread and offset to the peak synchrony were measured by fitting Gaussian functions to the SCCCs for the tactile task. Six examples are illustrated at the *left* beginning with broad correlogram peaks at the *top* and progressing to narrower peaks at the *bottom*. *Right*: half-widths and peak locations of all pairs with significant synchrony that could be fit with Gaussian functions (M1: blue star; M2: red plus; M3: green cross). Letters marked on the scatterplot (*a–f*) correspond to the SCCCs shown on the *left*. Peak delays are all shown as positive values because negative delays are simply due to the (arbitrary) ordering of electrodes. *B*: similar curves and scatterplot shown when the monkey is performing the visual task.

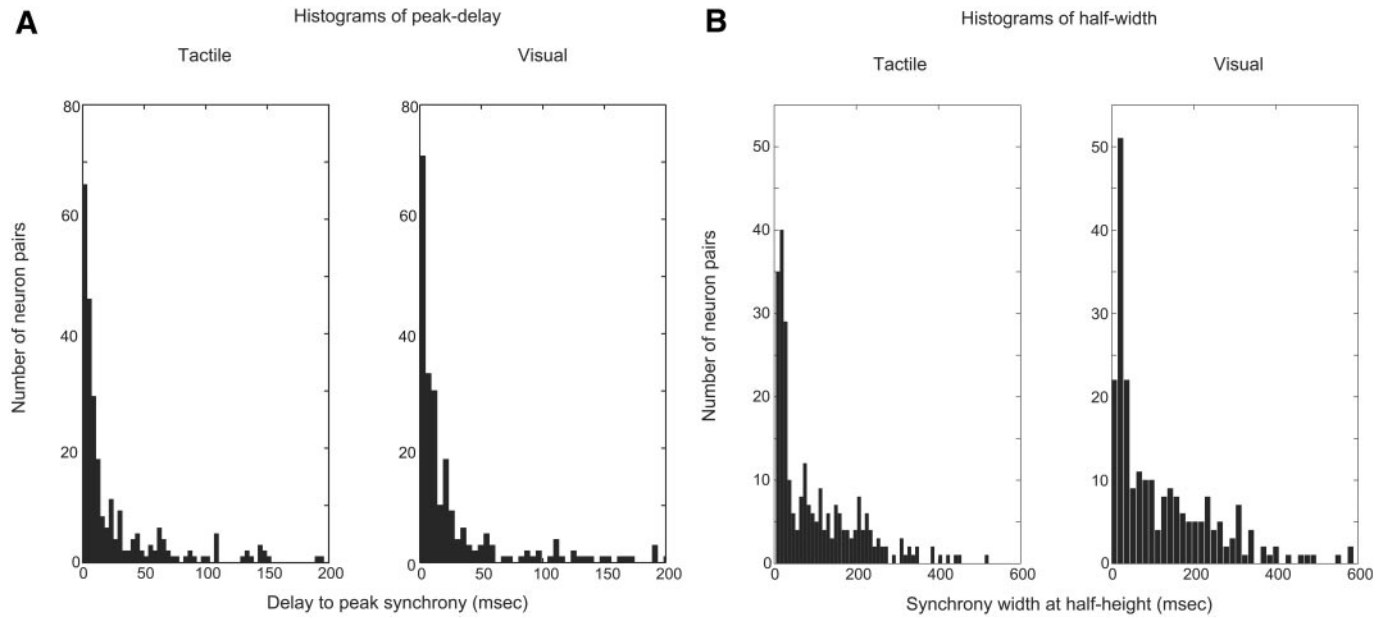


FIG. 6. *A*: histograms of the peak delays of all the neuron pairs shown in Fig. 5, *A* (*left*) (tactile task) and *B* (*right*) (visual task) from all 3 monkeys combined. *B*: histograms of the half-widths of all the neuron pairs shown in Fig. 5, *A* (*left*) (tactile task) and *B* (*right*) (visual task) from all 3 monkeys combined.

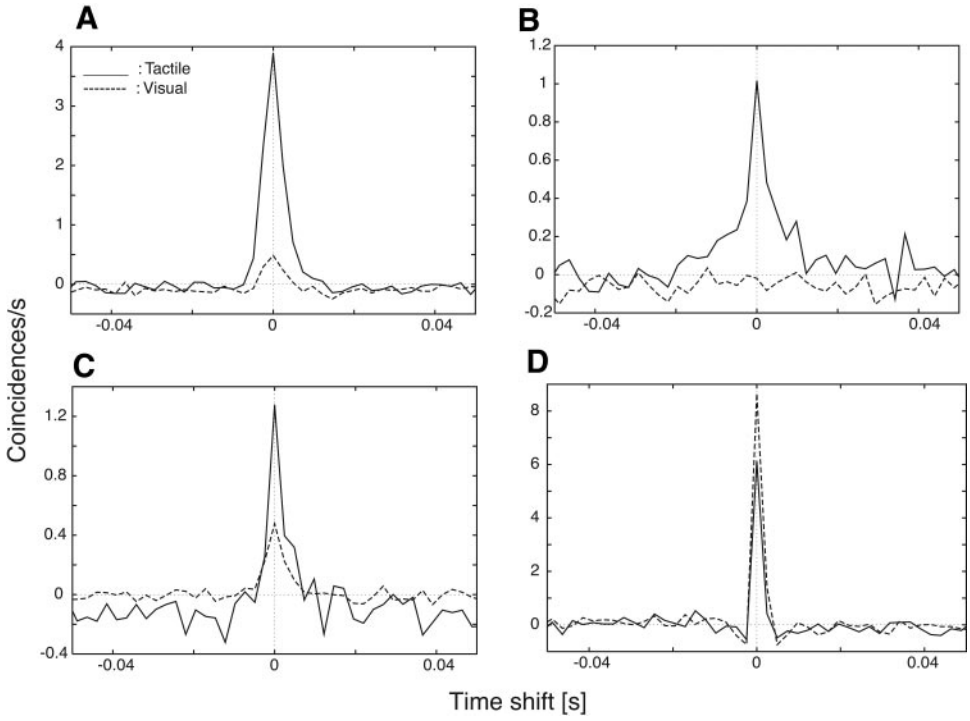


FIG. 7. Cross-correlograms (SCCCs) for 4 pairs of neurons from monkeys M1 (*C*), M2 (*A*, *B*), and M3 (*D*). SCCCs for the tactile and visual tasks are represented by the solid and dashed lines, respectively. Ordinate of each SCCC displayed here has been normalized to coincidences/s to account for differences in trial duration by dividing the counts in each SCCC bin by trial duration (2.5 s for *A*, *B*, *C*; 4.5 s for *D*).

gram peaks for neuronal pairs can be systematically modified by attentional manipulations.

As mentioned in METHODS, we observed an increase in firing rate after the throwing of the switch in monkey M2. We surmised that such joint increases in the firing rates could contribute to synchrony as observed in the correlograms. As discussed in *Control for movement effects*, a 100-ms-long portion of the spike train was deleted after the throwing of the switch and the statistical analysis was repeated. Columns 2 and 3 of Table 2 show the results. It is seen that removal of this period substantially decreased the number of synchronous pair (from 116 to 40) and thus many synchronous events happened during this period. Importantly, however, the number of pairs that show changes in the degree of synchrony with the attentional state decreases much less[2] (from 41 to 29 pairs). Therefore the percentage of synchronous pairs that change their synchronous state dramatically increases (from 35 to 72%) when this period is removed and the evidence for attentional modulation of synchrony becomes, if anything, much stronger. This is consistent with a scheme in which there are two types of synchrony. The first one (which is the one we are mainly interested in) is strongly correlated with selective attention and is unaffected by the removal of the period right after the motor movement. The second type is explained by rate effects or other possible artifacts and disappears when activity right after the switch throw action is removed but its presence (when this activity is not removed) superposes and reduces the apparent percentage of attention-correlated synchrony. The percentage of pairs that increased synchrony with attention changed slightly (from 85 to 79%).

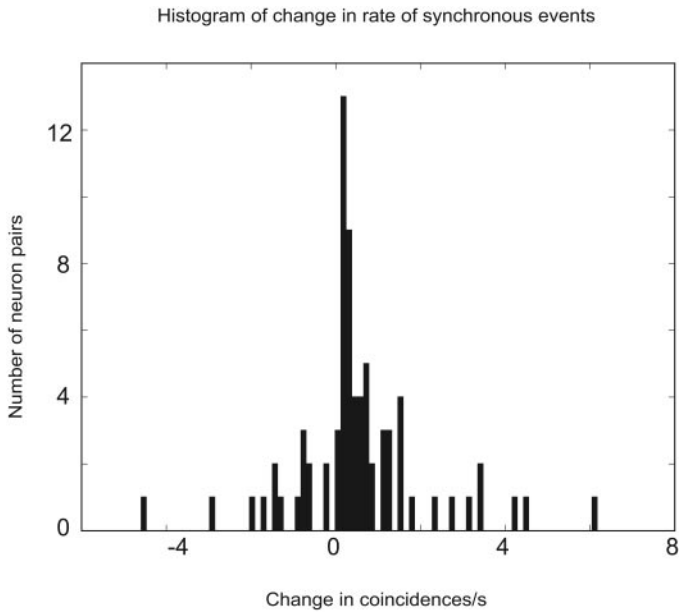


FIG. 8. Histogram of the overall change in rate of synchrony (coincidences/s) for all pairs with a significant attentional effect combined for all 3 monkeys (cf. Table 1). This measure of the change in rate of synchronous events (coincidences/s, displayed on the abscissa) was calculated as the sum of differences between normalized tactile and visual SCCC bins (over ±25 ms). Negative numbers in the histogram correspond to decreased synchrony in the tactile task.

As yet another check, we repeated the analysis, comparing the true negatives (attentive task with no throwing of the switch) with the visual task (nonattentive task). In this case, the 100-ms-long interval was deleted only from the trials when the monkey threw the switch while performing the visual task because no response occurred during the true negative trials. We performed two different analyses. In the first one, the spike trains generated in the true-negative tasks were used unchanged; results are shown in column 4 in Table 2. In the second analysis, spikes within 100 ms after a motor response

[2] A slight decrease in the number of significant pairs is indeed expected because the period over which the statistical significance can be achieved is decreased.

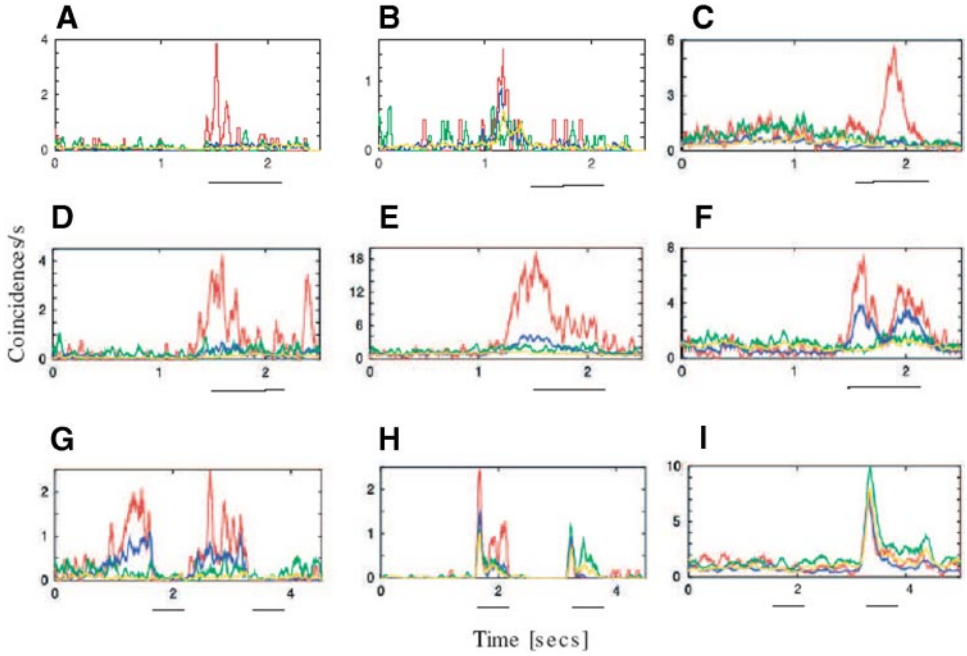


FIG. 9. Typical coincidence-rate plots. Plots *A* and *B* are from monkey M1, *C–F* are from M2, and *G–I* are from M3. All were affected significantly by attention. Coincidence bin size was 2.5 ms for M1 and M2; 4.5 ms for M3. Red curve: tactile task; green curve: visual task; blue curve: rate of synchrony expected by chance in tactile task; yellow curve: rate of synchrony expected by chance in visual task. Responses to all target letters were used. Bars underneath the abscissa of each plot denote the period of time when the tactile stimulus was in contact with the finger pad of the monkey.

(during the visual task) were removed; results are shown in column 5 in Table 2. A very similar pattern to that described in the previous paragraph was observed in this case. In either case, the fraction of neurons showing synchrony was much lower than that in the baseline case (Table 1) but the fraction showing a change with the attentional state substantially increased. The percentage of neuron pairs with an increase in synchrony during the attentional task remained almost the same (79% during both the tactile and true negative cases).

The changes in synchrony that we observed cannot be explained by stimulus-driven events because the tactile stimulus was identical in the visual and tactile tasks, nor can they be explained by attention-induced modulation of the neuronal firing rates because we controlled for this effect by subtracting the shift predictor. This latter point was further confirmed by an analysis showing that changes in the rate of synchrony were uncorrelated with changes in firing rate (measured as the change in summed response rate; correlation coefficient: −0.0243). We note, however, that even a low correlation coefficient is no guarantee for an absence of systematic correlation; as an example, the relationship between two quantities could show a V-shaped structure when one is plotted against the other, which would give rise to a low correlation coefficient. Therefore we took the additional precaution of showing, in Fig. 11, a scatterplot of the signed magnitudes of the change in rate of synchrony and the change in firing rate between the

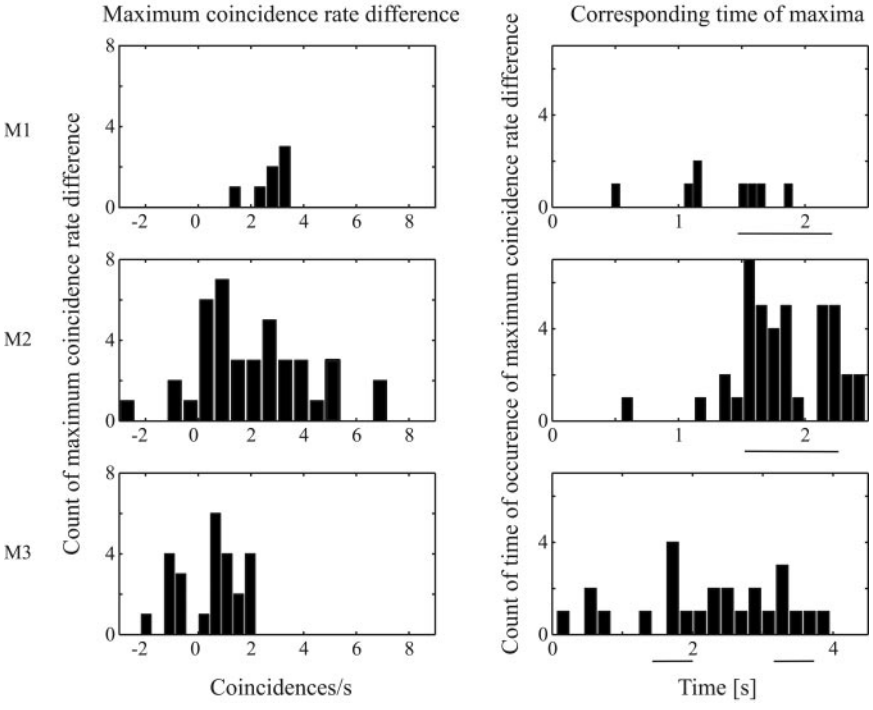


FIG. 10. Maximum difference in nonaccidental coincidence rates between the tactile and visual trials. *Left*: histograms of the maximum nonaccidental difference in instantaneous coincidence rate (in coincidences/s) between the tactile and visual SCCCs for each neuron pair that showed a significant attentional effect. Coincidence bin size was 2.5 ms for M1 and M2; 4.5 ms for M3. Negative numbers in the histogram correspond to decreased synchrony in the tactile task relative to the visual task. *Right*: histograms of the times when the maximum change in nonaccidental coincidence rate was found. Abscissa represents the trial duration for each monkey (2.5 s for M1 and M2; 4.5 s for M3). Bars below the abscissas denote the period when the tactile stimulus was in contact with the finger pad.

TABLE 2. *Details of percentages for tactile versus visual tasks and true negative versus visual tasks for monkey M2*

Analysis	SCCC (M2, Tactile)		SCCC (M2, True Negatives)	
	No deletion	100 ms deleted	No deletion	100 ms deleted
Significant synchronous firing	116/145 (77.9)	40/145 (28.0)	49/145 (31.0)	39/145 (26.9)
Significant change in synchrony	41/116 (35.3)	29/40 (72.5)	27/45 (60.0)	24/39 (61.5)
Increased synchrony	35/41 (85.4)	23/29 (79.0)	16/27 (60.0)	19/24 (79.2)

All values at significance level $P < 0.05$. The first column lists the relevant analysis as described for Table 1 Column 2 shows the fraction (and percentage in parentheses) of neuron pairs for the intact spike train data set (tactile vs. visual tasks). Column 3 shows the fraction of neuron pairs for the data set after removing all spikes in both the tactile and the visual tasks 100 ms after throwing of the switch by the monkey, on a trial-by-trial basis. Column 4 shows the fraction of neuron pairs for the intact spike train data set (true negative vs. visual tasks). Column 5 shows the fraction of neuron pairs after all spikes in the visual task 100 ms after throwing of the switch by the monkey, on a trial-by-trial basis (no switch was thrown during the true-negative case).

tactile and visual states for all significant pairs in all three monkeys. No systematic relationship between these two quantities is apparent. The general lack of correlation between changes in firing rate and in synchrony status indicates that changes in firing rate are unlikely to be an explanation of the changes in synchrony. Vaadia and coworkers also reported a similar lack of correlation between impulse rate and synchrony in a different context (Haalman and Vaadia 1998; Prut et al. 1998; Vaadia et al. 1995). Correlation coefficients were also computed for other measures of the change in firing rate, e.g., for the absolute value of the change in firing rate, the average change in rate in the poststimulus response period, and so forth. In all cases, the correlation coefficients were low.

The outcome of our results was similar when we used the tactile trial data instead of the visual trial data as the null population, and also when we re-created the logic of the *t*-test within a bootstrap framework (see *Statistical methods* for a description of the randomization methods used). Results are shown in Table 3.

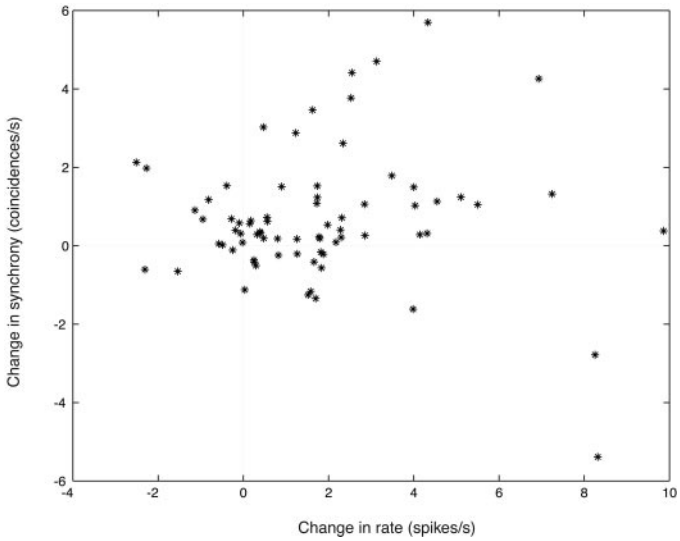


FIG. 11. Change in synchrony vs. the change in rate. Scatter distribution plot of the change in synchrony rate vs. change in firing rate of all pairs showing significant attentional effect from all monkeys combined. Change in synchrony was computed as the sum of the differences (on a bin-by-bin basis) between the tactile and the visual SCCCs over a ±25-ms window, whereas the change in firing rate of each pair was computed as the difference of the average firing rate (rate computed over the whole trial duration) of the 2 neurons between the 2 behavioral states. Correlation between the 2 was found to be negligible (for details see DISCUSSION).

DISCUSSION

Temporal structure of spike trains has been suggested previously as a basis for information processing in the brain (e.g., Perkel et al. 1967; Poggio and Viernstein 1964) and there are numerous reports of synchronous firing in the primate CNS (Abeles 1982; Abeles et al. 1993; Ahissar et al. 1992; Decharms and Merzenich 1996; Eckhorn et al. 1988; Haalman and Vaadia 1998; Laubach et al. 2000; Murthy and Fetz 1996b; Prut et al. 1998; Roy and Alloway 1999; Singer 1993; Vaadia et al. 1995; Young et al. 1992). Pure firing rate codes make inefficient use of neural connectivity (Stein 1967) and lead to additional difficulties, such as the binding problem (Crick and Koch 1990; Treisman 1996; Treisman and Gelade 1980), which could be alleviated or solved by adding information in the temporal structure of spike trains. Different temporal structures have been suggested as carriers of information, including oscillations (Eckhorn et al. 1988; Freeman 1975; Singer 1998), noise (Douglass et al. 1993; Stemmler et al. 1995), and synchrony, the latter being the focus of this report. Our results support the notion that information about the cognitive state (i.e., where attention is directed) is carried not only by the firing rate of neurons but also by the relative times of occurrence of action potentials between neurons. In this study, we investigated whether the degree of synchrony is modifiable and whether it changes when the animal changes its attentional focus.[3] We found that about 66% of the neuron pairs in SII showed significant correlated responses and that about 17% of those neuron pairs changed their degree of synchronous firing when the animal's focus of attention was switched between a visual and tactile task.

For the conclusions of this study to be valid, it is imperative that the animals switched their focus of attention between the visual and the tactile stimulus. There are several reasons to believe that the animals ignored the tactile stimuli while performing the visual task and vice versa and that this change in attentional focus is reflected in the activity of neurons in area SII. First, the animals did not respond to the tactile stimuli when attention was focused on the visual task. In these trials, the visual stimuli were presented asynchronously with the tactile stimulus and the animals were performing the visual task (performance >90%). Second, we observed significant

[3] Note that this question—how the representation of attended stimuli differs from that of unattended stimuli—is related to but different from which stimulus out of several present is selected. Although the latter has been investigated by several modeling studies (e.g., Behrmann et al. 1998; Itti et al. 1998; Niebur and Koch 1996; Olshausen et al. 1993; Usher and Niebur 1996), theoretical work concerning the former is more limited.

TABLE 3. *Results of additional statistical tests for change in synchrony with attention*

Monkey	Tactile	Visual	*t*-Test
M1	6/50 (12.0%)	8/50 (16.0%)	5/50 (10.0%)
M2	32/116 (27.6%)	41/116 (35.3%)	35/116 (30.2%)
M3	27/264 (10.2%)	25/264 (9.5%)	28/25 (10.6%)

The first column lists monkeys (M1: letter discrimination, constant target; M2: letter discrimination, varied target; M3: bar orientation discrimination). Columns 2, 3, and 4 show the fraction of neuron pairs with significant attentional effect ($P < 0.05$). The results were obtained using different bootstrap procedures. Column 3 shows the fraction obtained by drawing randomly with replacement (both times) from the visual single-trial correlograms. These percentages are the ones used throughout the paper for interpretational purposes (i.e., SCCCs). Column 2 shows the fraction in which the random drawing was done in a similar fashion as in column 3, except now from the tactile block of trials. Column 4 shows the percentage of neuron pairs obtained using a bootstrapped *t*-test. Percentages are shown enclosed in parentheses.

changes in firing rates in about 80% of the neurons when the animals' focus of attention switched between the two tasks, suggesting that the neural processing of tactile information changes with the animal's behavioral state. Third, during brief periods when the tactile stimuli were irrelevant (i.e., time-out and reward periods; for details see Hsiao et al. 1993) and the monkey was presumably not attending to the tactile stimulus, the firing rates were the same as in the visual task.[4]

The differences between the neural responses evoked during the tactile and visual tasks are most parsimoniously explained by the intrinsic differences in the animal's behavioral state. These differences could be attributed to differences in the arousal state of the animal, in the specific task of the animal or in the amount of attention, or cognitive effort devoted to the stimuli. We controlled for arousal effects by rewarding the animal at about the same rate during the tactile and visual tasks, whicht ensured that the animals were in a constant state of alertness throughout the experiment (for details see METHODS). Although we used the same visual task in all three animals, the tactile tasks differed in both the details of the stimulus and the degree of difficulty, judging by the human subjective ability to perform the tasks (see METHODS). The tactile and visual tasks were not equated for difficulty and humans subjectively report that the visual task is easier to perform than any of the three tactile tasks. We believe that the differences in the change of synchrony between the three animals do not arise from a generalized change in arousal in the animal but instead from differences in attentional effort required to specifically perform the tactile tasks. There have been only a few neurophysiological attention studies in monkeys where task difficulty was manipulated systematically. In one study of visual attention, Spitzer et al. (1988) found that the responsiveness and selectivity of neurons in V4 bars changed as the task was made more difficult. The results suggest that attention plays a greater role in sensory processing than simply enhancing the responses of neurons. There have been no comparable studies in touch. However, Burton and Sinclair (2000) showed that the effects of attention in animals performing a vibration task were independent of the diversion task that the animal was required to perform. Together these studies support the notion that the effects of attention that we observed were independent of the modality of the diversion task that we trained the animals to perform and support the idea that the degree of synchrony may change with task difficulty.

Although the differences in neural responses between different tasks and different monkeys are smaller than those that are sometimes found between different animals performing the same task, we acknowledge that a potential weakness of the study is that the same animals were not used in all three behavioral tasks. It would have been very difficult to train the three animals to do all three tasks. However, because all three animals performed the same visual control task, we claim that the baseline that we are comparing the results against was consistent between the three animals. In addition, all three animals were cued to perform the tactile tasks using the video monitor (screen). The difference was that in M2, the animal needed to attend to the screen after every hit, whereas the other animals (M1 and M3) needed to look at the screen only to see whether the task had switched to the visual task. It is difficult to control for these visual differences. For example, although for M1 and M2 the tactile form task is the same, the attentional load between the tasks is clearly different. All three animals had to attend to every stimulus whether it was an oriented bar or an embossed letter of the alphabet. In summary, although it is difficult to be certain that the effects of synchrony are due to the differences in task difficulty across tasks, it is clear that there are attention-related synchrony effects in all three animals and that synchrony is not a task-specific effect and most likely plays a role in sensory processing. Our favored hypothesis is that attention modifies both the firing rate of neurons and the degree of synchronous firing between neurons. Decreases in synchrony observed during selective attention may be the neural correlate of active suppression of distracting stimuli and increases in synchrony may be involved in enhancing the effect onto postsynaptic populations of selected stimuli (Niebur et al. 2002).

Precision of synchrony

Although we observed a wide range of peak widths in the correlograms (Figs. 5 and 6), we chose to use a 50-ms window length (±25 ms) about zero delay as our measure of temporal synchrony. We believe that this is a reasonable estimate of the measure of temporal synchrony for two reasons. First, 50 ms is approximately the period at which tactile stimuli begin to be perceptually integrated (Craig 1996). Second, a close inspection of the correlograms showed that this roughly bisects the distribution of half-widths: around 44% of the neuron pairs had SCCCs with half-widths <50 ms (Fig. 6). Similar attentional effects were also observed at shorter coincidence intervals; for instance, Fig. 4, *A–C* shows changes for a coincidence window of 2.5 ms and Table 1 shows similar attentional effects at a smaller coincidence window (±5 ms).

Interpretation of results

It is not surprising that we found a high percentage of neuron pairs with correlated firing in SII cortex. Most neurons in SII have large receptive fields that cover multiple digits, which suggests that there is a high degree of convergence as information flows from the periphery to SI and then on to SII cortex

[4] There were not enough spike data available to decide with a level of significance comparable with our other analyses whether the synchrony status changed during the time-out periods.

(Fitzgerald et al. 2006a,b). The percentages of correlated pairs found in the present study are comparable but slightly higher than what has been reported earlier in similar studies (Haalman and Vaadia 1998; Vaadia et al. 1995). Although our results do not provide us with information about the underlying neural connectivity nor the mechanistic details of how such synchrony could be generated (Aertsen et al. 1989), a plausible working hypothesis is that the high percentage of correlated neurons is explained by the large, overlapping receptive fields in SII cortex. The simplest explanation is that common input, flowing along common anatomical pathways from the periphery to the cortical neurons that we record from, generates synchronous activity on the timescales observed.

Our main result is that a large fraction of neuron pairs fire more synchronously when the constituent neurons represent an attended stimulus, compared with when they represent the same but unattended stimulus. Chapman and Meftah (2005) recently showed that attention enhances the responses in a task-specific way. In their study they found that when animals attended to the roughness of stimuli, only the texture-sensitive neurons showed changes in responsiveness. Thus it is not surprising that only a fraction of the neurons in the population show significant changes in synchrony because only 30% of the neurons in SII cortex show orientation-tuned responses (Fitzgerald et al. 2006a; Hsiao et al. 2002). Neurons play different roles in perceptual processing. If only a subset of the neurons in a region is engaged in representing the attended stimulus, then only that subset should show increased synchrony. This seems even more plausible in light of the fact that the monkeys are heavily overtrained on the experimental tasks.

It should also be noted that the fraction of neurons showing changes in synchrony is larger than the corresponding fraction of pairs (see RESULTS); for example, if 35% of neuron pairs in a population fire synchronously and we sample from this population in an unbiased way, then 59% of the neurons in the population are synchronous (given that $\sqrt{0.35} = 0.59$). The highest percentage of neurons that changes synchrony between attentional states was observed after eliminating the rate effects correlated with motor response and was found to be 72% of all pairs that show significant synchrony. Under the same premises, this means that 85% of the neurons in this population modify their synchrony level depending on the attentional state.

We observed substantial differences in the percentages of affected neuron pairs between monkeys that may have more than one explanation. Distance between electrodes is probably not a pertinent factor because we found no correlation between the distance between pairs of neurons and changes in synchrony (data not shown). Monkey M3 showed smaller changes in synchrony than that of monkeys M1 and M2. One possibility is that the number of neurons engaged in representing statically indented bars is smaller than the number engaged by scanned moving complex forms like letters; however, this does not explain the substantial difference between M1 and M2, both of which performed letter-discrimination tasks.

A second possibility, which may explain the difference between M1 and M2, is that the attentional demands differed between tasks. Shiffrin and Schneider (Schneider and Shiffrin 1977; Shiffrin and Schneider 1977) showed that humans performing visual-discrimination tasks respond more quickly and accurately when given the same reference pattern on every trial than when the reference pattern changes on every trial. They concluded that this was because in the first case subjects adopted a strategy in which they matched the test signal against a consistent internal map (a "consistent mapping" strategy) and that under these conditions stimuli were processed predominantly in a parallel "automatic attention" mode. In contrast, when the target stimuli are changed from trial to trial, subjects must use a "varied mapping" strategy, which involves a serial scanning of the items in a "controlled attention" mode. This is exactly the difference between the two tactile tasks performed by monkeys M1 and M2. This seemingly small but well-controlled difference in the tasks—shown to have a clear, strong, and easily reproducible effect in human visual psychophysics—also may lead to differences in the temporal structure at the single cell (or cell pair) level in our study. Shiffrin and Schneider provide extensive evidence that the cognitive load in the second design is more taxing. Over the years, a more differentiated view of this basic picture has evolved (see, e.g., a special issue of the *American Journal of Psychology*, vol. 105, 1992) but there is little doubt that the attentional demands in these two paradigms are different and that attentional demands are much higher in varied-mapping than in consistent-mapping tasks. Thus this difference in cognitive load may account for the larger percentage of neurons that show changes in synchrony with attention in M2. One way of testing this hypothesis would be to train another animal to do a letter-identification task to systematically switch its attention back and forth between tactile and visual tasks while varying the target letter continually in some blocks and keeping it fixed in other blocks.

The changes in synchrony reported here are consistent with those predicted by theoretical analyses (Crick and Koch 1990) and a computational model of attention (Niebur and Koch 1994), although some differences are observed. The Niebur and Koch (1994) model that motivated this study accounts for the selectivity inherent in attention by a mechanism that causes an increase in synchrony in the representation of the attended location of a stimulus to increase its synaptic efficacy. Although the basic hypothesis—that directing attention to a stimulus leads to a change in synchrony—is corroborated,[5] the model predicted increase of synchrony with attention in all pairs. In contrast, our data show a minority of cell pairs (20%) with a decrease of synchrony. More detailed models will be required to understand this discrepancy.

Irrespective of whether this particular computational model is correct, increasing synchrony between neurons is a powerful mechanism for increasing the combined synaptic effect of a subset of neurons. If a significant number of the neurons that cooperate in the distributed representation of an object or location in space fire more synchronously than neurons representing other objects or locations, then their combined message is more potent. A change in synchrony may be an important neural mechanism of selective attentional processing.

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[5] Even the size of the observed correlation functions was approximately predicted; compare Fig.7*A* with Fig.4 in Niebur and Koch (1994).

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REFERENCES

Abeles M. *Local Cortical Circuits*. New York: Springer-Verlag, 1982.

Abeles M, Bergman H, Margalit E, Vaadia E. Spatiotemporal firing patterns in the frontal cortex of behaving monkeys. *J Neurophysiol* 70: 1629–1638, 1993.

Aertsen AM, HJ, Gerstein GL, Habib MK, Palm G. Dynamics of neuronal firing correlation: modulation of effective connectivity. *J Neurophysiol* 61: 900–917, 1989.

Ahissar E, Vaadia E, Ahissar M, Bergman H, Arieli A, Abeles M. Dependence of cortical plasticity on correlated activity of single neurons and on behavioral context. *Science* 257: 1412–1415, 1992.

Behrmann M, Zemel RS, Mozer MC. Object-based attention and occlusion: evidence from normal participants and a computational model. *J Exp Psychol Hum Percept Perform* 24: 1011–1036, 1998.

Bernander O, Koch C, Usher M. The effect of synchronized inputs at the single neuron level. *Neural Comput* 6: 622–641, 1994.

Bouyer J, Montaron M, Rougeul A. Fast fronto-parietal rhythms during combined focused attentive behaviour and immobility in cat: cortical and thalamic localizations. *Electroencephalogr Clin Neurophysiol* 51: 244–252, 1981.

Brody CD. Slow covariations in neuronal resting potentials can lead to artifactually fast cross-correlations in their spike trains. *J Neurophysiol* 80: 3345–3351, 1998.

Burton H, Sinclair RJ. Tactile-spatial and cross-modal spatial attention effects in the primary somatosensory areas 3b and 1–2 of rhesus monkeys. *Somatosens Mot Res* 17: 213–228, 2000.

Burton H, Sinclair RJ, Hong S-Y, Pruett JR, Whang KC. Tactile-spatial and cross-modal attention effects in the second somatosensory and 7b cortical areas of rhesus monkeys. *Somatosens Mot Res* 14: 237–267, 1997.

Chapman CE, Meftah E-M. Independent controls of attentional influences in primary and secondary somatosensory cortex. *J Neurophysiol* 94: 4094–4107, 2005.

Craig JC. Interference in identifying tactile patterns: response competition and temporal integration. *Somatosens Mot Res* 13: 199–213, 1996.

Crick F, Koch C. Towards a neurobiological theory of consciousness. *Semin Neurosci* 2: 263–275, 1990.

Decharms RC, Merzenich MM. Primary cortical representation of sounds by the coordination of action potential timing. *Nature* 381: 610–613, 1996.

deOliveira SC, Thiele A, Hoffmann KP. Synchronization of neuronal activity during stimulus expectation in a direction discrimination task. *J Neurosci* 17: 9248–9260, 1997.

Desmedt JE, Tomberg C. Transient phase locking of 40 Hz electrical oscillations in prefrontal and parietal human cortex reflects the process of conscious somatic perception. *Neurosci Lett* 168: 126–129, 1994.

DiCarlo JJ, Lane JW, Hsiao SS, Johnson KO. Marking microelectrode penetrations with fluorescent dyes. *J Neurosci Methods* 64: 75–81, 1996.

Douglass J, Wilkens L, Pantazelou E, Moss R. Noise enhancement of information transfer in crayfish mechanoreceptors by stochastic resonance. *Nature* 365: 337–340, 1993.

Eckhorn R, Bauer R, Jordan W, Brosch M, Kruse W, Munk M, Reitboeck H. Coherent oscillations: a mechanism of feature linking in the visual cortex? Multiple electrode and correlation analyses in the cat. *Biol Cybern* 60: 121–130, 1988.

Efron B, Tibshirani RJ. *An Introduction to the Bootstrap*. New York: Chapman & Hall, 1993.

Fitzgerald PJ, Lane JW, Thakur P, Hsiao SS. Receptive field properties of the macaque second somatosensory cortex: representation of orientation on different finger pads. *J Neurosci* 26: 6473–6484, 2006a.

Fitzgerald PJ, Lane JW, Thakur P, Hsiao SS. Receptive field (RF) properties of the macaque second somatosensory cortex: RF size, shape, and somatotopic organization. *J Neurosci* 26: 6485–6495, 2006b.

Freeman WJ. *Mass Action in the Nervous System*. New York: Academic Press, 1975.

Fries P, Reynolds JH, Rorie AE, Desimone R. Modulation of oscillatory neuronal synchronization by selective visual attention. *Science* 291: 1560–1563, 2001.

Haalman I, Vaadia E. Emergence of spatio-temporal patterns in neuronal activity. *Z Naturforsch C* 53: 657–669, 1998.

Hatsopoulos NG, Ojakangas CL, Paninski L, Donoghue JP. Information about movement direction obtained from synchronous activity of motor cortical neurons. *Proc Natl Acad Sci USA* 95: 15706–15711, 1998.

Hsiao SS, Lane JW, Fitzgerald PJ. Representation of orientation in the somatosensory system. *Behav Brain Res* 135: 93–103, 2002.

Hsiao SS, O'Shaughnessy DM, Johnson KO. Effects of selective attention on spatial form processing in monkey primary and secondary somatosensory cortex. *J Neurophysiol* 70: 444–447, 1993.

Hyvarinen J, Poranen A, Jokinen Y. Influence of attentive behavior on neuronal responses to vibration in primary somatosensory cortex of the monkey. *J Neurophysiol* 43: 870–882, 1980.

Itti L, Niebur E, Koch C. A model of saliency-based fast visual attention for rapid scene analysis. *IEEE Trans Pattern Anal Machine Intell* 20: 1254–1259, 1998.

Jiang W, Tremblay F, Chapman CE. Neuronal encoding of texture changes in the primary and the secondary somatosensory cortical areas of monkeys during passive texture discrimination. *J Neurophysiol* 77: 1656–1662, 1997.

Johnson KO, Phillips JR. A rotating drum stimulator for scanning embossed patterns and textures across the skin. *J Neurosci Methods* 22: 221–231, 1988.

Laubach M, Wessberg J, Nicolelis MAL. Cortical ensemble activity increasingly predicts behaviour outcomes during learning of a motor task. *Nature* 405: 567–571, 2000.

Luck SJ, Chelazzi L, Hillyard SA, Desimone R. Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *J Neurophysiol* 77: 24–42, 1997.

Maynard EM, Hatsopoulos NG, Ojakangas CL, Acuna BD, Sanes JN, Normann RA, Donoghue JP. Neuronal interactions improve cortical population coding of movement direction. *J Neurosci* 19: 8083–8093, 1999.

Meftah E-M, Shenasa J, Chapman CE. Effects of a cross-modal manipulation of attention on somatosensory cortical neuronal responses to tactile stimuli in the monkey. *J Neurophysiol* 88: 3133–3149, 2002.

Mikula S, Niebur E. The effects of input rate and synchrony on a coincidence detector: analytical solution. *Neural Comput* 15: 539–547, 2003.

Moran J, Desimone R. Selective attention gates visual processing in the extrastriate cortex. *Science* 229: 782–784, 1985.

Motter BC. Neural correlates of attentive selection for color or luminance in extrastriate area V4. *J Neurosci* 14: 2178–2189, 1994a.

Motter BC. Neural correlates of feature selective memory and pop-out in extrastriate area V4. *J Neurosci* 14: 2190–2199, 1994b.

Mountcastle V, Reitboeck H, Poggio G, Steinmetz M. Adaptation of the Reitboeck method of multiple microelectrode recording to the neocortex of the waking monkey. *J Neurosci Methods* 36: 77–84, 1991.

Murthy V, Fetz E. Coherent 25 to 35 Hz oscillations in the sensorimotor cortex of awake behaving monkey. *Proc Natl Acad Sci USA* 89: 5670–5674, 1992.

Murthy VN, Fetz EE. Oscillatory activity in sensorimotor cortex of awake monkeys: synchronization of local field potentials and relation to behavior. *J Neurophysiol* 76: 3949–3967, 1996a.

Murthy VN, Fetz EE. Synchronization of neurons during local field potential oscillations in sensorimotor cortex of awake monkeys. *J Neurophysiol* 76: 3968–3982, 1996b.

Niebur E, Hsiao SS, Johnson KO. Synchrony: a neuronal mechanism for attentional selection? *Curr Opin Neurobiol* 12: 190–194, 2002.

Niebur E, Koch C. A model for the neuronal implementation of selective visual attention based on temporal correlation among neurons. *J Comput Neurosci* 1: 141–158, 1994.

Niebur E, Koch C. Control of selective visual attention: modeling the "where" pathway. In: *Advances in Neural Information Processing Systems*, edited by Touretzky DS, Mozer MC, Hasselmo ME. Cambridge, MA: MIT Press, 1996, vol. 8, p. 802–808.

Niebur E, Koch C, Rosin C. An oscillation-based model for the neural basis of attention. *Vision Res* 33: 2789–2802, 1993.

Olshausen B, Andersen C, Van Essen D. A neurobiological model of visual attention and invariant pattern recognition based on dynamic routing of information. *J Neurosci* 13: 4700–4719, 1993.

Parasuraman R. (Editor). *The Attentive Brain*. Cambridge, MA: MIT Press, 1998.

Pashler H. *The Psychology of Attention*. Cambridge, MA: MIT Press, 1996.

Perkel DH, Gerstein GL, Moore GP. Neuronal spike trains and stochastic point processes: II. Simultaneous spike trains. *Biophys J* 7: 419–440, 1967.

Poggio GF, Viernstein LJ. Time series analysis of impulse sequences of thalamic somatic sensory neurons. *J Neurophysiol* 27: 517–545, 1964.

Poranen A, Hyvarinen J. Effects of attention on multiunit responses to vibrations in the somatosensory regions of the monkey's brain. *Electroencephalogr Clin Neurophysiol* 53: 525–537, 1982.

Prut Y, Vaadia E, Bergman H, Haalman I, Slovin H, Abeles M. Spatiotemporal structure of cortical activity: properties and behavioral relevance. *J Neurophysiol* 79: 2857–2874, 1998.

Reynolds JH, Desimone R. The role of neural mechanisms of attention in solving the binding problem. *Neuron* 24: 111–125, 1999.

Roy A, Steinmetz PN, Johnson KO, Niebur E. Model-free detection of synchrony in neuronal spike trains, with an application to primate somatosensory cortex. *Neurocomputing* 32–33: 1103–1108, 2000a.

Roy A, Steinmetz PN, Niebur E. Rate limitations of unitary event analysis. *Neural Comput* 12: 2063–2082, 2000b.

Roy S, Alloway KD. Synchronization of local neural networks in the somatosensory cortex: a comparison of stationary and moving stimuli. *J Neurophysiol* 81: 999–1013, 1999.

Schneider W, Shiffrin RM. Controlled and automatic human information processing: I. Detection, search and attention. *Psychol Rev* 84: 1–66, 1977.

Shiffrin RM, Schneider W. Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychol Rev* 84: 127–190, 1977.

Singer W. Synchronization of cortical activity and its putative role in information processing and learning. *Annu Rev Physiol* 55: 349–374, 1993.

Singer W. Consciousness and the structure of neuronal representations. *Philos Trans R Soc Lond B Biol Sci* 353: 1829–1840, 1998.

Sokolov A, Lutzenberger W, Pavlova M, Preissl H, Braun C, Birbaumer N. Gamma-band MEG activity to coherent motion depends on task-driven attention. *Neuroreport* 10: 1997–2000, 2000.

Spitzer H, Desimone R, Moran J. Increased attention enhances both behavioral and neuronal performance. *Science* 240: 338–340, 1988.

Stein RB. The information capacity of nerve cells using a frequency code. *Biophys J* 7: 197–826, 1967.

Steinmetz PN, Roy A, Fitzgerald P, Hsiao SS, Johnson KO, Niebur E. Attention modulates synchronized neuronal firing in primate somatosensory cortex. *Nature* 404: 187–190, 2000.

Stemmler M, Usher M, Niebur E. Lateral interactions in primary visual cortex: a model bridging physiology and psychophysics. *Science* 269: 1877–1880, 1995.

Tass P, Haken H. Synchronized oscillations in the visual cortex—a synergetic model. *Biol Cybern* 74: 31–39, 1996.

Tiitinen H, Sinkkonen J, Reinikainen K, Alho K, Lavikainen J, Näätänen R. Selective attention enhances the auditory 40-Hz transient response in humans (Letter). *Nature* 364: 59–60, 1993.

Treisman A. The binding problem. *Curr Opin Neurobiol* 6: 171–178, 1996.

Treisman A, Gelade G. A feature-integration theory of attention. *Cogn Psychol* 12: 97–136, 1980.

Treue S, Maunsell JHR. Attentional modulation of visual motion processing in cortical areas MT and MST. *Nature* 382: 539–541, 1996.

Usher M, Niebur E. A neural model for parallel, expectation-driven attention for objects. *J Cogn Neurosci* 8: 305–321, 1996.

Vaadia E, Haalman I, Abeles M, Bergman H, Prut Y, Slovin H, Aertsen A. Dynamics of neuronal interactions in monkey cortex in relation to behavioral events. *Nature* 373: 515–518, 1995.

Vega-Bermudez F, Johnson KO, Hsiao SS. Human tactile pattern recognition: active versus passive touch, velocity effects, and patterns of confusion. *J Neurophysiol* 65: 531–546, 1991.

Womelsdorf T, Fries P, Mitra PP, Desimone R. Gamma-band synchronization in visual cortex predicts speed of change detection. *Nature* 439: 733–736, 2006.

Young M, Tanaka K, Yamane S. On oscillating neuronal responses in the visual cortex of the monkey. *J Neurophysiol* 67: 1464–1474, 1992.