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Low-Threshold Ca^{2+}-Associated Bursts Are Rare Events in the LGN of the Awake Behaving Monkey

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Ruiz, Octavio, David Royal, Gyula Sáry, Xin Chen, Jeffery D. Schall, and Vivien A. Casagrande. Low-threshold Ca^{2+}-associated bursts are rare events in the LGN of the awake behaving monkey. *J Neurophysiol* 95: 3401–3413, 2006. First published March 1, 2006; doi:10.1152/jn.00008.2006. It has been proposed that low-threshold Ca^{2+} (LT)-associated bursts in the lateral geniculate nucleus (LGN) of awake animals communicate significant or unexpected visual events to cortex. The present study investigated this hypothesis by examining the incidence of LT bursts in 146 cells recorded from the LGN of three macaque monkeys. Bursts were defined as clusters of two or more action potentials separated by not more than 4 ms and preceded by a ≥100-ms quiescent interval. The incidence of bursts was examined in several intensive-training Go-NoGo and target selection tasks as well as in training-free tasks where natural scenes with both familiar and novel contents were shown. Our chief findings were as follows. *1*) Bursts occur in the majority of cells under every condition tested, *2*) burst incidence is very low (<1 burst every 10 s), *3*) bursts occur in association with a receptive field stimulus on average only once every 23 times in 65% of cells tested, *4*) cells responding with bursts to the stimulus also tended to exhibit higher levels of spontaneous bursting, *5*) the presence of bursts did not depend on the novelty of the stimulus or its behavioral relevance. When the monkeys explored static natural scenes, *6*) bursts were not correlated with short-term changes in the image sampled by the cell's receptive field during saccades. Burst incidence *7*) did not increase when images were novel or when they evoked an emotional reaction, and *8*) bursts did not decrease when images were familiar. *9*) Bursts were not correlated with saccades in the dark, but *10*) more spikes participated in bursts in the dark. Although these results confirm the occurrence of LT bursts in LGN cells of awake monkeys, they do not support the hypothesis that these bursts are a privileged means of transferring sensory information, that they signal unexpected or significant visual events, or that they are involved uniquely in the coding of natural scenes.

INTRODUCTION

The role of the thalamus and, in particular, of the lateral geniculate nucleus (LGN) is not well understood. The massive connections from cortical and brain stem areas to first-order relay nuclei, such as the LGN, and the complex intrinsic properties of voltage- and time-dependent membrane conductances in LGN cells suggest a more complicated role than that of a simple relay in the visual pathway (Casagrande et al. 2005; Guillery and Sherman 2002).

Thalamic cell firing patterns vary with an animal's level of consciousness. These changes in firing have been proposed to result from both the interconnectivity of thalamus with other areas of the brain and the intrinsic properties of the thalamic cells themselves (Llinas 1988; McCormick and Bal 1997; Steriade and Llinas 1988; Steriade et al. 1993). One of the ionic conductances implicated in these different state-dependent firing modes is the low-threshold calcium (Ca^{2+}), or I_T, current (McCormick and Pape 1990). In vitro studies have shown that this current is activated by depolarizing the cell membrane after a long period of hyperpolarization (approximately ≥100 ms). Opening of I_T Ca^{2+}channels results in the production of clusters of high-frequency Na^+/K^+ action potentials (heretofore, "LT bursts"). A sustained depolarization would change the cell's response to tonic mode in which the cell responds with streams of single action potentials (McCormick and Pape 1990). Depending on the activation status of I_T, LGN relay cells would then respond in burst or tonic modes to ongoing visual events (Denning and Reinagel 2005; Sherman 1996, 2001). Extrapolating from studies in anesthetized, paralyzed preparations, the two firing modes have been proposed to potentially code different aspects of visual information in awake animals. In tonic mode, the spike train would faithfully encode stimulus features, whereas in burst mode, spikes would be used to detect the presence of a new stimulus in the visual field. Thus bursts could be used as a "wake-up " call to visual cortex switching the thalamus out of the burst mode and into the tonic mode (Guido and Weyand 1995; McCormick and von Krosigk 1992; Scharfman et al. 1990).

The hypothesis that LT bursts signal significant visual or other sensory information in awake animals contrasts with other observations in slow-wave sleep and in anesthetized preparations. Under the latter conditions, sensory input is greatly diminished even though LT bursts are frequent, due presumably to the increased hyperpolarization of thalamic cells. Few studies have attempted to test directly the burst/tonic firing mode hypothesis in the LGN of awake preparations, and, to our knowledge, very few have involved awake monkeys (Martinez-Conde et al. 2002; Ramcharan et al. 2000, 2005). Studies in macaque monkeys are important because their visual system employs the "primate plan" common to humans. Primates, unlike many afoveate mammals, scan their environment bringing their fovea onto a region of interest. Therefore the goal of the present study was to examine the incidence of LT bursts in the LGN of awake behaving macaque monkeys using stimuli and tasks that should elicit LT bursts assuming such bursts are relevant to visual behavior. More specifically, we

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tested how the incidence of LT bursts varied with different epochs and conditions in several simple visuomotor tasks, free viewing of novel and familiar natural static scenes, image structure in natural scenes or blank fields, and the presence or absence of visual input. We also examined the relationship of LT bursts to saccades and how burst incidence evolves over time during the free viewing of static images.

METHODS

Subjects and LGN localization

Three male bonnet macaque monkeys (*Macaca radiata*, 6.0–8.0 kg) were used in this study. Because the methods for locating the LGN are described in detail elsewhere (Royal et al. 2006), only a short summary is presented here. We used magnetic resonance imaging (MRI) maps to position a recording chamber over the LGN. All the procedures, care and training of the monkeys conformed to the guidelines of the National Institutes of Health Guide for the Care and Use of Laboratory Animals and the guidelines of the Vanderbilt University Animal Care and Use Committee under an approved protocol.

Surgery

Attachment of the recording chamber, the head post, and eye coil were performed under sterile conditions under general anesthesia (either ketamine and xylazine or 1.5–3% isofluorane in O_2 as described in detail in Royal et al. (2006). Briefly, this involved securing head posts and wells with titanium screws and dental cement, and implanting an eye coil under the conjunctiva of the right eye (Judge et al. 1980).

Recording

Monkeys were seated in a primate chair in front of a computer monitor, within a frame generating a magnetic field received by the eye-coil. The head of the monkey was fixed by means of a head post attachment to the chair. Single-unit recordings were made with Parylene-coated tungsten microelectrodes (1–3 MΩ; FHC). The cellular activity was amplified and band-pass filtered, and spikes were discriminated with an amplitude-and-time window discriminator (BAK Instruments, Mount Airy, MD). A PC-based system running Tempo (Reflective Computing, St. Louis, MO) was used to control experiments, present stimuli, and store analog eye-position data and digital spike-timing data. Eye-position and neuronal activity were sampled at 250 Hz and 1 kHz, respectively.

Visual stimuli, LGN receptive field mapping, and cell classification

Stimuli for the first set of experiments (intensive-training visual tasks; see following text) were presented on an otherwise dark monitor in a light-tight room. The monitor was placed 57 cm from the eyes of the monkey and subtended 36 × 29° of visual angle. The monitor refresh rate and resolution were 70 Hz and 640 × 480 pixels, respectively. A grounded conductive-glass screen (3M, model AF250XXL) covered the monitor's face to reduce electrical noise.

The monkeys were trained to fixate a single-pixel (1/17°) fixation spot (FS) presented at the center of the monitor while a flashing bar (1–4 Hz) swept the right visual hemifield to locate and map LGN cell receptive fields (RFs). The stimulus' size, speed, flash rate, and location could be adjusted in real time allowing for precise RF mapping. Four equiluminant colored squares, white (CIE $x = 304$, $y = 325$), red (CIE $x = 632$, $y = 336$), green (CIE $x = 290$, $y = 605$), and blue (CIE $x = 143$, $y = 60$), (luminance = 1.8 cd/m^2) were used to assess the response type (ON or OFF) and color preference of the isolated unit. The stimulus that produced the maximum excitation or suppression over baseline response was selected and used for the remainder of the session. During subsequent trained visuomotor tasks, the stimulus was enlarged beyond the edges of the RF center to compensate for microsaccades around the FS and provide for consistent stimulation across trials. Only ON-center cells were used in this study because their characterization and stimulation were more reliable in our setup (bright localized stimuli on a dark screen in a uniformly dark room). Only units that were well isolated and showed clear responses to the appropriate stimulus were chosen for further analysis.

The monkeys are still participating in experiments, thus exact histological confirmation of recording locations was not possible. Due to this limitation, strict criteria were applied to confirm that recorded single units were LGN cells and to classify the responses as belonging to parvocellular (P), magnocellular (M), and koniocellular (K) (see Royal et al. 2006 for details). Cells that could not be classified as M, P, or K but were clearly well-isolated ON-center LGN cells were still included in our sample.

Intensive-training tasks

The monkeys were trained to perform three tasks for reward: blocked Go-NoGo, interleaved Go-NoGo, and target selection. We first describe the Go-NoGo task (Fig. 1). Each trial started with a dark monitor and a white FS at the center of the screen (baseline). During this period, the monkeys were required to maintain fixation in a 1° × 1° window. After a random period of 500 ms ±30%, the color of the FS changed to cue the monkey about the task's behavioral requirements (cue epoch). After another 500 ms ±30%, a stimulus was displayed on the screen inside the single-unit's RF center, and the monkey either had to remain fixated or make a saccade to the stimulus, depending on the color of the cue. A red FS cued the monkey to remain fixated (NoGo condition), and a green FS instructed the monkey to shift gaze to the stimulus in the RF (Go condition). In both conditions, the stimulus remained on until the reward was given (350–650 ms). In the blocked Go-NoGo task, the Go or NoGo trials were presented in blocks of 20–30 trials each until completion of two blocks per condition in an ABAB or ABBA sequence. A new trial was presented every 2–4 s (mean = 3 s). Trials were aborted if the monkey failed to respond correctly. Only successful trials were included in the analyses reported here.

The interleaved Go-NoGo task was identical to the blocked Go-NoGo task except that trials of Go and NoGo were pseudorandomly interleaved. In the target-selection task, the cue was always green (Go) and two stimuli were presented on every trial. The stimuli were located at the same eccentricity, one of them in the RF, and the other outside the RF either in the opposite hemifield or in the opposite quadrant of the same hemifield. The monkeys were required to guess which target (RF or non-RF condition) was correct in each block of trials and repeat a saccade to this location to obtain reward. Absence of reward indicated to the monkeys that they were required to switch to the other stimulus for the next block of trials to obtain a reward. The monkeys adopted a "win-stay, lose-shift strategy" to obtain the maximum number of rewards in the shortest time.

The time between the end of the RF characterization, and the beginning of the first task was 20 s to 1 min. This was also the interval between the end of a task and the beginning of a new task. The monkey could not predict task order. Both the monitor and the room were kept dark during pauses between tasks.

Free-viewing tasks

The monkeys were recorded in two tasks where they were free to move their eyes at will (i.e., they were not required to fixate). These tasks required no training, and so recordings began as soon as each task was introduced. The only other difference in the setup, from the

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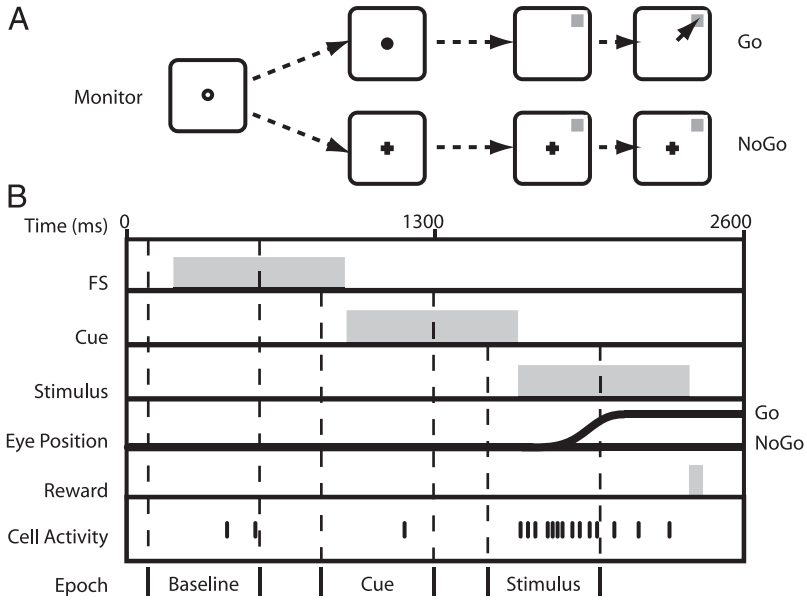

FIG. 1. Trained tasks. *A*: sequence of stimulus and behavioral events during the blocked Go-NoGo task. Trials began with the presentation of a white fixation spot (FS) at the center of the screen. After a randomly variable period (500 ms ± 30%), the color of the FS changed from white to either green (Go) or red (NoGo) and remained on while the monkey fixated the colored cue for another randomly variable period (500 ms ± 30%). A stimulus was then presented in the single-unit's receptive field (RF) for 350–650 ms. The monkey was rewarded for either making a saccade to the stimulus (Go condition) or for continued fixation of the FS (NoGo condition). *B*: temporal sequence of trial events relative to trial start (0 ms) in the Go-NoGo task. The gray bars illustrate the time events occurring on the screen and the reward, aligned with the relevant screenshots shown in *A*. Eye position is illustrated for a single trial of the Go condition and a single trial of the NoGo condition. Additionally, cellular activity from 1 trial of the Go condition is illustrated in the form of a spike raster (cell activity). For the purpose of analysis, trials were divided into 3 epochs of either 500 or 250 ms.

intensive-training tasks, was that the monitor resolution was increased to 1,024 × 768 pixels, to display high-resolution images.

In the picture task, the monkeys were presented with natural scenes and blank fields (Fig. 2). Three categories of images were shown in an interleaved sequence. The first category contained scenes that the monkeys commonly see in the animal facility, including familiar people and other monkeys. We operationally defined this condition as the "familiar" condition. The second category was made up of unfamiliar images which we operationally defined as the "novel" condition. The novel condition consisted of a variety of scenes that these cage-born monkeys should never have seen including such items as street scenes, sky with clouds, and fish. The third category was a blank field (blank condition) that was presented at one of three luminance levels in different sessions, either matched to the average luminance of the pictures (4.6 cd/m^2; gray blank), set to the maximum luminance of the monitor (27 cd/m^2; white blank), or set to the intra-picture black background field (below our instrument limits, $<$0.1 cd/m^2; black blank). Each image and the blank fields were presented for 7 s. The images were presented in the same order in every session, and the monkeys were rewarded between image presentations. An infrared camera was used to observe the monkeys' reaction to the images.

We also recorded LGN activity while the monkeys sat in a completely dark room and were free to move their eyes at will. Even if this situation is not, strictly speaking, a task, we will refer to it here as the free saccades in the dark (or FreeSacDark) task to avoid confusion with measures involving conditions within tasks and epochs. In no case did the monkeys exhibit slow eye movements typical of sleep during the FreeSacDark task. Unlike in the picture task, the monkeys spent from 45 min to 2 h in complete darkness during the FreeSacDark task and were thus dark adapted for these recordings. In some instances, an infrared camera also was used to observe the monkeys, and they appeared to be awake and alert. In fact, at the start of the FreeSacDark task, the monkeys would often keep their eyes centered as if waiting for the FS to reappear. Only after a period of time would they begin making what appeared to be exploratory saccades. During both the picture and FreeSacDark tasks, juice or water was delivered between trials (once every 7 s).

Burst-identification and epoch lengths

Bursts were defined as two or more spikes occurring within an interval of ≤4 ms and preceded by a quiescent period of ≥100 ms. This criterion is conservative minimizing the chance of assigning spike clusters to LT bursts when they were not part of a burst. Firing patterns defined this way were found to be LT bursts 99% of the time in the anesthetized paralyzed cat (Lu et al. 1992; Ramcharan et al. 2000). A burst was considered complete when the interval between successive spikes became >4 ms (Alitto et al. 2005). The fraction of spikes in bursts was calculated by dividing the number of spikes belonging to bursts by the total number of spikes in the same epoch or condition. The analysis of the data also was performed using two more liberal criteria (50- or 25-ms quiescent periods). All the calculations were performed with custom programs written in MATLAB (Math Works).

In the intensive training tasks, we compared the number of bursts occurring during the baseline epoch with the number occurring during the cue and stimulus epochs. Because a trial is a continuous event, we

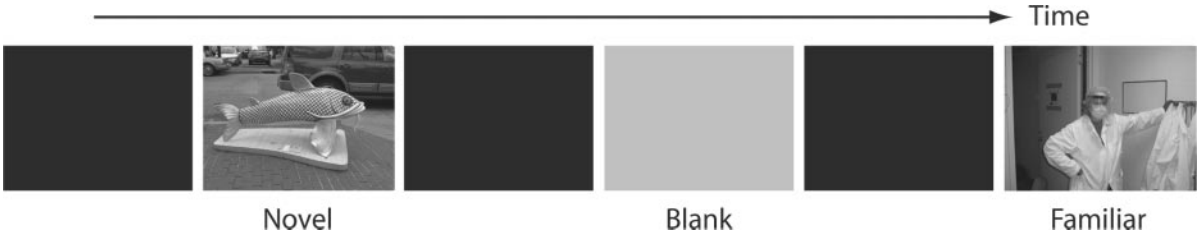

FIG. 2. The picture task. Alternating novel, blank, and familiar images were presented to the monkeys in a dark room without any training or eye-fixation demands. Each image was presented for 7 s and was followed by an intertrial interval of 7 s during which the monitor was dark. The majority of the picture task sessions were run with a blank image the luminance of which was matched to the mean luminance of the set of novel and familiar images (4.6 cd/m^2; "gray blank"). Eye position and cellular activity were recorded only during image presentations, and monkeys were rewarded with water or juice only at the conclusion of each image presentation after data acquisition had terminated.

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operationally defined these epochs as periods of 500 ms, excluding any trials where epochs overlapped. The baseline epoch began with fixation, the cue epoch began 100 ms before the cue onset, and the stimulus epoch began 100 ms prior to stimulus onset (Fig. 1*B*). To maximize the possibility of counting stimulus-elicited bursts, we also analyzed bursts by narrowing the epoch window around the onset of the stimulus to 250 ms (100 ms before to 150 ms after stimulus onset). In this case, baseline and cue epochs were shortened similarly. In the picture and FreeSacDark tasks, each of the entire 7 s trials were analyzed without dividing trials into epochs.

Statistics

Statistical comparisons were made using a Mann-Whitney *U* test for two independent groups and the Kruskal-Wallis test for three or more independent groups. Differences between paired measurements were assessed with the Wilcoxon signed-ranks test, and differences among three related samples were evaluated with the Friedman's test for *k* dependent samples. Dependences between two variables were assessed evaluating Spearman correlations (Siegel and Castellan 1998). Alpha levels of $P < 0.05$ were considered significant. The statistical analyses were performed with custom programs written in SAS (SAS Institute).

Relation between bursts and saccades

We tested the association between bursts and saccades by measuring eye movements before, during, and after bursts in the picture and FreeSacDark tasks. To do so, we first identified the time (*b*) of the cardinal spike of each burst. Then for each burst, we defined three 100-ms windows centered 100 ms before the burst, on the burst itself, and 100 ms after the burst ($c = -100, 0, +100$ ms, respectively). For each burst, the eye-position change within each window was calculated as

$$e_{b,c} = \sqrt{(x_{b+c-\Delta t/2} - x_{b+c+\Delta t/2})^2 + (y_{b+c-\Delta t/2} - y_{b+c+\Delta t/2})^2};\ c = -100,0,+100 \text{ ms}$$

with $e_{b,c}$ representing the eye-position change in the window centered at time *c*, associated with burst *b*; Δt is the window width (100 ms); and *x* and *y* are the horizontal and vertical components of the eye position. To examine the effect of shorter-latency image changes on burst incidence, the same calculations were repeated with narrower time windows ($\Delta t = 30$ ms), positioned closer to the bursts ($c = -30$ ms, 0 ms, +30 ms).

RESULTS

We recorded from 146 LGN ON-center cells of which 50% were P, 6% were M, and 1% were K. Their average eccentricity was 8.8° (range: 1–17°). Although LT bursts were found in all cell classes and in all tasks, they were rare events, occurring less than once every 10 s regardless of task. There was no evidence that such bursts were reliable indicators of stimuli or behavioral events. Details are presented in the following text in four main sections. First we describe the incidence of bursts in different epochs of the trained behavioral tasks. Next we describe burst incidence under untrained free viewing conditions. Third we consider bursts in relationship to eye movements. Finally we examine whether burst incidence changes as monkeys became more familiar with the images over time.

Burst incidence in trained behavioral tasks

Figure 3 shows raw data from two typical cells while monkeys performed either the Go condition (*A*) or the NoGo condition (*B*) of the interleaved Go-NoGo task. In *B,* the arrow indicates the only burst detected in these 111 trials. Across all of our trained behavioral tasks, a total of 1,279 bursts were

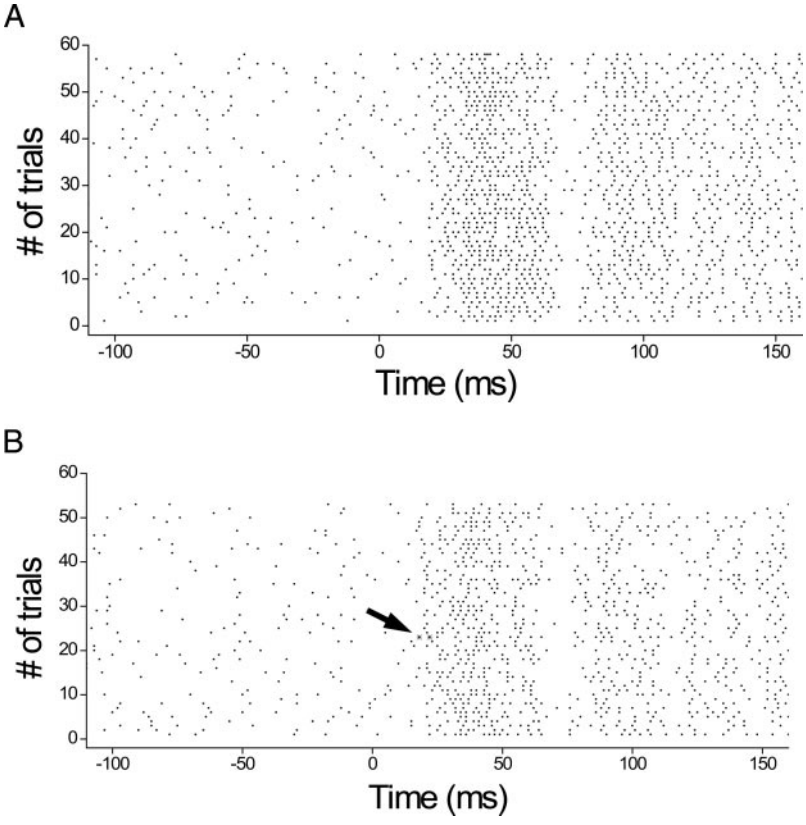

FIG. 3. Bursts detected in 2 cells during the Go condition of the blocked Go-NoGo task (*A*) and the NoGo condition of the interleaved Go-NoGo task (*B*) recorded from 1 monkey. The trial number and time are indicated in these raster plots showing all recorded spikes as tick marks. All trials have been aligned to stimulus onset ($t = 0$). Note that only 1 burst (→ in *B*) was detected in 111 trials.

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detected in 7,896 trials with 773 bursts occurring before the stimulus and 506 during or after the stimulus.

In Fig. 4 we examined for differences in burst incidence in relation to different tasks and conditions. This figure shows the response of 83 LGN cells (from all 3 monkeys) during the three epochs (baseline = B, cue = C, stimulus = S) of the two conditions of the blocked and interleaved Go-NoGo tasks and the target-selection task. The spike rate in the 500-ms stimulus epoch window was different in the Go and the NoGo conditions because the monkeys moved their eyes during this epoch. Neither the burst rate (*B*) nor the fraction of spikes in bursts (*C*) during the stimulus epoch showed significant differences attributable to the behavioral condition within any given task (*P* values between 0.15 and 0.71; Wilcoxon tests of the Go vs. NoGo conditions of the Go-NoGo tasks, and RF vs. non-RF condition of the target-selection task).

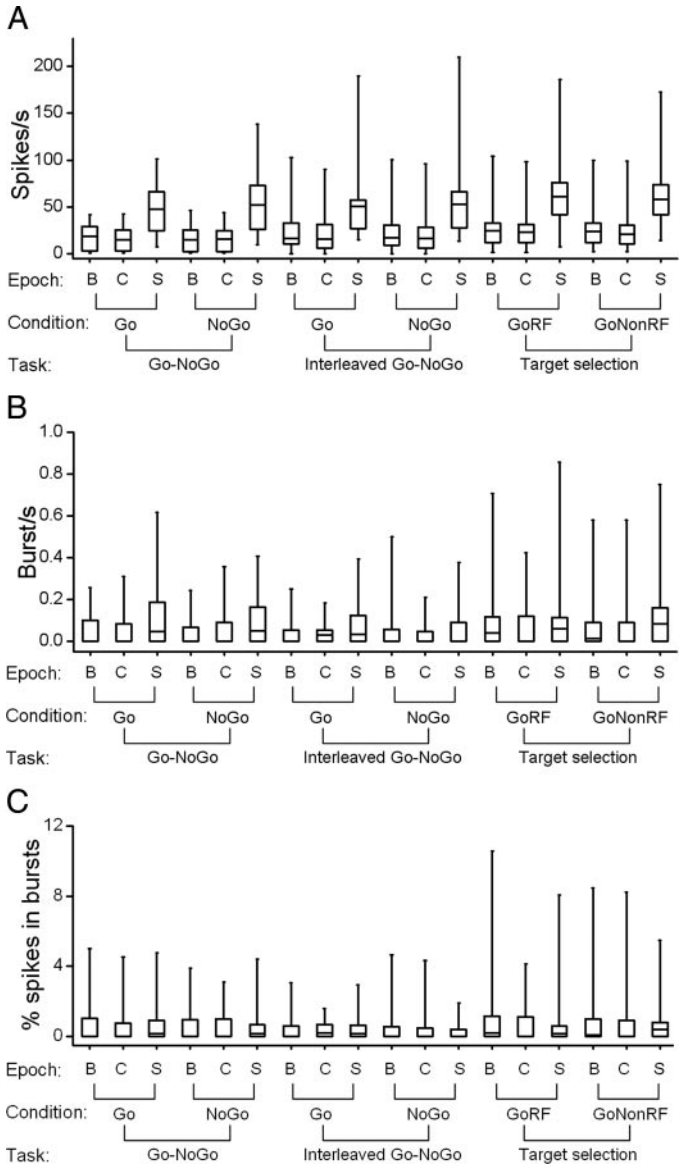

FIG. 4. Spike rate and burst incidence recorded during the visually guided saccade tasks [83 magnocellular (M), parvocellular (P), and koniocellular (K) cells from all LGN layers of all 3 monkeys]. Data from each of the 3 epochs (baseline, B; cue, C; and stimulus, S) in the 2 conditions of the 3 tasks. Epoch durations are equal to 500 ms. Box-and-whisker plots show the median, 25 and 75% quartiles, and minimum and maximum values. *A*: spike rate. The cellular activity was approximately equal during the baseline and cue epochs and increased significantly during the stimulus epoch. *B*: burst rate. The burst rate also increased during the stimulus epoch of every task and condition. *C*: fraction of spikes in bursts. The fraction of spikes in bursts also increased during the stimulus epoch of most tasks and conditions. No significant differences were found in the spike rate, burst rate, or fraction of spikes in bursts between the Go and NoGo conditions of the 2 Go-NoGo tasks or between the GoRF and GoNon-RF conditions of the target-selection task.

Using two more liberal criteria to define bursts ($\geq$2 spikes within 4 ms, after 50- or 25-ms quiescent periods; see METHODS), we found that the measured burst incidence increased monotonically with the reduction of the quiescent period. No apparent differences across conditions or epochs emerged (Royal et al. 2003).

We also examined whether different classes of LGN cells (K, M, P) showed differences in burst incidence. Given the large numbers of tasks, conditions and epochs, however, it was not possible to statistically tease apart cell classes for each condition. We were, however, able to compare P and M burst incidence in the target-selection task and found no differences in the fraction of spikes in bursts across cell classes during the stimulus epoch.

The 500-ms B, C, and S epoch lengths resulted in occasional overlaps between epochs in some trials (these were discarded from the analysis). Also eye movements would have interfered with the cell response to the stimulus in all the conditions other than the NoGo condition. Therefore, we reanalyzed the data shortening the three epoch lengths from 500 to 250 ms; e.g., for the stimulus epoch, the window was set from 100 ms before to 150 ms after the stimulus onset. The baseline and cue epochs were also shortened to 250 ms. The spike rate measurements in the baseline, cue, or stimulus epochs did not change. The burst rate and the fraction of spikes in bursts in the stimulus epoch did show an increase, however, when this shorter window was used, suggesting that more bursts occurred close to the stimulus onset. None of the spike rate, burst rate, or the fraction of spikes in bursts during the stimulus epoch, however, showed significant differences attributable to the behavioral relevance of the stimulus within any given task (*P* values between 0.17 and 0.94; Wilcoxon tests of the Go vs. NoGo conditions of the Go-NoGo tasks and RF vs. non-RF of the target-selection task). Importantly, stimulus-associated bursts were rare events occurring on average every 23 trials and not occurring at all in 35% of cells (see also Fig. 3).

Burst rate in the stimulus epoch was positively correlated with spontaneous bursts (baseline and cue epochs combined; $r = 0.43$, $P < 0.0001$ Spearman correlation; Fig. 5). Burst rate in the stimulus epoch was negatively correlated with the spontaneous spike rate ($r = -0.21$, $P < 0.03$) and uncorrelated with the spike rate during the same stimulus epoch ($P = 0.66$).

Given the low incidence of bursts, we searched for evidence that bursts were signaling rare events associated with the stimulus. First we calculated the distribution of stimulus-associated bursts as a function of the time elapsed from the beginning of each task (blocked and interleaved Go-NoGo and target selection tasks). This relation is shown in Fig. 6. The horizontal axis represents the distance (in number of trials) from the beginning of the task; the height of the bars represents the number of bursts in the stimulus epoch. The cells in our sample ($n = 83$) responded with a burst at the beginning of the task on only two occasions, representing 1.9% of the total

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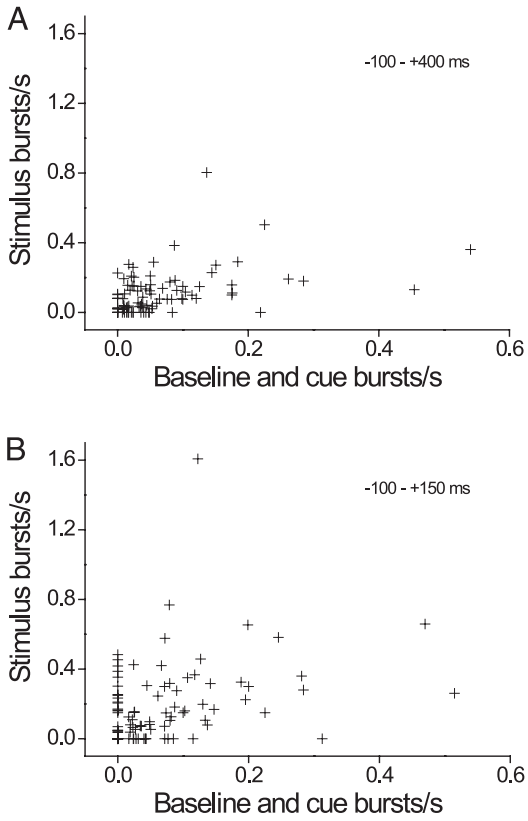

FIG. 5. Relationship between spontaneous and stimulus-associated bursting. Data from all the cells recorded during the visually guided saccade tasks (83 M, P, and K cells from all layers of the LGN from 3 monkeys). Baseline, cue, and stimulus epochs were either 500 ms (*A*) or 250 ms (*B*) in duration. The spontaneous burst rate was calculated by combining baseline and cue epochs.

number of tasks performed. No evidence of a transient peak of burst incidence and a subsequent decrease was observed.

If stimulus-associated bursts were correlated with the relevance ascribed by the monkey to the stimulus (e.g., being the target of a saccade instead of just a distracter in the target selection task), one would expect more stimulus-associated bursts to occur on the trials where the monkey switched from a NoGo to a Go task or between the RF and non-RF stimuli during the target selection task. Figure 7 shows the distribution of bursts for the blocked Go-NoGo (*A* and *B*) and the target-selection tasks (*C* and *D*). In each panel, the horizontal axis represents the distance (in number of trials) from the first correct response of the monkey to a condition change (*A,* NoGo to Go; *B,* Go to NoGo; *C,* non-RF to RF; *D,* RF to non-RF). The vertical axis represents the corresponding number of bursts in the stimulus epoch. There was no tendency for bursts to occur more frequently in the first trials after a change in the relevance of a stimulus as judged by the monkey's behavior. Stimulus-associated bursts that appeared linked with a condition change (bars at abscissa equal to 0 in the 4th panels) occurred only in 6 of 363 condition changes, representing 1.7% of the total number of condition changes.

Incidence of bursts under free viewing conditions

To further test the proposal that LGN bursts signal significant events in the visual world, we evaluated the incidence of LGN bursts as the monkeys freely inspected static natural scenes. Two categories of images were shown, "familiar" and "novel," interleaved with blank fields (see Fig. 2). An example of the recordings obtained during this task is shown in Fig. 8. In each panel, the *top trace* represents the eye movements and, *below*, one can see the activity of the recorded cell and the detected bursts (▼). Bursts occurred in every cell recorded in this task ($n = 32$) during all the conditions (familiar, blank, and novel), but their incidence was very low (median = 0.06 and mean = 0.09 bursts/s), equivalent to less than one burst every 10 s.

The reaction of the monkeys to the different pictures varied across subjects and recording sessions, but the majority of the time the pictures in the familiar set (gowned researchers, familiar macaque monkeys, and other animals in the facility) elicited a series of "emotional" displays. Reactions like ear flattening, grimacing, yawning, open mouth displays, grinning, etc. are well known to indicate fear, surprise, or aggression on the part of monkeys. Aggressive reactions (mouth threats with teeth exposed) and submissive behaviors (lip smacks and grimaces) occurred in our setup primarily in response to pictures of human faces (or standing humans in lab coats) and monkey and other primate faces. These gestures and postures are typically expressed by normal macaque monkeys exposed to social stimuli, e.g., another monkey or a human being (Chevalier-Skolnikoff 1973; Hinde and Rowell 1962; Kalin et al. 1991; Kenney et al. 1979; Maestripieri and Wallen 1997). In contrast, the novel images (clouds, unknown groups of people, unfamiliar natural scenes) as well as the blank fields never elicited such displays. Therefore, even if our classification of the images into novel and familiar was imprecise, the two sets of images clearly were not treated in the same way by the monkeys. Based on behavior, one could classify the images as engaging or nonengaging.

The activity of LGN cells recorded in these tasks under different conditions is summarized in Fig. 9. We found no significant differences attributable to the novel versus familiar categories either in the spike rate ($P = 0.34$, Wilcoxon test, 32 cells; Fig. 9*A*), burst rate ($P = 0.66$; Fig. 9*B*), or fraction of spikes in bursts ($P = 0.50$; Fig. 9*C*).

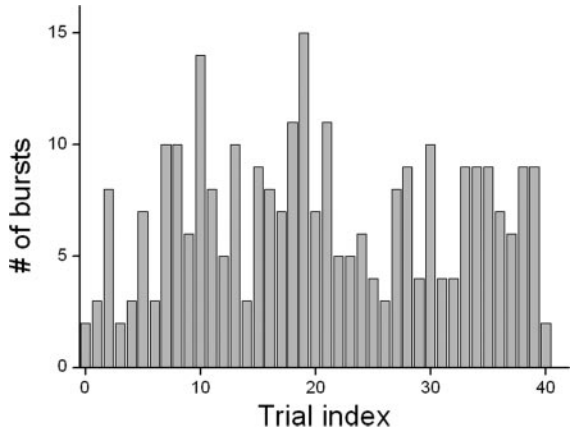

FIG. 6. Stimulus-associated bursts as a function of the time elapsed from the beginning of a task (blocked and interleaved Go-NoGo, and target-selection tasks; $n = 83$). The trial index represents the distance (in number of trials) from the beginning of the task while the height of the bars corresponds to the number of bursts recorded in the stimulus epoch using an epoch length of 250 ms.

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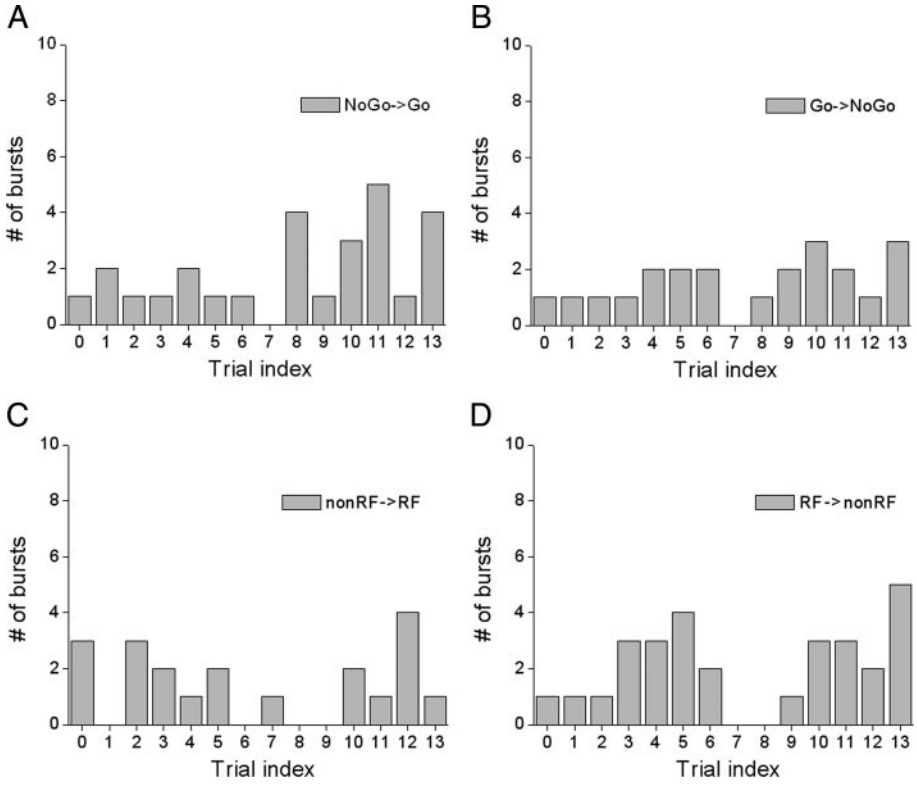

FIG. 7. Stimulus-associated bursts as a function of the time elapsed from a condition change in the blocked Go-NoGo and target-selection tasks (stimulus epoch length = 250 ms). In all panels, the trial index represents the distance (in number of trials) from the monkey's 1st correct response to a condition change. The vertical axis represents the corresponding number of bursts in the stimulus epoch. The mean time between successive trials is 3 s. *A*: transition from NoGo to Go in the Go-NoGo task. *B*: transition from Go to NoGo. *C*: transition from non-RF to RF in the target-selection task. *D*: transition from RF to non-RF. Other conventions as in Fig. 6. See text for additional details.

We then compared the cell activity when the monkeys were presented with either blank fields or natural scenes. Before doing this analysis, we noticed that the spike rate (Fig. 9*A*) and the burst rate (Fig. 9*B*) exhibited some dependence on overall luminance of the blank (black, gray, white). Therefore, to make the fairest comparison, we selected only the subset of cells recorded in sessions where the luminance of the blank was set equal to that of the novel and familiar scenes (20 cells). While the spike rate (Fig. 9*A*) depended on the type of image shown in the screen (familiar, novel, gray blank; $P = 0.0002$; Friedman's χ^2 test), neither the rate of bursts (Fig. 9*B; P* = 0.051) nor the fraction of spikes in bursts (Fig. 9*C; P* = 0.056) showed this relation. Moreover, despite parallel changes exhibited by the spike rate and burst rate with the luminance of the blanks (Fig. 9, *A* and *B,* respectively), the fraction of spikes in bursts did not change significantly ($P = 0.55$; Kruskal-Wallis test).

As before, the burst incidence depended on the criterion used to define a burst and increased monotonically with shorter quiescent periods. Thus the mean incidence of bursts in the picture task was 0.09 ± 0.09 bursts/s (100-ms quiescent period followed by ≥2 spikes in no more than 4 ms), 0.26 ± 0.20 bursts/s (50-ms quiescent period), and 0.70 ± 0.60 bursts/s (25 ms quiescent period).

Finally, we compared the incidence of bursts in the picture task with the burst incidence during long periods of absence of visual stimulation (FreeSacDark task, lasting from 1 to 4 min). The activity of 31 LGN ON-center cells recorded in the FreeSacDark task is represented by the rightmost box and whisker plots in the three panels of Fig. 9. We found that the

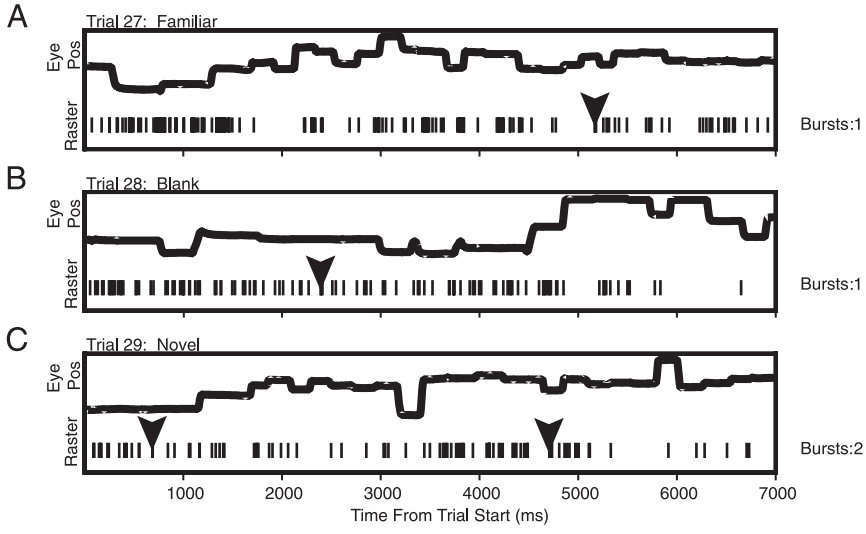

FIG. 8. Example records of eye position and cellular activity recorded during 3 consecutive trials of the picture task. In each panel (*A–C*), the *top trace* represents the eye position expressed as the distance from the fixation spot (FS). *Bottom*: cellular activity in the form of a spike raster. *A*: familiar condition. *B*: blank condition. *C*: novel condition. Bursts found in the example rasters are marked (▼).

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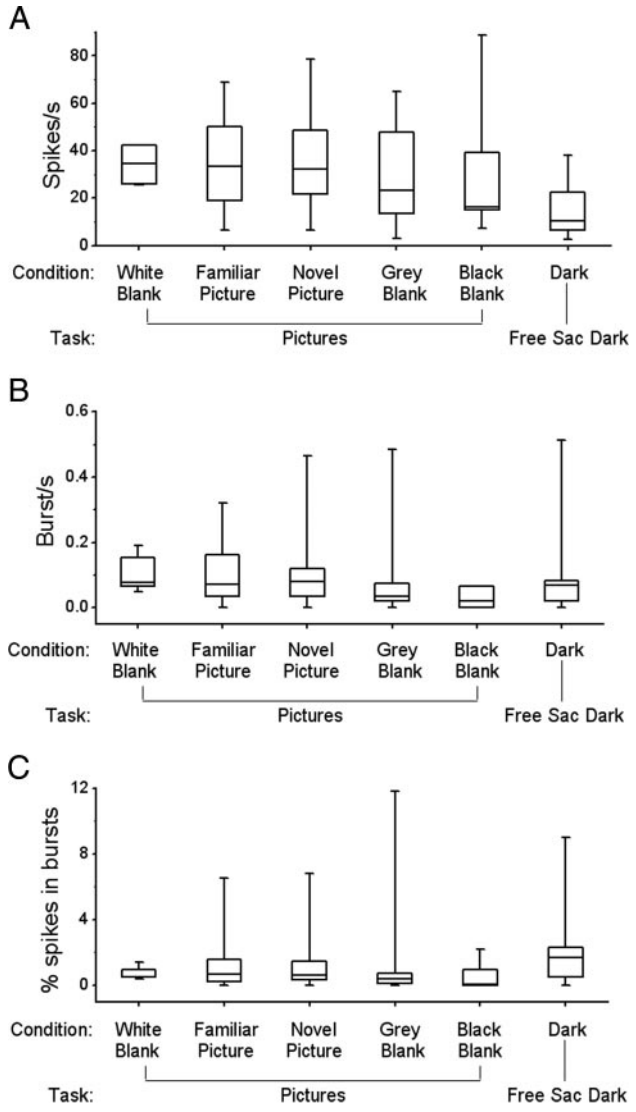

FIG. 9. Activity and burst comparisons of LGN ON cells recorded during the picture task (32 cells) and the FreeSacDark task (31 cells). In each panel, the 5 leftmost box-and-whisker plots represent data from the picture task, whereas the rightmost entry (FreeSacDark) represents the data from the free saccades in the dark task. In the picture task, the 2 categories of images "familiar" and "novel" were interleaved with blank fields, and the luminance of the blanks was set to different levels in different sessions. In 5 cells the blank was white (white blank), in 20 cells the blank was equiluminant to the Pictures (Gray Blank), and in 7 cells, the blank was black (black blank). The familiar and novel box-and-whisker plots combine the response of the 32 cells from all sessions. *A*: spike rates varied as a function of the luminance of the image. *B*: similar to *A*, burst rates increased with increasing luminance. *C*: fraction of spikes in bursts in all conditions of the picture task was: median = 0.53% and mean ± SD = 1.1 ± 1.7%. The fraction of spikes in bursts, in the dark, was: median = 1.7% and mean ± SD = 1.7 ± 1.9%.

spike rate was lower in the FreeSacDark task than in the picture task ($P < 0.0001$; Mann-Whitney test; familiar, novel, and blanks combined). No difference in the burst rate between tasks ($P = 0.74$) was found, but a higher fraction of spikes in bursts occurred in the FreeSacDark task than during the picture tasks ($P = 0.01$; picture task's median = 0.53% and mean ± SD = 1.1 ± 1.7%; FreeSacDark task's median = 1.7% and mean ± SD = 1.7 ± 1.9%). Therefore more spikes participated in bursts in the LGN in a task where there was no stimulus-driven input from the retina.

When the quiescent period was 50 ms, the fraction of spikes in bursts is larger in the FreeSacDark task than during the picture task ($P = 0.037$; Mann-Whitney test). When the quiescent period was 25 ms, no significant difference was found between the FreeSacDark and the picture tasks ($P = 0.74$).

Incidence of bursts associated with saccadic eye movements

LGN cell activity can exhibit changes associated with eye movements, namely a depression before or during a saccade followed by an enhancement once the eyes land at their new location (Bartlett et al. 1976; Jeannerod and Putkonen 1971; Lee and Malpeli 1998; Martinez-Conde et al. 2002; Ramcharan et al. 2001; Reppas et al. 2002; Royal et al. 2006). If the suppression is associated with the hyperpolarization of relay cells, one would predict an increase in burst probability after a saccade. Also because natural images would be expected to contain areas that both match and do not match the RF preferences of the recorded cell, an LGN cell the RF of which moves from a nonpreferred to a preferred location in the image would be expected to suddenly increase its activity after a period of inhibition and perhaps emit a burst.

We probed the association between bursts and saccades by measuring saccadic eye movements before, during, and after bursts identified in the picture and FreeSacDark tasks (eye movements were evaluated during 3 nonoverlapping time windows centered at $t = -100$, 0, and $+100$ ms, respectively, relative to the burst, with a window width of 100 ms). The results are shown in Fig. 10. The two panels show the absolute-value changes in eye position in the preburst, during-burst, and postburst time windows for the picture task (*A,* calculated from 552 bursts) and the FreeSacDark task (*B,* from 609 bursts). In general, there were very few eye movements near a burst as reflected by the close-to-zero medians and the close-to-zero 75% quartiles in all the box-and-whisker plots of both panels. No statistical differences were found among the preburst, during-burst, and postburst eye movement periods, either in the picture task ($P = 0.83$; Friedman's χ^2 test) or the FreeSacDark task ($P = 0.47$).

Given that in the Go-NoGo and target-selection tasks some bursts were observed in close association with the onset of the stimulus, we repeated the peri-burst saccade analysis with time windows set closer to the bursts (30-ms windows centered at -30, 0, and $+30$ ms relative to the time of the burst's cardinal spike; not shown). The results were similar to those obtained with the 100-ms windows; no statistical differences were found between the preburst, burst and postburst eye movements either in the picture task ($P = 0.78$; Friedman's χ^2 test) or the FreeSacDark task ($P = 0.55$).

Does the incidence of bursts change over time?

It has been proposed that LGN bursts emphasize stimuli that are surprising in a given context (Sherman 2001). All three of our monkeys spent >1 yr performing the Go-NoGo and target-selection tasks already described, so the sudden presentation of natural images on the screen should have been novel and surprising. We thus expected that the burst rate would decline as the novelty of the pictures wore off. We examined the incidence of bursts on successive sessions of the picture task

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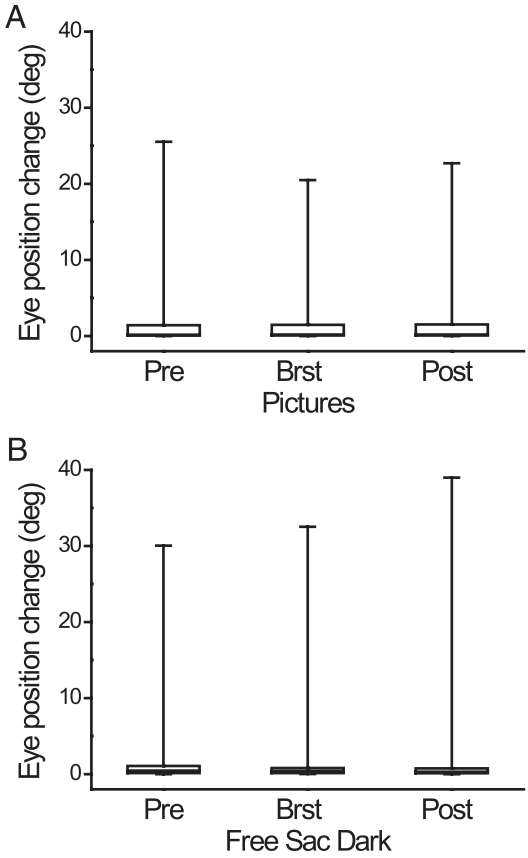

FIG. 10. Peri-burst eye position changes during the picture and the FreeSacDark tasks. *A*: box-and-whisker plot of the peri-burst eye-position changes during the picture task. The *leftmost entry* summarizes the eye-position changes preceding an identified burst (preburst time window: –150 to –50 ms relative to the burst). The other 2 entries correspond to the burst window (–50 to +50 ms) and to the postburst window (+50 to +150 ms). *B*: peri-burst eye-position changes during the FreeSacDark task. Same format as in *A*.

(Fig. 11). While some cells had more bursts than others, no trend in the fraction of spikes in bursts was observed for the blanks ($P = 0.22$; Spearman correlation) (*A*), familiar pictures ($P = 0.92$; *B*), or novel pictures ($P = 0.064$; *C*). Therefore, if the picture repetition over sessions modified the interest of the monkeys, this was not reflected in the incidence of bursts occurring in our sample of LGN cells.

We also examined if the incidence of bursts changed with time in a finer scale, namely over the 7 s of exposure to each image. It is impossible to test this prediction in our sample of cells on a trial-by-trial basis due to the scarcity of the bursts (many of the trials showed no bursts). Therefore we divided the trial length into 1-s bins and counted the bursts occurring in each bin in different sessions. Contrary to expectations, the burst rate in the first second of the picture presentation was not higher than that during the remaining period, and no clear trend in burst rate was observed over time (Fig. 12). This result held for both the novel (*A*) and familiar (*B*) picture conditions and contrasted with the spike rate (— and ■ in the same panels), which clearly decreased over the same 7-s trial.

The decrease in spike rate and the absence of change in burst rate over time was also observed during the presentation of the equiluminant gray blanks (Fig. 12*C*). The black blanks did not produce a transient increase in spike rate at the beginning of the trial nor an apparent adaptation over the trial (Fig. 12*D*). Thus the high initial spike rate and subsequent decrease over time likely resulted from light adaptation because the images were presented after between-trial periods of darkness. The constancy of the burst rate is more difficult to explain. One would expect that the fraction of spikes in bursts would change proportionately to produce an invariant burst rate. A second possibility is that bursts originate from a process not related to the visual input, and that this process remained relatively constant during the trial (see DISCUSSION).

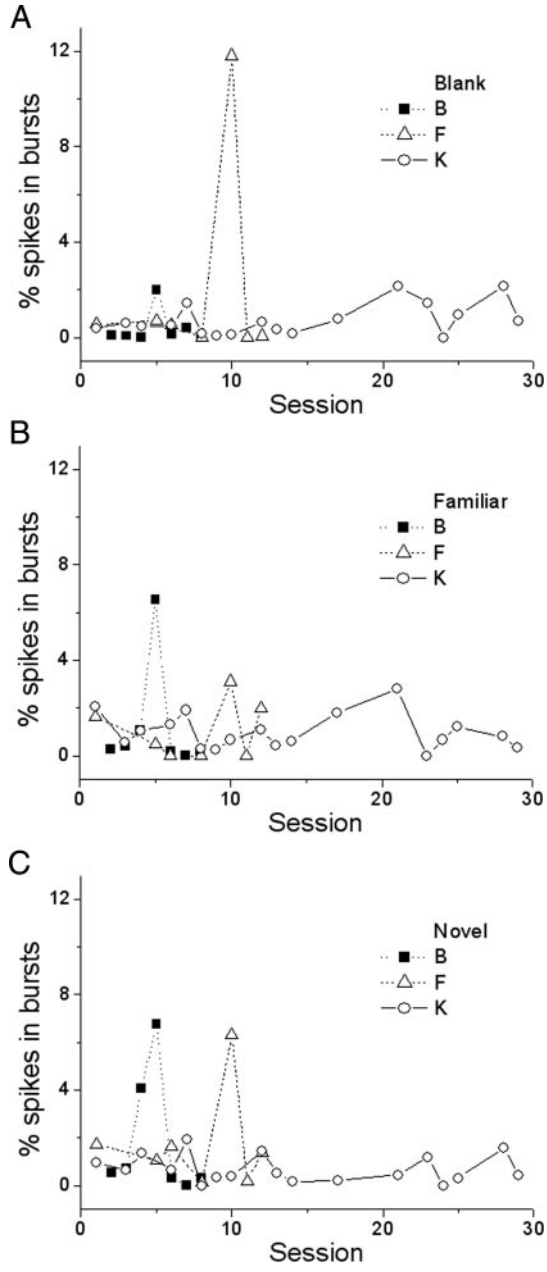

FIG. 11. Fraction of spikes in bursts as a function of recording session number and individual monkey. *A*: blanks. *B*: familiar pictures. *C*: novel pictures. No trend in the incidence of bursts was observed with the repeated application of the test. B, F, and K refer to individual monkeys. Other conventions as in Fig. 4.

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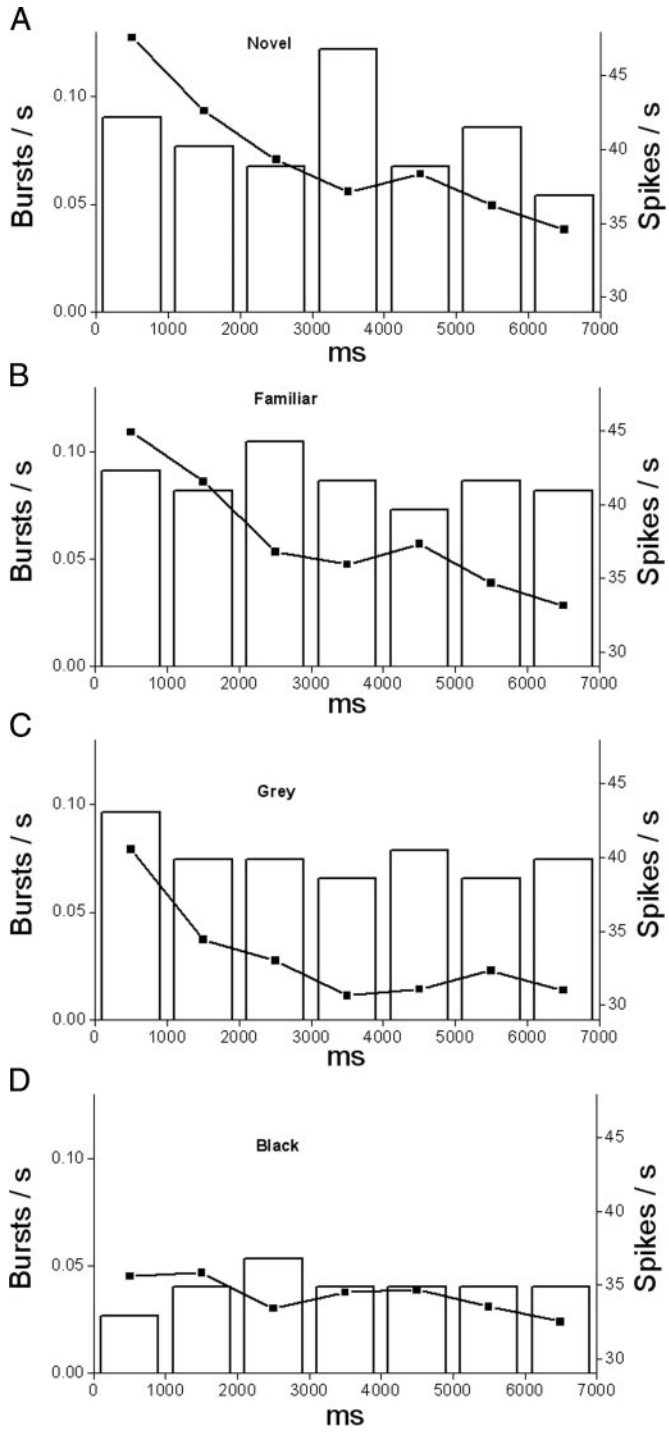

FIG. 12. Burst rates and spike rates as a function of time during the picture task. *A*—*C*: burst rate (□) and spike rate (— and ■) observed in 1-s bins over all the trials collected during the novel (*A*), familiar (*B*), and gray blank (*C*) conditions ($n = 20$). Although the mean spike rate decreases with time across each condition, presumably because of adaptation to the luminance of the images, burst incidence remains stable. *D*: burst rate and spike rate during the black blank condition of another set of cells ($n = 7$).

DISCUSSION

This paper examined the incidence of LT bursts in the LGN of awake behaving macaque monkeys under a variety of conditions. Our chief findings are that bursts occur in the majority of cells under every condition tested, burst incidence is very low (<1 burst every 10 s), bursts occur in association with a RF stimulus, on average, only once every 23 times in 65% of cells tested, cells responding with bursts to the stimulus also exhibited more bursts during baseline and cue epochs, and the presence of stimulus-associated bursts did not depend on the novelty of the stimulus or its behavioral relevance. When the monkeys explored static natural scenes bursts were not correlated with short-term changes in the image sampled by the cell's RF during saccades. Burst incidence did not increase when images were novel or when they evoked an emotional reaction, and bursts did not decrease when the images became familiar. Bursts were not correlated with saccades in the dark, but more spikes participated in bursts in the dark. Although these results confirm the occurrence of bursts in LGN cells of awake monkeys, they do not support the hypothesis that LGN bursts signal unexpected or significant visual events or that bursts are uniquely involved in the coding of natural scenes. The next subsections discuss and compare these findings with the results of others under a variety of conditions and also consider the functional significance of bursts.

Bursts: stimulus detection and novelty

According to the tonic/burst hypothesis (Sherman 2001), one would predict that a LGN relay cell, potentially silenced through hyperpolarization associated with stimulus absence/removal, or by the presence of an opposite-polarity stimulus, would respond with a burst to the onset of the preferred stimulus. The burst could thus act as a "wake-up call" to the rest of the visual system, "calling attention" to an unexpected stimulus, and/or to improve the detection of a stimulus (Sherman 2001). Not surprisingly, as reported by others in the somatosensory thalamus of rabbits (Swadlow and Gusev 2001), we found that more bursts occurred in cells that exhibited lower baseline activity because this, by definition, would allow more opportunity for the long periods of hyperpolarization necessary to produce an I_T burst. Given the finding that bursts are more likely to fire cortical neurons (Swadlow and Gusev 2001), the high spontaneous burst rate implies a high stimulus-independent activation of cortical neurons in burst responding cells. If bursts were to act effectively as a wake up call to changing stimulus conditions, increased stimulus-independent bursting would appear disadvantageous.

In awake cats, Weyand et al. (2001) showed that the repeated presentation of a stimulus in the RF of LGN cells produced bursts in some cases and that the incidence of these bursts declined with repeated presentation of the stimulus. Our data do not support this observation for monkeys because we failed to observe any increase in the incidence of bursts associated with the first presentation of a stimulus in a series of stimuli versus later presentations of the same stimulus. It is possible that there are major species differences between monkeys and cats in the transfer of sensory information to cortex or that other differences in the behavioral demands of the tasks could account for these differences. The latter explanation seems less likely given the large variety of behavioral situations we tested.

It could be argued that the smaller incidence of bursts during the stimulus presentation in our experiments is still consistent with a wake-up call. Our monkeys were overtrained in the Go-NoGo and target selection tasks. They knew the sequence

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of events and the location where the stimulus would appear. Therefore the stimulus was anything but a surprise, and the LGN cells were more likely to be operating in tonic mode. This is why we presented novel images in a way that the monkeys could not have anticipated: natural scenes appearing on a monitor where none had ever been presented before. The low incidence of bursts, however, and their lack of dependence on the relative familiarity of the images does not suggest a special role of LGN bursts in novel or surprising events.

Bursts and temporal changes in the visual input

In anesthetized cats, different patterns of full-field luminance changes produce different proportions of bursts in the LGN (Denning and Reinagel 2005). Also in anesthetized cats, slow luminance changes trigger more bursts than fast luminance changes. Therefore bursts can be considered nonlinear amplifiers of slow changes in luminance in anesthetized cats (Lesica and Stanley 2004). These observations were interpreted as suggesting that burst incidence is larger for natural scenes and for luminance changes mimicking natural luminance changes and, extrapolating to unanesthetized preparations, that bursts are potentially suited to convey information about natural stimuli in awake animals. We did not characterize, in detail, the luminance and color changes at the exact locations sampled by the LGN cell RF while the monkeys scanned natural images. We could, nevertheless, make the following predictions: eye movements occurring on a blank screen should produce little relative change in RF stimulation and eye movements when the screen displayed rich natural scenes should have produced changes given the gradation of colors and luminance shifts. Thus, if bursts are optimized for coding natural luminance changes, bursts should have been more frequent while the monkeys viewed natural scenes (familiar and novel conditions) than during the gray blank conditions. Additionally, bursts should have correlated more with saccades during the presentation of natural scenes given the higher probability of RF stimulation. Contrary to these predictions, we found that the fraction of spikes in bursts did not change significantly when the monkeys viewed blanks versus natural scenes. More important, bursts were not associated with saccadic eye movements in the picture task.

Bursts and nonvisual inputs: saccades

According to the model of I_T priming by hyperpolarization, bursts could be associated with saccades not only because of luminance changes occurring when the RF is stimulated but also because of nonretinal inputs suppressing LGN cell activity during saccades (Bartlett et al. 1976; Jeannerod and Putkonen 1971; Lee and Malpeli 1998; Martinez-Conde et al. 2002; Ramcharan et al. 2001; Reppas et al. 2002; Royal et al. 2006). For the vast majority of trials in both the FreeSacDark and picture tasks, burst production did not correlate with eye-position changes. Therefore we conclude that the saccadic suppression was insufficient to prime the low-threshold Ca^{2+} spikes, either under conditions when visual information was present or when it was absent.

Martinez-Conde et al. (2002), using a different criterion for bursts, report a higher probability of bursts after microsaccades. Using the same burst criterion we used here, however, a number of studies of LGN activity found no correlation between eye movements and burst incidence (Bartlett et al. 1976; Jeannerod and Putkonen 1971; Lee and Malpeli 1998; Ramcharan et al. 2001; Reppas et al. 2002; Royal et al. 2006). The rate of saccades per burst reported in the cat, a burst every 5.7 saccades (Lee and Malpeli 1998), is higher than what was observed in our monkeys (a burst every 45 saccades). This large difference could be attributable in part to methodological differences in saccade identification but most likely reflects the observation that cats make less frequent eye movements than primates.

Bursts in awake, sleeping, and anesthetized animals

The incidence of bursts in our preparation was less than one burst every 10 s under a variety of visuo-behavioral conditions. The incidence of bursts in the LGN of awake macaque monkeys in the absence of visual stimulation in our study is comparable to that reported by Ramcharan et al. (2000) (fraction of spikes in bursts = 1.7% in our FreeSacDark task and 1.3% in their monkeys in the waking state without any visual stimulation). These two values are five times smaller than the burst incidence in the monkeys studied by Ramcharan et al. (2000) during slow-wave sleep (fraction of spikes in bursts = 9.8%). Therefore burst firing is considerably lower in wakefulness than during sleep as concluded by these same authors (Ramcharan et al. 2000).

The higher incidence of bursts in monkeys during sleep parallels observations in cats. Weyand et al. (2001) found a 9:1 ratio of sleep to waking burst rates. Also in cats, McCarley et al. (1983) report relative burst rates of ~4:2:1 for slow-wave sleep, desynchronized sleep, and waking, respectively. Anesthetics increase the incidence of bursts in cats. Thus the rate of bursts in awake cats (0.09 bursts/s, in the cells that burst at all) (Guido and Weyand 1995) increases to 0.45/s in pentothal-anesthetized cats (average of all the cells reported by Denning and Reinagel 2005). It may be unjustified to compare bursts rates across species, but, if done, one finds that the incidence of bursts in pentothal-anesthetized cats is 5–10 times higher than the incidence of bursts in our awake behaving monkeys; the fraction of spikes in bursts reported by Lesica and Stanley (2004) is 13 and 26% under their two different conditions of stimulation. It is noteworthy that a qualitatively similar dependence of LT bursts on animal state was found in the medial geniculate nucleus of the guinea pig where the highest proportion of bursts occurred under ketamine/xylazine anesthesia and the least number of bursts were detected when the animals were awake (Massaux et al. 2004). Therefore there appears to be agreement that bursting is rare in the waking state in most sensory relay nuclei (Ramcharan et al. 2005) and that, regardless of the specific criterion used to define a burst, the incidence of LGN bursts increases with unconsciousness in a progression that seems to go from wakefulness to desynchronized sleep, to slow-wave sleep, and finally to deep pentobarbital anesthesia. One would then have to postulate that bursts have two completely opposite roles depending on the brain's state: to participate in "sensory disconnection" during sleep and anesthetic-induced unconsciousness, and to convey wake-up signals to the cortex while awake.

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Bursts in other pathways

Our results do not necessarily apply to other nuclei of the thalamus or to other species. In rabbits, for example, more bursts (defined as we have done here) are produced in the somatosensory ventrobasal nucleus in awake drowsy rabbits than we see under any conditions in the LGN of our awake monkeys (Swadlow and Gusev 2001). Also in rabbits there seems to be a clear correlation between EEG-defined inattentiveness and an increase in burst rate (Swadlow and Gusev 2001). Additionally, in the somatosensory thalamus of the rat, Fanselow et al. (2001) show that bursts, defined with a criterion different from ours, occur more often during exploratory whisking than during quiet immobility. Bursts also appear to occur more frequently in "higher-order" nuclei (such as the pulvinar) of the thalamus of awake monkeys than is observed in the LGN, indicating that bursts may have some other, as yet-to-be identified, purpose (Ramcharan et al. 2005; see also following text). Perhaps our monkeys were never sufficiently bored to lapse into a state sufficient to show the large increase in burst rate in the LGN also seen in the LGN of inattentive rabbits (Bezdudnaya et al. 2005). The point, however, is that if bursts are meaningful under waking conditions in monkey LGN, we should have seen evidence of this given the wide variety of conditions our monkeys were exposed to and the hours and hours of recording time that we sampled.

Other functions for LGN bursts?

If the bursts studied here and in the thalamus of sleeping animals are the same, and if both are a consequence of LT current activation, what might their role be? The fact remains that bursts do occur in both the awake and sleeping thalamus. So why is this the case? Despite the absence of correlation with stimulus novelty, repetition, and behavioral relevance, a few bursts were found in association with stimulus onset. Therefore it could be the case that LT bursts are not utilized in any way that reflects the direct transfer of sensory information to cortex but for some other purpose. Given that LT bursts are associated with an influx of calcium, it is possible that bursts reflect some form of plasticity (Abarbanel et al. 2003; Karmarkar and Buonomano 2002; Shouval et al. 2002), perhaps utilized in calibrating the operating range of LGN cells or in the transfer of stored information as has been proposed for "sharp wave bursts" initiated in the hippocampus during slow wave sleep (Buzsaki 1998). Although it is not clear if the latter bursts are the same as LT bursts, the localized fast spikes involved are (like LT bursts) associated with calcium influx. Buzsaki (1998) has postulated that an important component of sharp wave bursts may be initiated subcortically and could be involved in release of modulatory transmitters (e.g., acetylcholine) necessary for synaptic plasticity. In this context, one might expect more bursting in higher-order thalamic nuclei such as pulvinar because it is likely that these nuclei are more closely involved with hippocampal circuits. Therefore it would not be surprising to find more bursting in higher-order thalamic nuclei as Ramcharan et al. (2005) report and more bursting in all areas during sleep when visual memories are being consolidated. This could also explain higher bursting during inattentive phases (Swadlow and Gusev 2001). Perhaps the brain is continuously engaged in such long-term changes but only during periods when demands for sensory processing and vigilance are low.

Another reason that LGN bursting may be more common in some other thalamic nuclei than in the LGN could be because the retina normally has a powerful driving input and shows relatively high spontaneous activity. This constant bombardment rarely allows the prerequisite hyperpolarization to occur (Rowe and Fischer 2001). In the ventrobasal complex of the somatosensory thalamus, for example, the situation appears to be different because the input pathways (the principal sensory and spinal thalamic nuclei) show much less spontaneous activity, hence allowing for more thalamic bursts.

An additional possibility is that LT bursts occurring in isolation are only minimally relevant and that our use of single-unit recordings is methodologically inadequate to tease apart the overall relevance of bursting. By this we mean to suggest that the behavioral relevance of bursting during conscious states may be tied strongly to the synchrony of bursts across small ensembles of thalamic neurons. It is conceivable that a small number of synchronous bursts could facilitate spatiotemporal binding of visual information. This possibility is interesting from the point of view of information processing but is seemingly inconsistent with the observation that synchronized bursts are actually more common during sleep (Destexhe and Sejnowski 2002). Furthermore, if bursts were involved in binding, one might predict a dramatic increase in burst incidence when visual discrimination demands were increased, yet this was not observed in our study.

Clearly further study is required to determine whether burst and tonic modes of firing patterns in the thalamus truly represent distinct and meaningful modes of thalamo-cortical communication.

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