RESPONSE SELECTIVITY AND g-FREQUENCY FLUCTUATIONS OF THE MEMBRANE POTENTIAL IN VISUAL CORTICAL NEURONS

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ABSTRACT

With *in vivo* intracellular recordings we show that the rapid, γ-range fluctuations of the membrane potential occur during responses to visual stimuli in both simple and complex cells in cat visual cortex. The strength of these rapid fluctuations correlated with the stimulus optimality. Furthermore, the amplitude of the γ-fluctuations correlated with the phase of stimulus-imposed slow changes of the membrane potential. The combination of these features makes cortical neurons capable to encode the slow changes in the visual world in a kind of amplitude modulation of the high frequency fluctuations. This assures reliable transformation of the membrane potential changes into spike responses without compromising the temporal resolution of visual information encoding in the low frequency range.

INTRODUCTION

Fast oscillations at frequencies >20 Hz is an inherent property of cortical activity. In individual neurons, rapid fluctuations of the membrane potential improve the temporal precision and reliability of generation of action potential trains, and are capable to impose a narrow temporal window for the integration of synaptic inputs [10,11,15]. Due to these properties, rapid fluctuations of the membrane potential may be instrumental for synchronization of neuronal activity [8,9,15] and modulation of the input-output relationship of neurons [16]. So far, oscillations of the membrane potential at frequencies above 20 Hz were observed in neurons with complex receptive fields [2,7] and in a sub-population of simple cells [5]. To investigate, whether fast oscillations of the membrane potential are typical for the whole population of visual cortical cells, we made intracellular recordings and analyzed the relation between spike response selectivity and fast fluctuations of the membrane potential in cells with simple and complex receptive fields in cat visual cortex.

METHODS

We did intracellular recordings from visual cortex cells in adult cats. The details of surgery and maintenance of animals are described elsewhere [16] and were approved by a local animal welfare committee (Bezirksregierung Arnsberg, Germany). Intracellular recordings were made with sharp electrodes filled with 2.5 potassium acetate, resistance 70-120 MΩ. For visual stimulation we used moving gratings of different orientation, presented for 4-6 sec in a pseudorandom sequence. Cells were classified as simple or complex according to standard criteria [12] and using the spike response modulation index, defined as a half of the peak-to-peak modulation divided by the mean increase of the spiking frequency during presentation of an optimal moving grating [4,13]. This allowed to correlate the properties we have studied to the simple/complex classification. Power spectra were calculated using fast Fourier transformation (FFT) of 4096 ms epochs of the membrane potential

traces, starting with the beginning of grating movement. Before FFT, action potentials were removed from the traces [16]**.** Response components of a certain frequency band were extracted as follows. We performed an FFT of the membrane potential trace, then zeroed in the results all coefficients corresponding to the frequencies outside that given band, and then performed a reversed FFT. The low frequency range was set to cover the temporal frequency of the visual stimulation, which was 0.3-3 Hz in different cells. The high frequency component was always set to the γ-range (25 - 70 Hz).

RESULTS

We demonstrate, that (i) rapid, γ-range fluctuations of the membrane potential occur during responses to visual stimuli in both simple and complex cells; (ii) the strength of the γ-range fluctuations correlates with stimulus optimality and (iii) γ-frequency fluctuations of maximal amplitudes are phase-locked to the positive peaks of stimulus-induced, low frequency changes of the membrane potential.

Fig. 1 shows an example of the membrane potential fluctuations in the γ-frequency band during responses to optimally oriented moving gratings. In both, simple and complex cells, γ-band fluctuations have amplitudes of several mV, which are definitely capable of influencing generation of the action potentials.

To study the relationship between the stimulus optimality and the spectral composition of the membrane potential fluctuations we used two complementary approaches. First, we compared the power spectra of the membrane potential traces during the responses to stimuli of different orientations. In the simple cell shown in Fig. 2, as well as in the majority of other cells in our sample, fluctuations of the membrane potential in the γ-frequency range (25-70 Hz) were strongest during

presentation of the optimal stimulus (Fig. 3). For the whole sample, the γ-power of the membrane potential fluctuations was stronger than during presentation of stimuli of any other orientation ($p<0.001$, paired samples tests). Second, we examined the relation between the strength of the spike response and the γ-power of the membrane potential fluctuations in responses of each cell to the stimuli of different orientations (Fig. 2D). We found a strong and significant correlation between the γ-power of the membrane potential fluctuations and spiking during responses to stimuli of different orientations in the majority of cells (88%). In 80% of cells the correlation coefficient was higher than 0.75 ($p<0.001$). Taken together, these data demonstrate that changing the stimulus orientation led to parallel changes of the spike responses and the membrane potential fluctuations in the γ-range: stronger spike responses were associated with a stronger γ-power.

Next, we assessed the possible difference in the strength of the γ-range membrane potential fluctuations between complex and simple cells. Cells were classified as simple of complex according to the spike response modulation index, which is defined as the half of the peak-to-peak modulation divided by the mean increase of the spiking frequency [4,13]. The modulation index is higher than 1 in simple cells, but is less than 1 in cells with complex receptive fields. The strength of the γ-range fluctuations of the membrane potential was not correlated with the response modulation index and thus with simple/complex classification of the visual cortical neurons (Fig. 3B). Therefore, the strength of the γ-range fluctuations of the membrane potential did not differ significantly in simple and complex cells.

Finally, we studied a phase relation between the low frequency changes of the membrane potential and the strength (amplitude) of γ-range fluctuations, extracting the response components of certain frequency band from the responses to visual stimuli (Fig. 4, A,C). The γ-range fluctuations of the membrane potential occurred predominantly on the depolarizing peaks of the low frequency

membrane potential modulation (Fig. 4). Several approaches, which we used to quantify this relation, showed its significance and reliability in both simple and complex cells.

DISCUSSION

Contrary to previous studies, in which γ-range oscillations of the membrane potential were found predominantly in complex cells in the visual cortex [2,7], our quantitative analysis showed, that the strength of the γ-band fluctuations of the membrane potential does not differ in cells with simple and complex receptive fields. Thus, γ-frequency fluctuations of the membrane potential is a general property of visual cortical cells, and the advantages of the γ-frequency fluctuations for generation of precise patterns of action potentials may be exploited in both simple and complex cortical neurons.

Our analysis demonstrated that the strength of the γ-frequency fluctuations of the membrane potential correlates with stimulus optimality: stronger spike responses were associated with a stronger γ-power. Taken together with the earlier data which showed the inverse relation between the threshold of spike generation and the rate of the membrane potential rise [3]; the correlation between the gain at which membrane depolarization is translated into trains of action potentials and the γ-power of the membrane potential [16]; as well as in vitro data [10,11,15], these data support the notion that γ-range fluctuations of the membrane potential enhance the spike generation in cortical neurons, and thus contribute to improvement of the response selectivity.

A mechanism similar to stochastic resonance has been recently suggested to be exploited in the visual cortex to detect weak signals and to enhance contrast invariance of orientation specificity [1,14]. However, a potential drawback of the stochastic high frequency noise is that outside a narrow range of the relations between the spike generation threshold and the amplitudes of noise and signal, it disturbs encoding of the low frequency temporal structure of a stimulus [6]. Our finding, that γ-range

fluctuations of maximal amplitudes are phase-locked to the positive peaks of stimulus-induced, low frequency changes of the membrane potential show that visual cortex neurons may use a kind of amplitude modulation of the high frequency component to encode the temporal structure of the response in the low frequency range. The use of the amplitude-modulation encoding may expand the borders of applicability of stochastic resonance to the function of nerve cells.

REFERENCES

[1] J.S. Anderson, I. Lampl, D.C. Gillespie, and D. Ferster, The contribution of noise to contrast invariance of orientation tuning in cat visual cortex, Science 290 (2000a) 1968-1972.

[2] J.S. Anderson, I. Lampl, I. Reichova, M. Carandini, and D. Ferster, Stimulus dependence of two-state fluctuations of membrane potential in cat visual cortex, Nat. Neurosci. 3(6) (2000b) 617-621.

[3] R. Azouz, and C.M. Gray, Dynamic spike threshold reveals a mechanism for synaptic coincidence detection in cortical neurons in vivo, Proc. Nat. Acad. Sci. USA 97 (2000) 8110-8115.

[4] A.F. Dean, and D.J. Tolhurst, On the distinctness of simple and complex cells in the visual cortex of the cat. J. Physiol. 344 (1983) 305-325.

[5] C.M. Gray, and D.A. McCormick, Chattering cells: Superficial pyramidal neurons contributing to the generation of synchronous oscillations in the visual cortex, Science 274 (1996) 109-113.

[6] N. Ho, and A. Destexhe, Synaptic background activity enhances the responsiveness of neocortical pyramidal neurons, J. Neurophysiol. 84 (2000) 1488-1496.

[7] B. Jagadeesh, C.M. Gray, and D. Ferster, Visually evoked oscillations of membrane potential in cells of cat visual cortex, Science 257 (1992) 552-554.

[8] P. König, A.K. Engel, P.R. Roelfsema, and W. Singer, How precise is neuronal synchronization? Neur. Computation 7 (1996) 469-485.

[9] I. Lampl, and Y. Yarom, Subthreshold oscillations of the membrane potential: a functional

synchronizing and timing device, J. Neurophysiol. 70 (1993) 2181-2186.

[10] Z.F. Mainen, and T.J. Sejnowski, Reliability of spike timing in neocortical neurons, Science 268 (1995) 1503-1506.

[11] L.G. Nowak, M.V. SanchezVives, and D.A. McCormick, Influence of low and high frequency inputs on spike timing in visual cortical neurons, Cereb. Cortex 7 (1997) 487-501.

[12] G.A. Orban, Neuronal operations in the visual cortex. Springer, Berlin, Heidelberg, New York, Tokyo. 1984.

[13] B.C. Skottun, R.L. Valois, D.H. Grosof, J.A. Moshon, D.G. Albrecht, and A.B. Bonds, Classifying simple and complex cells on the basis of response modulation, Vision Res. 31 (1991) 1079-1086.

[14] T.W. Troyer, A.E. Krukowski, N.J. Priebe, and K.D. Miller, Contrast-invariant orientation tuning in cat visual cortex: Thalamocortical input tuning and correlation-based intracortical connectivity, J. Neurosci. 18 (1998) 5908-5927.

[15] M. Volgushev, M. Chistiakova, and W. Singer, Modification of discharge patterns of neocortical neurons by induced oscillations of the membrane potential, Neuroscience 83 (1998) 15-25.

[16] M. Volgushev, J Pernberg, and U.T. Eysel A novel mechanism of response selectivity of neurons in cat visual cortex, J. Physiol. 540.1 (2002) 307-320.

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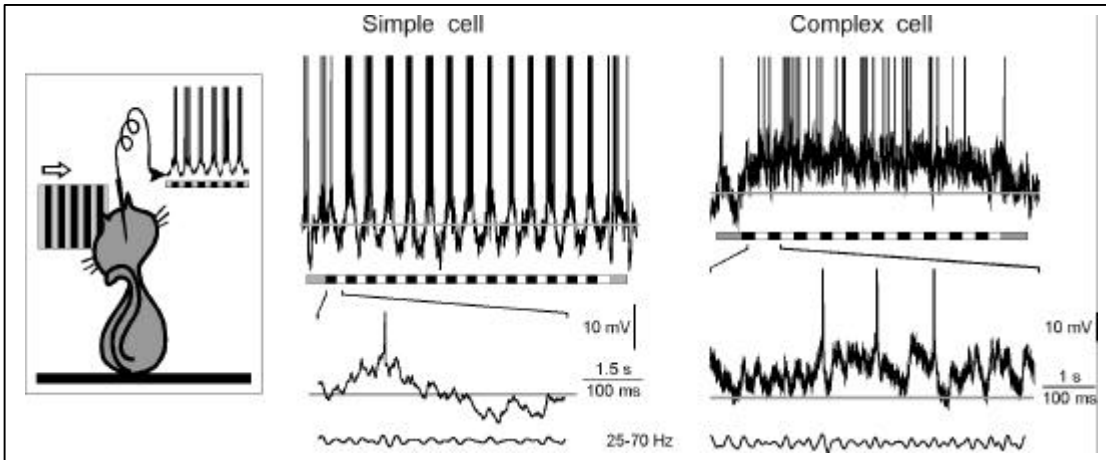
FIGURE LEGENDS

Fig. 1. Responses of a simple and a complex cell in cat visual cortex to presentation of moving gratings. From top to bottom: Traces of the membrane potential, with action potentials truncated; Part of the membrane potential trace at expanded temporal resolution, and γ-range (25-70 Hz) component of it. The bar below the traces indicates grating onset, the black-white pattern indicates grating movement and temporal frequency (2 Hz in both cases). Grey horizontal lines show mean membrane potential during the intervals without stimulation.

Fig. 2. The strength of γ-range fluctuations of the membrane potential correlates with the stimulus optimality. A: Membrane potential responses of a simple cell to an optimally oriented grating moving in the optimal direction, in the opposite (null) direction and to the orthogonal to the optimal (nonoptimal) orientation. B: Power spectra of the membrane potential responses. C: Dependence of the strength of spike response and of the spectral power in the γ-range on stimulus orientation, and their correlation (D).

Fig. 3. The strength of γ-range fluctuations of the membrane potential correlates with the stimulus optimality. Summary data. A: γ-power of the membrane potential fluctuations during the optimal response plotted against the γ-power during the nonoptimal response. B: The strength of the γ-power of the membrane potential fluctuations during presentation of the optimal, nonoptimal and null stimuli plotted against spike response modulation index.

Fig. 4. γ-range oscillations are strongest at the peaks of low frequency fluctuations of the membrane potential in simple and complex cells. A,C: From top to the bottom: Membrane potential traces, and the response components, extracted from them. In the lower panels, low frequency response component and the envelope of the amplitude of the γ-range fluctuations are normalized and superimposed. B,D: Relationship between the low frequency and γ-range fluctuations of the membrane potential.



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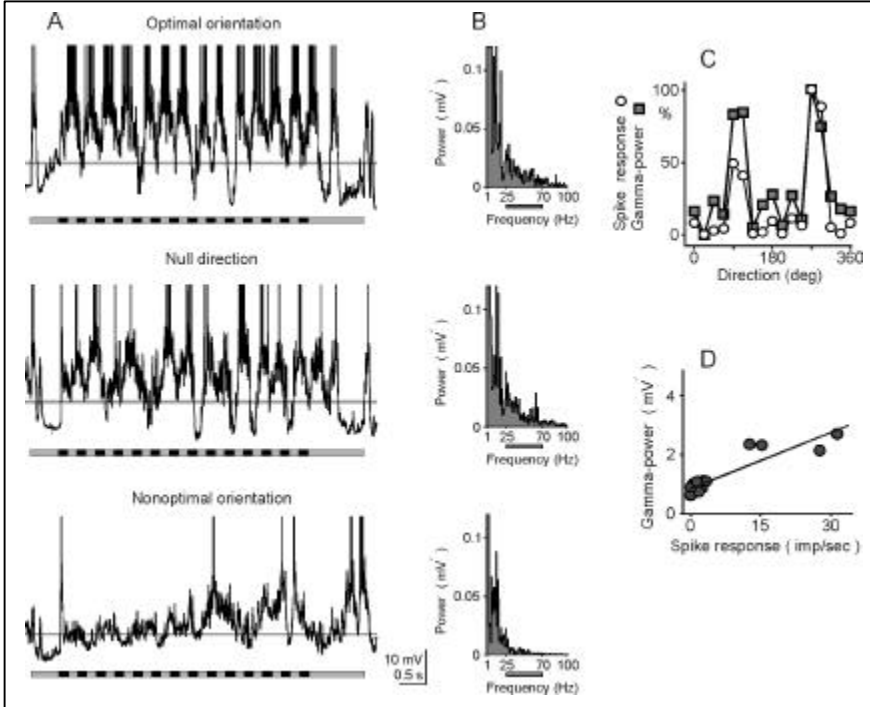

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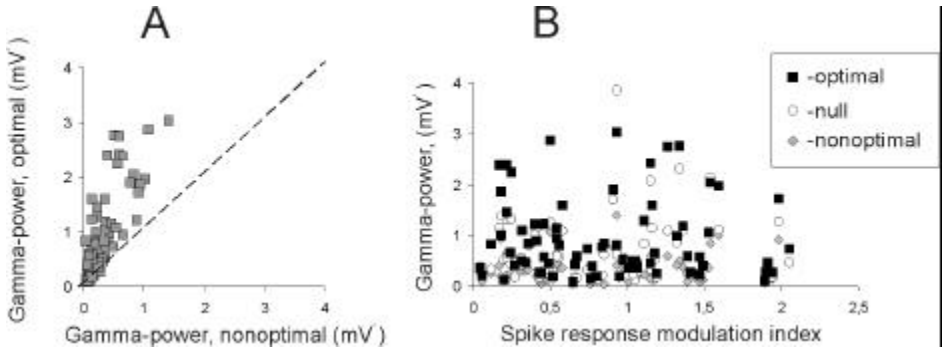

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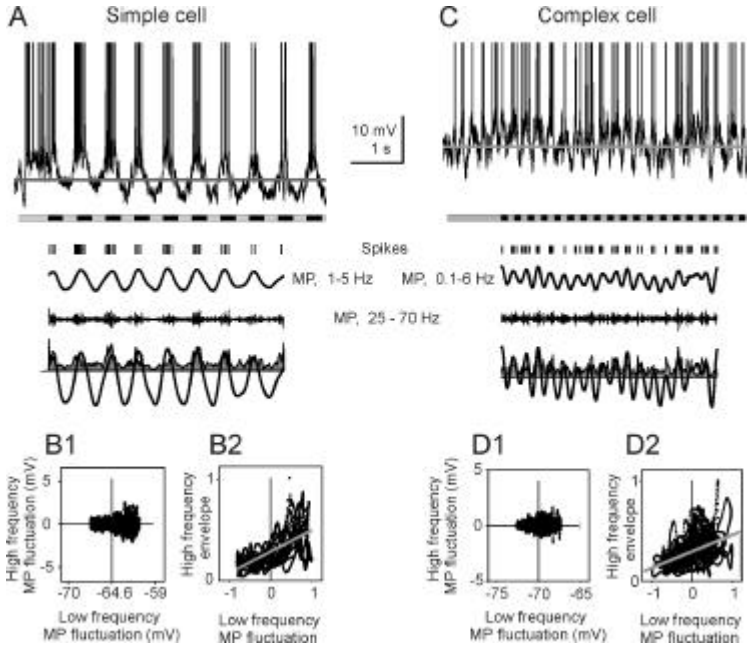

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