Adaptation-induced plasticity and spike waveforms in cat visual cortex

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Orientation-selective neurons shift their preferred orientation after being adapted to a nonpreferred orientation. These shifts of the peaks of tuning curves may be in the attractive or repulsive direction in relation to the adapter orientation. In anesthetized cats, we recorded evoked electrical responses from the visual cortex in a conventional manner. The recorded spikes in cortex may present two typical waveforms: regular spikes or fast spikes. However, there is no evidence whether the shapes of spikes are related to the attractive or repulsive shifts of orientation tuning curves of cells. Our results show that after adaptation the recorded cells with both attractive and repulsive shifts display one or the other shape of spike. However, the magnitude of shifts is systematically higher for regular spikes, which is attributed to putative pyramidal cells, whereas tuning curves for fast spikes have smaller magnitudes and are evoked by putative interneurons. ***NeuroReport*** **00:000–000 © 2011 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Introduction

Neurons in the mammalian visual cortex are tuned to respond to visual stimuli such as contour orientation, motion direction, and speed [1–3]. In previous studies, it has been shown that it is possible to modify the preferred stimulus which optimally excites neurons by applying a nonpreferred adaptation stimulus [4,5] in adult visual cortex. Adaptation studies in recent years have presented a more complex picture where prolonged exposure to a nonpreferred orientation has shown modifications in neurons' preferred orientations [4,6,7]. Longer adaptation durations (≥ 6 min) were shown to induce attractive shifts more frequently than repulsive shifts [6,8,9], but repeated or prolonged exposure to an adapter is also known to reduce neuronal responsiveness to that same stimulus, especially if it is the neuron's preferred stimulus [10].

Preference for orientation is considered relatively stable in the primary visual cortex (V1) as an emergent property that is established early in life following the so-called critical period [11]. Classically, spike waveforms allow dissociating two functional cell-groups into excitatory pyramidal cells and inhibitory interneurons [12,13]; hence, it is worth investigating how these two cell types react to adaptation. To this aim, we dissociated the recorded cells and analyzed their respective orientation tunings before and after adaptation to a nonpreferred orientation. This study deciphers whether after adaptation there is a relation between behaviour (attractive or repulsive) of cells and their respective waveforms. The most novel and interesting finding in our results was that the regular-spiking cells always shifted with higher magnitude than fast-spiking cells after adaptation. Furthermore, both types of cells shifted their peaks of orientations in either direction.

Methods

Animal preparation and electrophysiological recordings

Experiments were carried with the approval of Université de Montréal animal care committee following the guidelines of the Canadian Council on Animal Care. Anesthetized and paralyzed cats were prepared for electrophysiological recordings in upper layers of visual cortex (two to three, recording depths 250–1500 μm) in a conventional manner fully described previously [8,9,14]. A brief account is provided below.

Adaptation protocol

After manual receptive field characterization (all receptive fields were within 15° of area centralis), nine electrically generated, oriented drifting gratings were selected and centered on the preferred orientation for the entire experiment. Tuning curves covered 180° (22.5° intervals). Test orientations were presented in monocular manner in random order. Each oriented stimulus was presented in blocks of 25 trials (4.1 s each) with a random intertrial interval (1.0–3.0 s) during which no stimulus was presented. Once control orientation tuning curves were characterized, an adapting oriented stimulus was presented continuously for 12 min. The adapting stimulus was a drifting grating whose orientation was generally set within 22.5 to 67.5° of the neurons' preferred orientations. No recordings were performed during this

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adaptation period. Immediately after adaptations, orientation tuning curves were measured starting with the adapting and control preferred orientations, whereas the remaining orientations were recorded in random order.

Data analysis

Once single cells were sorted out offline from multiunit spike trains accumulated during data acquisition (Spike 2, Cambridge Electronic Design, CED Limited, Cambridge, England), orientation tuning curves were constructed from raw data and fitted with the Gaussian function. This allowed us to determine the preferred orientation of neurons with precision and then measure shifts in orientation preference. The Gaussian function is defined as

$$y = b + \mathrm{rmx} \times \exp\{-[(x - x0)^2] / 2s^2\},$$

where b is the baseline, rmx is max firing rate, x is used orientation, $x0$ is optimal orientation, and s is sigma.

In the present study, over 82% of V1 neurons were well tuned to stimulus orientation. However, it was necessary to ensure that cells in our sample were properly tuned for orientation. In our experiments, 25 consecutive measurements of a neuron's response to the same stimulus yielded 25 slightly different tuning curves. Adaptation-induced shifts were measured as the distance between peak positions of the fitted tuning curves before and after conditioning. To assess the statistical significance of tuning shifts, curve fits were generated separately for each of the 25 trials, and the mean difference was tested by a paired t-test. In all cases, shifts in preferred orientation greater than 5° are statistically significant (paired sample two-tailed t-test, $P < 0.01$) [9].

Cells were sorted out offline from multiunit activity of the recording site and were analyzed cell by cell (single-unit activity). We measured the degree of shift for each cell. This allowed us to classify the cells on the basis of their behavior: attractive or repulsive, or with no shift (preferred orientation remained within 5° of the initial optimal orientation). The spike waveforms were dissociated in the ascending phase of the action potential by measuring the slope (dv/dt) of each spike within an interval of 0.2 ms. This computation allowed us to separate the regular-spiking cells from the fast-spiking cells [15,16].

Polar plots that calculate the bandwidth of each cell were constructed on the basis of its response at all orientations. Chi-square test was done to estimate significance of difference between the bandwidth of fast spikes and regular spikes.

Results

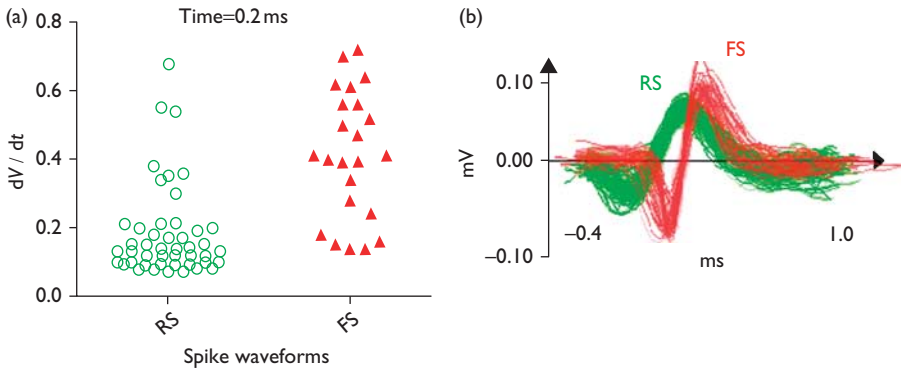
We recorded the multiunit activity of cells for stimulations at nine orientations in the primary visual cortex of anesthetized cats before and after adapting the neurons for a period of 12 min. We analyzed the single-unit activity of cells by spike sorting and we sorted out 73 cells (Table 1).

Figure 1a shows the distribution of regular and fast spikes according to dv/dt (slope) calculations in a time window of 0.2 ms. Both groups are clearly distinguished. In Fig. 1b, waveforms of all 73 cells were overlaid illustrating the difference between spike shapes, wherein red waveforms stand for fast-spiking cells ($n = 23$), whereas green

Table 1 **Classification of cells after adaptation**

		Attractive	Repulsive	No shift
Total cells ↓ → $n = 73$ cells		42 (57%)	18 (25%)	13 (18%)
Regular spikes	50 (68%)	30 (41%)	14 (19%)	6 (8%)
Fast spikes	23 (32%)	12 (16%)	4 (6%)	7 (10%)

Fig. 1

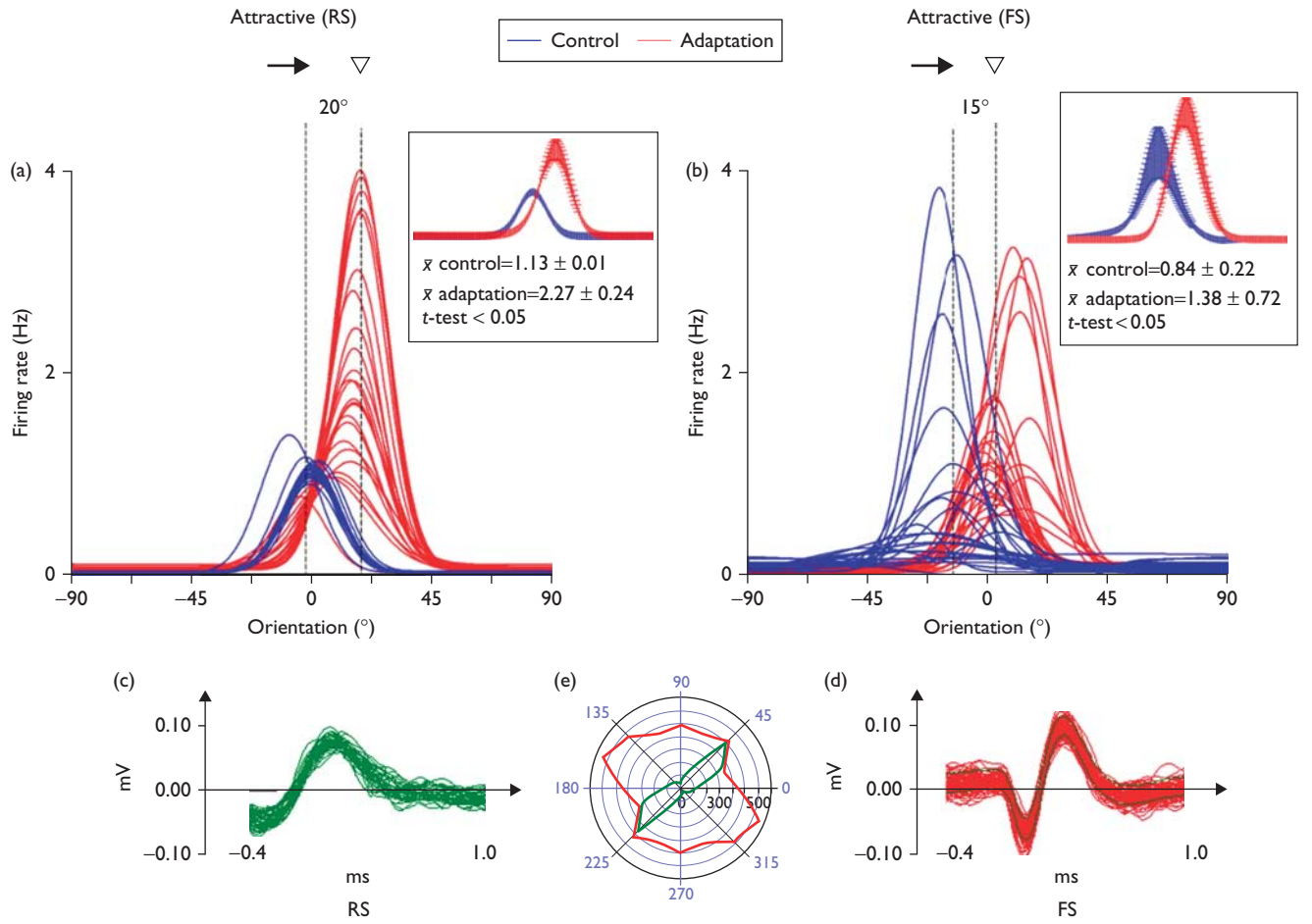


Comparison between regular spikes (RS) and fast spikes (FS). (a) Distribution of RS and FS based on dv/dt (slope) in a time window of 0.2 ms. (b) Superposition of RS and FS from all cells.

indicates regular-spiking cells ($n = 50$). Furthermore, we compared the distribution pattern of spikes for the rising phase of waveforms. We found that regular spikes and fast spikes were distinct by their ascending phase, that is, regular spikes always had a lesser slope than fast spikes (Fig. 1a and b). Also, after aligning the waveforms of fast spikes and regular spikes at the same origin we observed that regular spikes peak earlier than fast spikes by a phase difference of (almost) 0.1 ms (Fig. 1b).

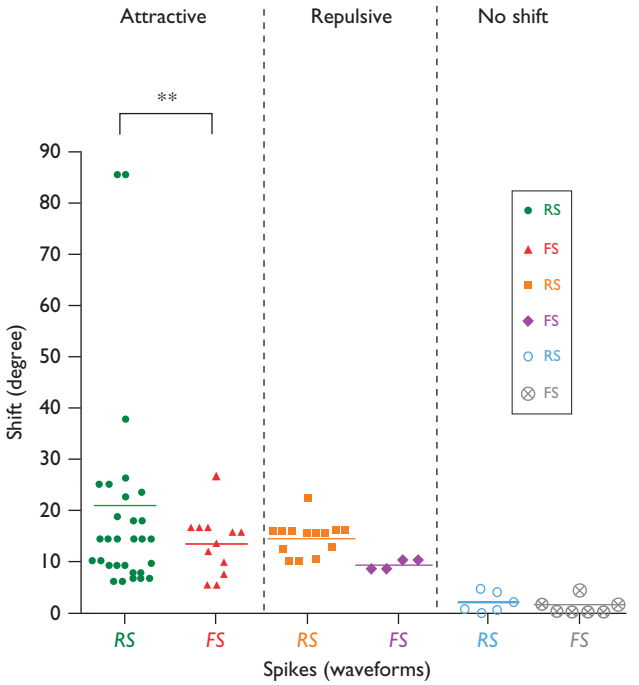
We then classified neurons on the basis of their behavior (attractive, repulsive, no shift) and shape (regular or fast). Overall results are summarized in Table 1. Figure 2 illustrates a typical example. In Fig. 2a and b, Gaussian tuning curves are plotted for two individual cells for all 25 trials. Waveforms for these cells are illustrated in Fig. 2c and d. The cell in Fig. 2a shifted by 20°, whereas the cell in Fig. 2b shifted by 15°. Both units shifted in the attractive direction (t-test, $P < 0.05$), even though they belonged to different groups. Consistent with published data [4,5], regular-spiking cells had a sharper tuning curve for orientation, whereas fast-spiking cells exhibited a broader tuning curve. Indeed, both types of cells react in attractive or repulsive directions. The polar plot (Fig. 2e) exhibiting the bandwidth illustrates the representative difference characterizing both types of cells. Fast-spiking cells responded strongly to more orientations creating broadly tuned bandwidths than regular-spiking cells that responded strongly to a few orientations (roughly optimal) creating narrowly tuned bandwidths (Fig. 2e) because discharge rates declined rapidly as the angle of orientation tilted away from the preferred axis [1,2,9–11]. Chi-square tests compared the responses at every tested orientation and showed a significant difference between both bandwidths ($P < 0.0001$, $\alpha < 0.05$, $n = 8$ orientations).

Fig. 2



An example of an attractive orientation tuning shift for a fast-spiking (FS) cell and a regular-spiking (RS) cell. (a) Cell displayed a 20° attractive shift following adaptation in the case of a regular waveform of the spike. Downward triangle indicates the adapting orientation. (b) Cell displayed a 15° attractive shift following adaptation in the case of a fast waveform of the spike. Downward triangle indicates the adapting orientation. (c) Example of an RS waveform. (d) Example of an FS waveform. (e) Polar plots (fast and regular cell superimposed) of two cells: RS cell and FS cell.

Fig. 3



Distribution of two classes of spikes according to postadaptation shift of attractive, repulsive, and no shift cells. This figure demonstrates that magnitudes of attractive and repulsive shifts are higher in regular-spiking (RS) cells than the fast-spiking (FS) cells (Fisher test between RS attractive cells and FS attractive cells: *P*-value <0.05). The maximum value of the shift was 85.5° and 26.7°, respectively, for RS and FS cells. The small number ($n=4$) of FS cells with repulsive reaction precludes statistical computations, yet the trend appears clear that the peaks of the orientation tuning curves for RS cells in the repulsive direction were also displaced to a larger extent.

Moreover, as shown in Fig. 3, regular-spiking cells for attractive behavior shifted within a range of 5–85.5° (average shift 21°) and the fast-spiking cells shifted within a range of 6–27° (average shift 14°; Fisher test, $P<0.05$). Similarly, regular-spiking cells for repulsive behavior shifted within a range of 10–23° (average shift 15°) and the fast-spiking cells shifted to 9°.

Discussion

The results of our study indicate that both types of functionally identified cells exhibit, following relatively long adaptation (12 min), shifts of their peaks of the orientation tuning curves in both directions, attractive and repulsive. The most interesting result that we found after induced adaptation to a nonpreferred orientation is that the regular-spiking cells and the fast-spiking cells shift in a consistent pattern with respect to each other, though to different degrees.

Therefore, directions of shifts are independent of types of waveforms. As expected from previous studies attractive shifts were more frequent [8]. Such common behavior suggests that neurons reacted collectively irrespective of the cell type. Our conclusion is in line with an earlier investigation showing that in most cases all cells recorded by a single electrode tip shift in the same direction [9]. These observations suggest that adaptation impacts a neuronal network, where a large proportion of cells change their preferred orientation jointly. However, fast-spiking units shift with a smaller magnitude than regular-spiking units. Various studies have indicated that fast-spiking cells are interneurons [17–21] with broader bandwidths of their tuning curves [15,22]. Their broader orientation tuning is a sign that these neurons are driven by a large spectrum of orientations with approximately equal strength. In that case, it is likely that each oriented input is contributing to the cell's response(s) with about comparable magnitude. Therefore, if one assumes that adaptation affects mostly the testing orientation, the other inputs maintain their excitatory drive producing relatively higher firing rates. The net result is a relatively lesser shift of the peak of the tuning curve.

On the other hand, the regular-spiking cells are pyramidal cells [21,23,24] with narrower bandwidths [15,22] exhibiting much sharper tuning curves. Consequently, the range of orientations generating higher firing rate is small, presumably due to a combination of inhibitory inputs [18] sharpening the bandwidths. Thus, optimal responses are produced by a smaller range of oriented input. Therefore, the modified equilibrium between excitation and inhibition that was induced by adaptation results in larger shifts because imposed orientation potentiate response, while remote orientations contribute less to the tuning curves. Indeed, in line with previous reports [4,8,9] responses evoked by flanked orientations did not change significantly.

Based on our findings, we hypothesize that in the primary visual cortex of cat after adaptation the pyramidal cells and interneurons interact and communicate with each other in an organized way to respond to orientation stimuli.

Conclusion

To our knowledge, this study is the first to show that the regular-spiking cells always shift more than the fast-spiking cells after adaptation to stimuli. We may conclude that in primary visual cortex of the cat, pyramidal cells and interneurons interact with each other in parallel to respond to induced adaptation stimuli. Pyramidal cells set the orientation selectivity and the interneurons regulate this selectivity.

Acknowledgements

Conflicts of interest

There are no conflicts of interest.

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