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A TEMPORAL STRUCTURE OF CORTICAL INFORMATION PROCESSING

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ABSTRACT

This article summarizes recent experiments designed to explore neural dynamics in the range of tenths of seconds and discusses its implications for different aspects of cortical information processing. The vast majority of neurons in the visual cortex of the cat (areas 17, 18 and 19, PMLS, and area 7) exhibit a complex temporal structure of neuron responses that can be characterized as damped aperiodic oscillations in the range of 6 to 20 Hz, which is not present at the thalamic level. Investigation of the internal receptive field (RF) organization during these oscillatory epochs has revealed that RFs are no static entities but are highly dynamic and variable. Each location within RFs is temporally independent that leads to considerable alterations of RF organization over time, indicating non-separability of space and time. When using stationary flickered stimuli, RF properties, such as orientation selectivity, turn out to be time dependent (dynamic orientation tuning); when moving stimuli were used, the speed and direction of stimulus motion become crucial variables that determined the overall response characteristics, thus rendering RFs time- and stimulus-variant. The temporal structure thus provides the indispensable substrate for the emergence of RF dynamics.

Including the temporal structure as a significant portion of the response considerably prolongs the time over which neurons respond to even simple patterns. Assuming an average length in the range of 200 to 500 ms, it follows that cortical neurons never reach a genuine steady state. We discuss further implications of this temporal structure such as time coding, interareal time-dependent interactions, and more generally, temporal interference patterns resulting from interaction between intrinsic neural and external stimulus-related dynamics. It remains to be seen whether the temporal structure represents an evolutionary adaptation to the dynamics of the structure of seeing as well as to the dynamics of the environment, whether exclusively visual or, what we suggest, generally applicable to cortical neural processing.

Keywords: Visual cortex, receptive fields, low frequency oscillations, time dependence, dynamic orientation selectivity, mutual stimulus dependency, temporal interference patterns.

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1. Introduction

During the last years, the exploration of neural dynamics has gained more and more attention. The present article deals in detail with the dynamics of neuron responses in the range of tenths of seconds as encountered in cat visual cortices. The rationale behind the analysis of neuron response dynamics can be quite different. In the most common approach (whether explicitly stated or not), neural dynamics are linked to modes of information processing, an idea that goes back to early cybernetics. As the experiments described here were performed in the visual system, the possible role of the dynamics for visual information processing is explored. In a more general way, the observed dynamics can be directly related to the dynamics of the inherent structure and the procedure of seeing [1]. A somewhat different approach focuses on a phenomenological description of the dynamics in terms of entire patterns [2]. In this approach, collective variables are obtained empirically and used for further analysis in which phase transitions play a crucial role. In contrast to the first method, information is not specified by the structure of the system investigated, but its meaning is defined in the same space as the function-specific variables. We believe that a combination of both approaches pledges a deeper understanding of brain functions, the dynamics are an important part. In the following, we present a preliminary state-of-the-art analysis and interpretation of the temporal structure of cortical neuron response. Although the data were derived from visual cortical neurons, we believe that the results reflect a basic and common cortical property generally true for cortical processing independent of modalities and specific areas.

1.1. *Receptive Fields as Spatial Filters*

Since the work of Hartline in 1938 [3], the concept of receptive fields (RFs) as one of the basic elements for information processing has been the guiding principle in the investigation of sensory systems. Although we perceive the visual world as a unitary entity, the neuronal machinery consists of elements that can analyse only small portions of the visual field. Knowing the structure, organization and properties of RFs is indispensable for understanding their contribution to signal processing and, more generally, to brain function.

Visual cortical neurons in area 17 have been described as responding in a rather specific way to the shape of a stimulus, especially to its orientation and its length, properties known as orientation-selectivity and hypercomplexity (end-stopping). According to the RF concept proposed by Hubel and Wiesel in 1962 [4], the selectivity of cortical neurons for geometrical dimensions, i.e. two-dimensional spatial distribution of brightness, is generated by a corresponding two-dimensional spatial distribution of excitatory and inhibitory inputs in the cortex. In this view, the spatial selectivity of a cell is essentially determined by the spatial arrangement of the afferent inputs to a neuron (see also Fig. 1). The distribution of excitation within RFs can be interpreted as a spatial filter or feature detector. On the whole, the RF concept is based on static response properties providing limited tolerance for adaptive and plastic processes.

Fifty years after the Hartline concept of RFs and about 25 years after the Hubel and Wiesel concept, there are still numerous questions even after repeated refine-

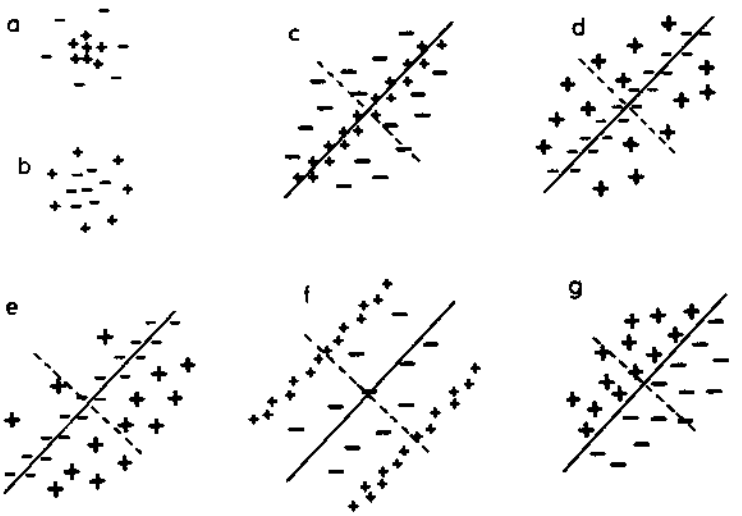

Fig. 1. Receptive field (RF) organization of thalamic (a,b) and cortical cells (c–g) as adapted from Hubel and Wiesel [4]. According to this scheme, RF properties are essentially determined by the two-dimensional distribution of excitatory and inhibitory inputs, which reflects the underlying dendritic field organization.

ments of the original idea. For example, there is the unsettled question of whether the dendritic field organization can account for the electrophysiological tuning characteristics of single-cell responses. There are controversial opinions concerning the existence and the extent of anisotropic dendritic field organization, and a genuine anisotropic organization that matches orientation tuning was never discovered [5]. More conflicting experimental evidence was provided by the considerable reorganization or retuning of RFs in the somatosensory and auditory cortex following manipulations associated with different types of learning [6], which are hard to conceive with the Hubel and Wiesel type of receptive field concept. The need for incorporating temporal aspects was emphasized by several groups that used response plane techniques for analyzing spatio-temporal interactions [7]. Finally, our experiments revealing substantial inherent dynamics of RF organization add further arguments for a revision and extension of static RF concepts [8]. An insightful review of those problems related to RF concepts is provided in [9].

1.2. *Functional Impact of Cortical Architecture*

In spite of the enormous functional diversity of neocortex in higher mammals, there is remarkable uniformity of its architecture. Relating function to structural features, we believe that some very fundamental aspects of this architecture determine its computational capacities and strategies.

Cortices are two-dimensionally extended sheets of neurons that are vertically segregated into laminae constituting a system, which can be regarded as a type of multi-input/multi-output systems. Although there is a multiplicity of shapes of neurons, the most frequent cell type is pyramidal cell that is exclusively excitatory. Inhibition is mediated by non-spiny stellate cells, which act in close vicinity of

pyramidal cell somata. While the dendritic and axonal fields of stellate cells are of short range, pyramidal cells show an interesting overall pattern, in which their dendritic fields in most cases reach from the site of their somata up to layer 1. This general anatomical pattern suggests that information from different layers can be combined in a very systematic way. The axonal fields of pyramidal cells also extend over several layers, suggesting distribution of output in multiple feedback loops. As the intrinsic elements outnumber the input fibers by an order of magnitude, intracortical processing based on positive feedback is assumed to be crucial for the functional performance and is supposed to dominate over effects that are mediated by direct, afferent input [10].

1.3. *A Network Model of Cortical Information Processing Incorporating Some Basic Aspects of Cortical Architecture*

All these anatomical constraints were incorporated into a computer model of cortical architecture based on a mean lamina-specific neuroanatomy of pyramidal and stellate cells [11]. The main outcomes of the model are: (i) low-frequency temporal oscillations occur, i.e. responses are structured in time in a way that is layer- and stimulus-specific; (ii) positive feedback loops are responsible for the observed temporal response dynamics; (iii) functional selectivity of neuronal responses is derived through successive iterations within the feedback system leading to variations of receptive field properties in time; and (iv) spatio-temporal behavior is no longer separable into two independent terms.

According to these simulations and the briefly outlined neuroanatomical considerations, neocortical neural networks are characterized by strong positive feedback. Cortical feedback architecture, however, has strong implications for the spatio-temporal organization of receptive fields [11].

1.4. *Nonlinear Behavior vs. a Complex Temporal Response Pattern*

Finally, there is a large body of evidence concerning nonlinear behavior of cortical neurons. If a receptive field is static and linear, its behavior can be predicted from a spatial distribution of weights. However, responses that are non-predictable in this sense may be produced in three different ways: (i) the cell is nonlinear in the strict meaning of systems theory; (ii) the cell has an elaborated, spatio-temporally non-separable dynamic behavior; and (iii) both mechanisms might be present. Testing the spatial summation properties of cells alone cannot distinguish among these possibilities.

1.5. *Hierarchical-Parallel Processing in the Cat Visual System*

Our experiments [12] were performed in the cortical visual areas 17, 18 and 19, and PMLS (posteromedial portion of the lateral suprasylvian sulcus) [13]. These areas are part of a highly interconnected system of serio-parallel processing consisting of multiple areas [14]. Based on the pattern of thalamocortical connections, both areas 17 and 18 in cats are thought to represent a parallel stage of primary areas directly receiving independent input from the LGN (lateral geniculate nucleus). The same is essentially true for area 19; however, it is thought to occupy a some-

what more advanced level than areas 17 and 18, because it additionally receives a substantial input from the LP-Pulvinar complex. This part of the visual thalamus located more medial to the LGN in turn receives midbrain and back projections from areas 17, 18 and 19. Finally, the suprasylvian areas are clearly on a more complex and different level of processing, as they receive their main input from the LP-Pulvinar complex and from areas 17, 18 and 19, while the LGN input remains marginal. While PMLS is discussed with respect to processing of motion and to its possible analogy to monkey mediotemporal cortex (MT), even less is known of areas 20 and 21, which some authors believe to be analogous to monkey inferotemporal cortex (IT). There is general agreement that the main input to the extrastriate areas is of the y- and w-type. It is therefore interesting to note that the x-type input is exclusively relayed via area 17. Based on these notions, it therefore seems conceivable that the areas studied in our experiments cover at least two to three different levels of information processing. For more details on the peculiarities of the cat's visual system, see [15].

In Fig. 2, an attempt is made to summarize the available data on thalamocortical and corticocortical connectivity patterns; for details see [16]. This scheme is not intended to yield a complete illustration of the interconnections of the visual system but to illustrate in a suggestive way the richness of connectivities within different stages of the visual system and its hierarchical structure. The recently described patterns of branching axons which provide identical input to several targets will add additional complications to models of the visual system [17].

1.6. *Synopsis*

The experiments summarized in this article deal with the spatio-temporal response properties of cortical receptive fields.

1. First, we will characterize the low-frequency temporal oscillations of activity and describe their general and area-specific properties. In the following, we use the terms *low-frequency temporal oscillation, temporally modulated response* and *temporal structure* as synonyms.

2. The existence of this low-frequency type of oscillations initiated the investigation of the time course of RF organization during the oscillatory episodes which will lead to the introduction of non-separability of spatial and temporal behavior. We turn briefly to theoretical aspects of non-separability and then discuss some implications arising from the introduction of non-separability.

3. We will deal with time dependence of RF properties (orientation selectivity and hypercomplexity). We demonstrate that selectivity is reached after a preceding non-selective state of excitation. Therefore, high level of selectivity is no longer correlated with maximal spike count, but is much better described in terms of temporal modulation of response.

4. We discuss the consequences of non-separability for the processing of moving stimuli. This results in a new dynamic model of RFs which is able to explain that RF properties become a function of the temporal and spatial parameters of the stimulus, such as its velocity and overall shape.

5. We will present experimental evidence for time coding, time dependence of interareal cooperativity, and feedback mechanisms. We will outline a general theory

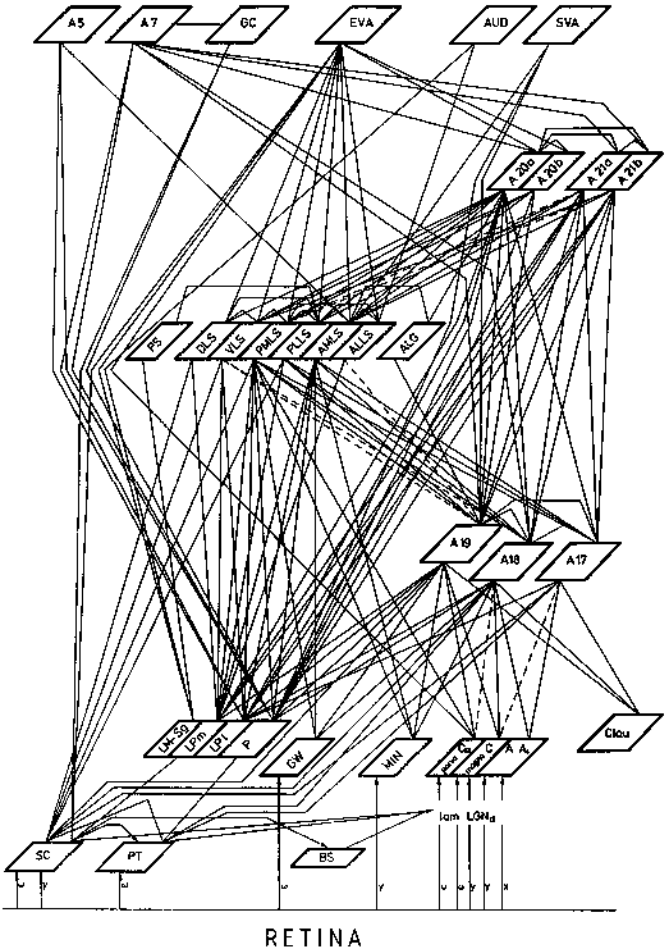

Fig. 2. Visual system of the cat as known from anatomical and electrophysiological experiments, illustrating the richness of connectivities and hierarchical organization. The different projections of the x-, y- and w-channels are indicated. Dashed lines indicate weak or uncertain projections. Note that many anatomical connections are often not substantiated by functional measurements. Basically all projections shown are reciprocally organized. Abbreviations: A: area; A/A_1: A-lamina of LGN; ALG: visual area in the anterior sulcus lateralis; ALLS: visual area in the anterolateral sulcus lateralis suprasylvius; AMLS: visual area in the anteromedial sulcus lateralis suprasylvius; AUD: auditory cortex; BS: brain stem; C: magnocellular lamina of LGN; C1–3: parvocellular laminae of LGN; Clau: claustrum; DLS: visual area in the sulcus lateralis suprasylvius; EVA: visual area in the anterior sulcus ectosylvius; GC: visual area in the gyrus cinguli (area 23); GW: geniculate wing; lam LGN_d: corpus geniculatum laterale, laminated, dorsal portion; LM-Sg: lateromedial portion of the suprageniculate complex; LPl: lateral zone of the nucleus lateralis posterior; LPm: medial zone of the nucleus lateralis posterior; LP-P: nucleus lateralis posterior – pulvinar complex; MIN: nucleus medialis intralaminaris; P: pulvinar (nucleus pulvinaris); PLLS: visual area in the posterolateral sulcus lateralis suprasylvius; PMLS: visual area in the posteromedial sulcus lateralis suprasylvius; PS: visual area in the posterior sulcus suprasylvius; PT: pretectum; SC: colliculus superior; SVA: visual area in the sulcus splenialis; VLS: area in the ventral sulcus lateralis suprasylvius. For details of the literature cited, see [16].

on dynamics of RF organization that incorporates what has so far been argued on oscillations, non-separability, feedback and delayed high-level selectivity.

6. Finally, we discuss some more far-reaching implications that include adaptive and plastic processes, analysis of temporal sequences, and more generally, the notion of temporal interference due to ongoing interactions between intrinsic and extrinsic dynamics, which culminates in the perspective that, figuratively, anything is temporal.

2. Low-Frequency Oscillations in Neuronal Responses following Photic Stimulation

Brain activity comprises a broad spectrum of periodic phenomena ranging from high-frequency oscillations (30–90 Hz, the so-called gamma range) to very low frequencies in the range of seconds or minutes (besides ultradian and circadian rhythms). For several years, we have been investigating a highly significant and reproducible temporal structure that can already be identified in post-stimulus time histograms (PSTHs) using simple flashed stimuli. Figure 3 shows the characteristics of this temporal structure: a low-frequency oscillation in the range of about 10 Hz, which is superimposed by high-frequency oscillations, and which might be supposed to be part of a much slower oscillatory pattern [16,18]. High-frequency oscillations have been intensively investigated by Freeman and his co-workers in the rabbit olfactory system [19]. More recently, for the cat visual system high-frequency oscillations were described [20] that gained much interest due to their putative involvement in feature linking mechanisms.

Low-frequency oscillations in the range of 10 Hz have been described not only in cortical visual areas of cats, but also in monkey striate cortex, rat somatosensory cortex, and cat auditory cortex [21]. Accordingly, **oscillatory behavior in the neuronal discharge in the range of about 10 Hz constitutes a fundamental attribute of cortical neurons and is found under a large variety of experimental conditions**. Our investigations focused on areas 17, 18 and 19 and PMLS in the cat, which cover 80% of the cat's visual cortex and about 30% of the cat's neocortex (cf. Fig. 2). This implies that our results on dynamic characteristics of discharge patterns and receptive field organization do not reflect sophisticated properties of neurons of highly specialized areas, but rather a common and general aspect of cortical information processing. Therefore, we consider this type of oscillation as the fundamental demonstration of a distinct temporal structure in the response pattern.

2.1. *Portrayal of the Temporal Structure*

At least two-thirds of all cortical neurons of our sample, no matter to which area they belong, have an oscillatory type of response [22]. There is a rather broad scatter of individual mean interpeak intervals with the average for each area of between 6 to 20 Hz, i.e. 150 and 50 ms, respectively (see Fig. 4). However, the frequency of this oscillation is not constant, but decreases with the duration of oscillation, i.e. the interpeak interval is shortest for the first two peaks. Mostly, the amplitude of the first peak is also the largest. Accordingly, the response pattern seen is not a genuine periodic oscillation, but is best described as a *damped aperiodic*

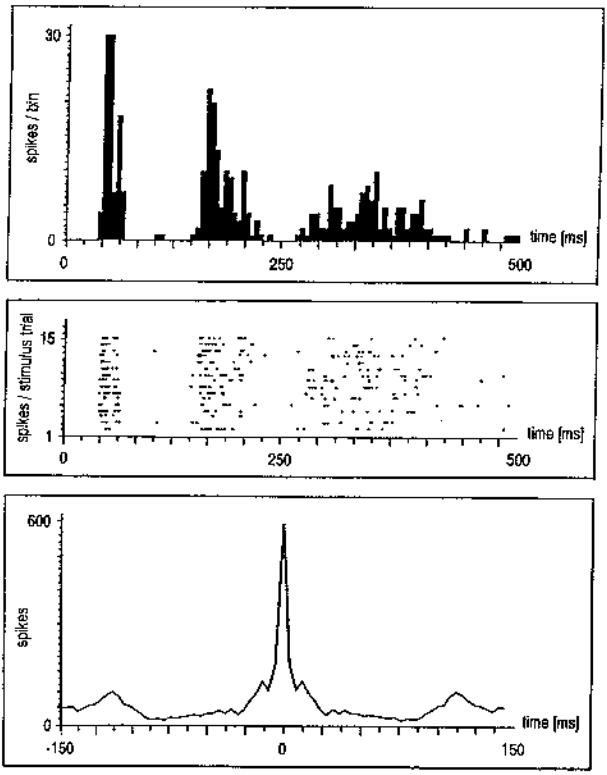

Fig. 3. Characterization of low-frequency oscillations. Response to stimulation of the excitatory receptive field portions (ERF-stimulation), flickered with repetition rates of 2.5 sec (1.25 sec on, 1.25 sec off). Illustrated is the on-response. Top: PSTH, first 500 ms after stimulation (bin width 5 ms). Middle: Dot-Display (same as PSTH). Bottom: autocorrelation, +/− 150 ms.

oscillation [23]. These oscillatory patterns emerge without exception phase-locked to the stimulation, which is the reason for the appearance of distinct oscillatory peaks in post-stimulus time histograms (PSTHs).

The maximal observed length of this oscillation is 500 to 600 ms during which seven to eight peaks may occur. The number of peaks observed is different in each area. Area 17 neurons resemble those of PMLS, as there is a considerable proportion of cells that show no oscillation, whereas all cells investigated in area 18 and the majority of cells in area 19 do show oscillations. The highest percentage of cells with long-lasting oscillation, i.e. five or more peaks, was found among the area 17 and PMLS neurons. It is important to note that this clear oscillatory type of response is entirely missing in our sample of geniculate cells.

To evaluate mutual dependencies of parameters describing the oscillatory pattern, we performed linear regression analysis for the following variables: amplitude of the first peak, latency of the first peak, number of peaks, amplitude ratio of the first and second peak, and time difference between the first and second peak. On the whole, we observed an overall lack of correlation between the different

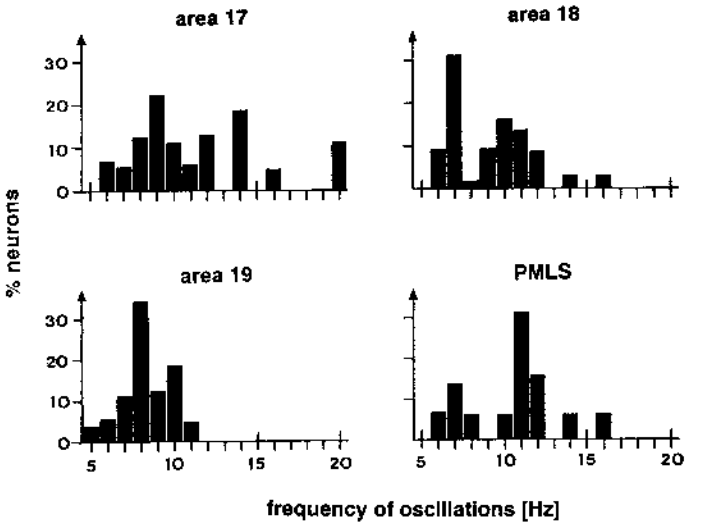

Fig. 4. Distribution of mean oscillatory frequencies for neurons of the areas 17, 18, 19 and PMLS (posteromedial portion of the lateral suprasylvian sulcus). Mean frequencies of all cells are between 6 and 20 Hz.

parameters, especially between response amplitude and latency or between response amplitude and number of peaks. This indicates that the temporal aspects of the response patterns are not linked to measures of spike count or of response strength.

Any mutual relationship between high-frequency oscillations and those in the range of 6 to 20 Hz as reported in this article have so far not been investigated. However, spectral analysis of parts of our data suggests that both types of oscillatory pattern might be present in the neural discharge simultaneously, but with different amplitude characteristics. Moreover, these investigations indicate that high- and low-frequency oscillations are only two poles at the end of the scale that spans the entire range between 5 and 100 Hz.

We conclude that adopting the oscillatory pattern as a significant portion of the response considerably prolongs the time over which neurons respond to even simple patterns. Assuming an average length of the temporal modulation in the range of 200 to 500 ms, this means that cortical neurons never reach a genuine steady state. As the dynamics of a visual scene – 100 ms are crucial for perceiving unblurred images [24] – are clearly below these values, it follows that a **continuous interaction between external stimuli in the visual world and the intrinsic temporal modulation** must occur, which makes neuronal responses highly dependent on the dynamics of stimulations. We therefore introduce the notion of *temporal interference*. Indeed, we found abundant evidence for this kind of interaction which is described in the following sections.

2.2. *Coincidence of Oscillations in Simultaneously Recorded Neurons*

In order to clarify whether nearby neurons oscillate inphase, we used two sets of simultaneous unit recordings and analysed the coincidence of oscillations in the

recording channels at a more expanded time scale. In one type of experiments, we recorded simultaneously single and multiple unit activities on one microelectrode in both area 17 and PMLS. Figure 5A illustrates a representative example of simultaneously recorded responses to on- and off-stimulation. Comparing the time course of oscillations, we found that close neighbouring neurons oscillate inphase: first, in all cases there was a high temporal coincidence of the peaks of oscillation between the single and multiple unit recording. Second, in the multiple unit recording we never observed any kind of blurring of the highly structured response pattern, which would have been an indication that the oscillation of the single neurons was out of phase. As a rule, we observed distinct peaks similar to those shown at the bottom of Fig. 5A.

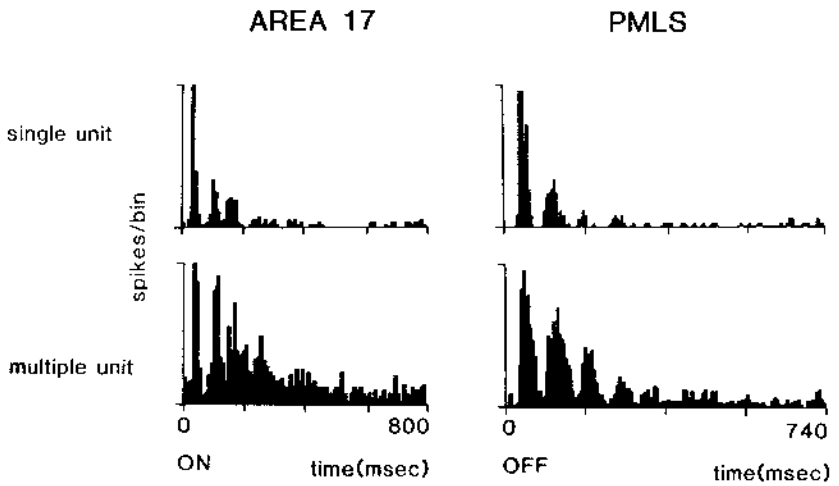

Fig. 5A. Example of simultaneous recordings of single (top) and multiple (bottom) unit activity at a penetration site in area 17 and in PMLS (posteromedial portion of the lateral suprasylvian sulcus). ERF-stimulation, flickered with repetition rates of 2.5 sec (1.25 sec on, 1.25 sec off). Illustrated are the on-response for the first 800 ms (bin width 10 ms) for the area 17 penetration and the off-response for the first 740 ms for the PMLS penetration. The single unit response shown at the top is not contained in the multiple unit recording. There is a high coincidence of oscillation between the single and the multiple unit recording, and a high inphase oscillation within the multiple unit recording, which leads to distinct peaks of excitation, i.e. there is no indication of blurring due to out-of-phase oscillation.

In a second type of experiment, we recorded simultaneously with two or more (up to eight) independent microelectrodes spaced at distances between 0.5 to 20 mm [25]. In these paired recordings, a quite different behavior was observed. Only occasionally coincidence of the oscillatory pattern occurred. As a rule, simultaneous recordings of this type across larger distances revealed a lack of inphase oscillations (Fig. 5B). This finding is a strong argument that the type of temporal structure reported here does not reflect merely a global state of cortical excitation (see also Section 6).

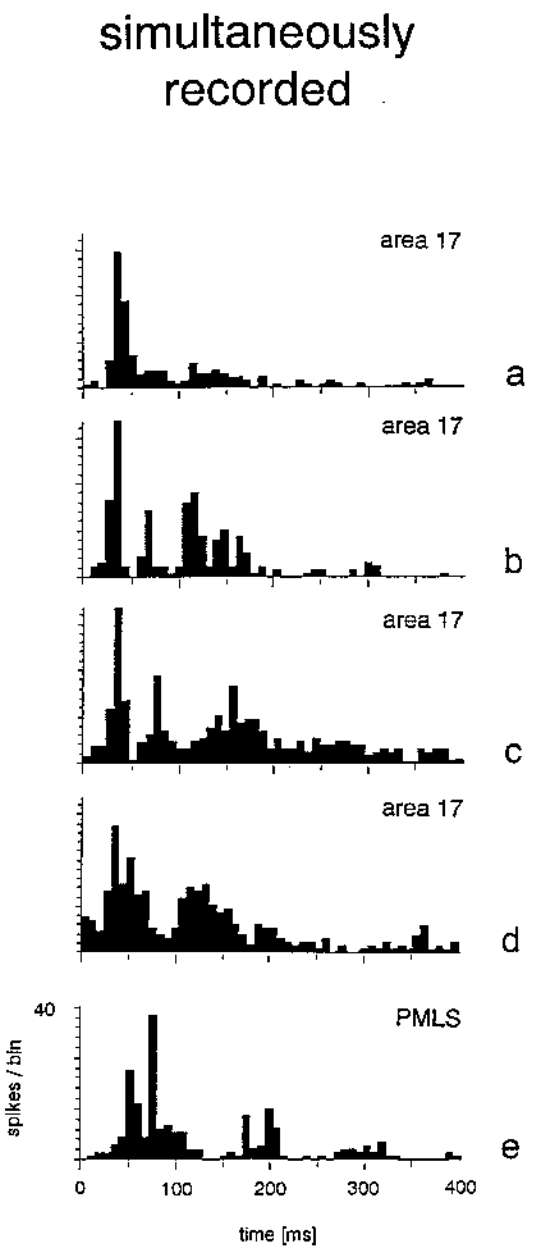

Fig. 5B. Simultaneous multielectrode recordings at five penetration sites, four in area 17 separated by 2 mm each (a–d) and one penetration in PMLS (e). ERF-stimulation, flickered with repetition rates of 2.5 sec (1.25 sec on, 1.25 sec off). Illustrated is the on-response for the first 400 ms (bin width 8 ms). In contrast to the simultaneous recordings shown in Fig. 5A, quite different oscillatory patterns can be observed. While one cell shows only very weak expression of temporal structure, the time course and phase relations of the other cells are remarkably different, suggesting that this temporal pattern does not reflect a global state of excitation.

3. Temporal-Spatial Aspects of Receptive Field Organization

So far, we have described a distinct temporal response structure of damped aperiodic oscillations in cortical neurons recorded in four visual areas. In this and the following section, we attempt to link RF properties to the temporally structured neuron responses, i.e. we investigate the time course of RF organization during the oscillatory episodes by means of a modified response plane technique [26].

3.1. *Temporal Distribution of Excitation within Receptive Fields*

Our technique for compiling sequences of response planes differs from conventional response planes in that it avoids integration of the response over time or the use of a peak response measure. Due to this, we can demonstrate that the spatial distribution of excitation and thus RF organization is not static, but changes over time. These changes are related to the oscillation of response, described in detail for *ERF-stimulation* (see Section 2.1). However, the oscillation of excitation is not spatially homogeneous throughout the entire RF. Each subfield within the receptive field exhibits its own temporal characteristic, i.e. the oscillatory pattern elicited at different locations within the receptive field may be different. In the sequences of response planes, the excitation appears as a 'wave' spreading over the entire receptive field. The observation that each spatial location has a temporal characteristic of its own is a clear indication that space and time are not separable.

This notion is rather equivalent to the finding of concentric arrangements of visual latencies within RFs, which has been described recently for area 17 complex cells and earlier for extrastriate cells of areas 18 and 19. Each temporally independent location within RFs corresponds to what has been called 'active points' [27]. In our terminology, these are the 'mechanisms' or 'processing submodalities' (*Proc-Subs*) that lead to non-separability of space and time as soon as a certain number of 'processing submodalities' is exceeded [28].

It is noteworthy that even during *ERF-stimulation*, a clear oscillatory pattern can emerge that is comparable to that obtained by *subfield-stimulation* (besides the differences in latencies and interpeak intervals) [22]. This fact, although not yet fully understood, calls for a powerful, synchronizing effect across the entire RF that acts on all subfields, thus preventing a smear of the temporal structure of the responses.

We conclude that the dynamics unveiled in the sequences of response planes make it rather unlikely that RFs are static and rigid entities. In contrast, they change dramatically over time, i.e. within the first hundreds of milliseconds after onset of stimulation. The temporal structure of neuron response thus provides, due to its lengthening of neuron response, the fundamental prerequisite for this type of RF dynamics. It is important to recall that the RF dynamics described so far were obtained with stimuli that allowed the system to reach steady state. In addition, no other clues such as contextual information were available. Therefore, we assume that **under these conditions the intrinsic dynamics of cortical neurons become apparent**. It seems conceivable, however, that **these dynamic processes are subject to adaptive or plastic alterations as soon as additional timing or contextual information is available** [29].

3.2. *Non-separability of Spatial and Temporal Behavior*

In a simple description, RFs may be regarded as spatial filters weighted with a temporal low pass characteristic, i.e. both spatial and temporal filterings can be treated as independent factors. The experimental data, however, suggest that this separability might not be maintained in cortical neurons. Unless the complete temporal behavior is taken into account, any statements concerning RF organization are either time-averages, hiding important aspects, or snapshots obtained at given moments revealing only partial information. For a complete description of RFs, it is necessary to obtain information of the response characteristics for every spatial location within RFs at every moment in time. This conclusion has considerable consequences for the understanding of RFs, as it makes RF organization time dependent, a property that is already obvious from the sequences of response planes as they display different RF properties at different moments after stimulation.

To clarify the discussion of spatio-temporal interactions in receptive fields, we will make use of the following definitions. First, a function $f(x,y,t)$ (e.g. a spatio-temporal response plane) is said to be separable if it has a spatial part $h(x,y)$ and a separate temporal part $g(t)$, such that

$$f(x,y,t) = h(x,y) \times g(t) \ . \tag{1}$$

If no such separation exists, the function is said to be non-separable. Second, we introduce the term *piecewise separability* for a function satisfying the equation

$$f(x,y,t) = \sum_{n=1}^{N} h_n(x,y) \times g_n(t) \ , \tag{2}$$

where N is a small integer (usually 2 or 4) [30].

The different types of separability may be illustrated by the following example. Suppose a set of spatial stimuli is presented with different temporal modulations, e.g. briefly flashed, flickered, or turned on or off. In a linear separable system, temporal behavior can be factorized out. Therefore, the spatial characteristic of the system would be the same for all temporal modulations of the stimulus. In a piecewise separable system, the temporal characteristic, g_n, together with the temporal modulation of the stimulus impose a weight on each spatial 'processing submodality', h_n. The set of weights will be different for each temporal modulation and the overall spatial filter will thus be modified by the temporal modulation of the stimulus. In the extreme case when the system is entirely non-separable, one should no longer talk of distinct 'processing submodalities' (*ProcSubs*). Under these conditions, time dependence of the spatial filter $h(x,y)$ is established.

In conclusion, our experimental data on non-separability suggest that there is a smooth transition from non-separability involving a low number of *ProcSubs* (a condition close to piecewise non-separability) to complete non-separability comprising a large number of *ProcSubs*. Accordingly, we cannot characterize the separability state of a cell by a fixed number of *ProcSubs*. Instead, we observe a rather continuous distribution. This is consistent with the assumption that the position of a cell even within a highly interconnected network can be more or less close to the site

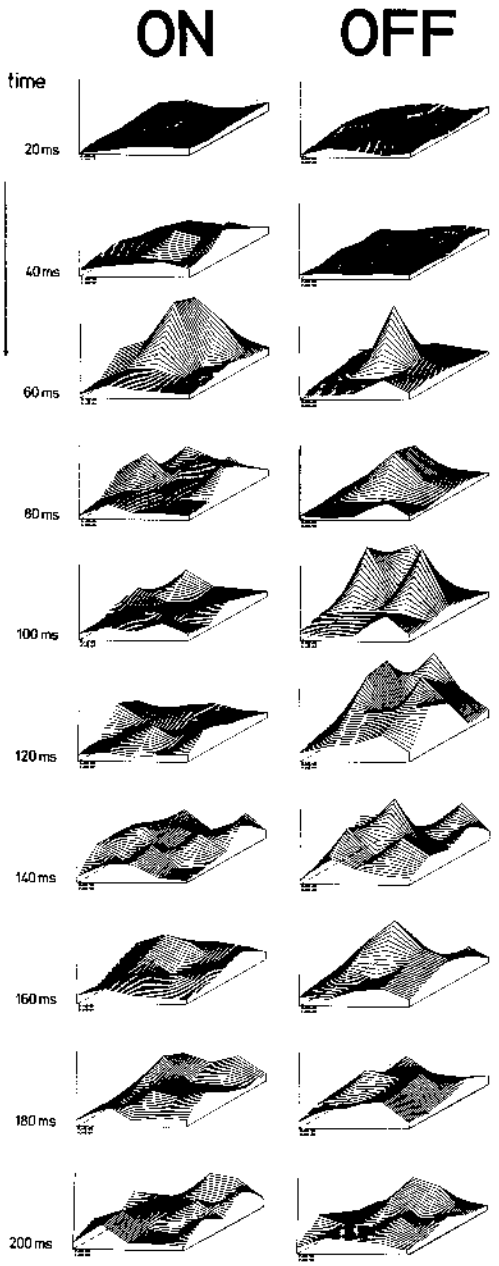

Fig. 6. Sequences of response planes for a neuron recorded in area 17. Time steps 20 ms. On-off stimulation within a grid of 5×5 subfields was used. Size of the stimulation matrix was 2.5 deg. (each subfield 0.5 deg.). Ordinate is spikes/time step (in this example, spikes/20 ms). This sequence illustrates the two-dimensional receptive field (RF) organization for each moment (i.e. each 20-ms time step) over the first 200 ms after photic stimulation. The RF organization changes dramatically over time. As each spatial location exhibits a temporal characteristic of its own, space and time are not separable in cortical cells that show such or similar behavior.

of the afferent input. In addition, the degree of feedback that a cell receives might not be uniform throughout the network. Both conditions are supposed to act on the degree of non-separability. The occurrence of a graded manifestation of non-separability predicts a considerable variability of time dependence of RF properties (see Figs. 6, 7 and 12). This prediction was fully substantiated by our experimental results and is discussed in detail in Section 4.

3.3. *Earlier Findings*

Although the interest in spatio-temporal receptive fields has been somewhat inhibited by the search for spatial feature detectors [for a comprehensive treatise of the history of RFs, see 9], the spatio-temporal frequency characteristics of cortical neurons and psychophysically assessable 'mechanisms' have been studied intensively [28]. When a transient visual mechanism was tested psychophysically with sinusoidal gratings flickered sinusoidally in time, it was reported that the threshold sensitivity curves are in fact separable into a spatial and a temporal part. However, when drifting gratings were used instead of flickering gratings, it was found that the spatial frequency characteristics did depend on the stimulus velocity, which was proportional to the temporal frequency of the stimulus [31]. Non-separability was also postulated in relation to spatio-temporal interpolation by [32]. Studies on X-type retinal ganglion cells have resulted in receptive field models with different temporal behavior for center and surround [33]. In our terminology, these fields are piecewise separable. In studies of striate cells using drifting sinusoidal gratings, the spatial frequency characteristics were found to be independent of the stimulus velocity; however, speed dependence of spatial frequency sensitivity was reported recently for area 18 neurons [34]. The latter result indicates spatio-temporal non-separability as do the more recent studies on RF organization using different types of response plane techniques [35]. Spatio-temporal receptive fields in the visual cortex have been discussed for several years and the notion of a 'receptive field for motion' also implies non-separability of space and time [36]. As for neurons at the lateral geniculate level, piecewise separability into three to four 'processing submodalities' can be inferred [37]. According to these experiments, geniculate cells may be closer to non-separability than have been assumed earlier. They show a behavior intermediate between those described for retinal ganglion cells [33] and those for cortical cells [38]. This raises the question of thalamocortical interactions and cortical involvement in establishing cortex-like non-separable spatio-temporal behavior [for computer simulations of this topic, see 39]. For several years, a Soviet group used a comparable approach to study dynamics of RF organization of cortical and geniculate cells and reported wave-like processes within RF organization; again these authors found mostly quantitative rather than qualitative differences between cortical and geniculate neurons [40].

As to different sensory modalities, it is interesting to note that in the acoustic system of the grass frog, a non-separable spectro-temporal behavior has been demonstrated that is present at a higher level of processing, but not at first- or second-order neurons [41].

4. Impacts of Non-separability for RF Organization

So far, we have described non-separability of spatial and temporal behavior as a characteristic feature of cortical cells, suggesting that RF properties are to a considerable degree controlled by dynamic factors. This section deals with a series of experiments designed to show the time dependence of RF organization. Again, we used stationary flashed stimuli in order to relate the resulting temporal response structure to a highly reliable and controllable time course of stimulation, which is not possible when using moving stimuli. Under those conditions, we found time dependence of RF size and of RF properties, such as orientation selectivity and hypercomplexity.

4.1. *Time Dependence of RF Size*

One important aspect of receptive field organization is its size in the visual field. It is generally believed that the measured dimensions of RFs are essentially determined by the kind of afferent input to the cell and the pattern of convergence. To test this assumption and to verify the possibility that non-separability may cause time dependence of RF size, we compiled temporal sequences of contour planes [42]. Figure 7 illustrates such sequences of contour planes obtained from horizontal sections at 50% maximal neuronal activity which shows the actual spatial extent of the receptive field for each moment, i.e. in time steps of 20 ms. We introduce the term *dynamic receptive field size*. The dimensions of the receptive field determined in this way clearly differ over time, changing between 0.5 and 2.0 degrees in diameter. When a time-averaged RF size is calculated, one obtains 2.5 deg. in diameter. These latter values correspond to the size obtained with hand-plotting. What normally is considered the RF size is, according to these findings, caused by temporal integration, which masks the changes that occur over time.

According to the observed changes of RF size and RF organization, we distinguished two different types of RF size dynamics. Type A exhibits only little change of RF size over time, but shows a shift or motion of RF discharge center (Figs. 6 and 7 on-response). Type B shows no motion of RF discharge center over time, but changes its dimensions. RFs of type B usually show the smallest size during the beginning of the response, followed by an expansion and subsequent contraction of the RFs (Figs. 6 and 7 off-response). A more schematic illustration is given in Fig. 8. While separable and piecewise separable organizations are rather straightforward definitions, *motion-* and *looming-type* non-separabilities are two examples for the general case. The terms *motion-type* and *looming-type* non-separability were chosen for spatio-temporal RFs to indicate their possible applicability in motion processing [43].

There are problems, however, that arise if these non-separability types are treated as detectors for motion comparable to classical feature detectors [44]. In this case, every possible spatio-temporal pattern in the stimulus space should be represented by a single neuron (or groups). Accordingly, one would face similar drawbacks concerning limited adaptational capabilities as discussed concerning spatial feature detectors. The question of how far the observed dynamics of RF organization are subject to alterations (by environment, by biotope or by the type

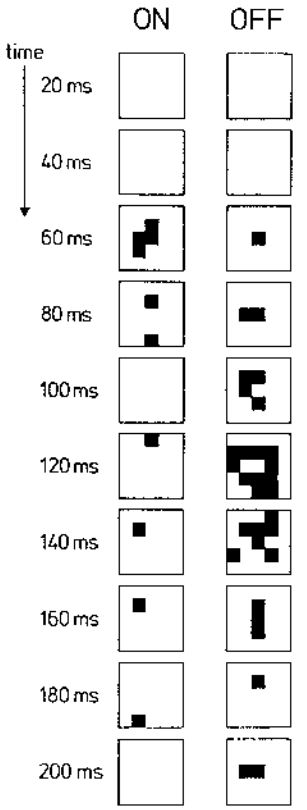

Fig. 7. Sequences of contour planes for the neurons shown in Fig. 6 recorded in area 17, illustrating the *dynamic receptive field size*. Time steps 20 ms. On-off stimulation within a grid of 5×5 subfields was used. Horizontal sections through the planes were applied at 50% maximal activity. Dark regions indicate spatial extent of excitatory regions within the receptive fields (RFs). Size of the stimulation matrix was 2.5 deg. (each subfield 0.5 deg.). These sequences illustrate RF diameter for each moment. Again there are dramatic changes over time that include systematic shift of RF location within the visual field as well as expansion and contraction.

of stimulation) is still open and requires further experiments (see also Section 8 and [45]).

4.2. *Time Dependence of RF Properties – Dynamic Orientation Selectivity*

Orientation selectivity and hypercomplexity (end-stopping property) can be regarded as the most prominent, textbook-like RF properties of cortical visual neurons. They describe specific neuronal responses to orientations or lengths of an elongated stimulus. To test their putative time dependence, we used stationary flickered bars of light (0.2 to 0.4 Hz) of different orientations and different lengths positioned in the RF center. We investigated the time course of orientation selectivity and hypercomplexity by compiling sequences of tuning curves for time steps of 20 ms. We introduce the terms *dynamic orientation selectivity* and *dynamic*

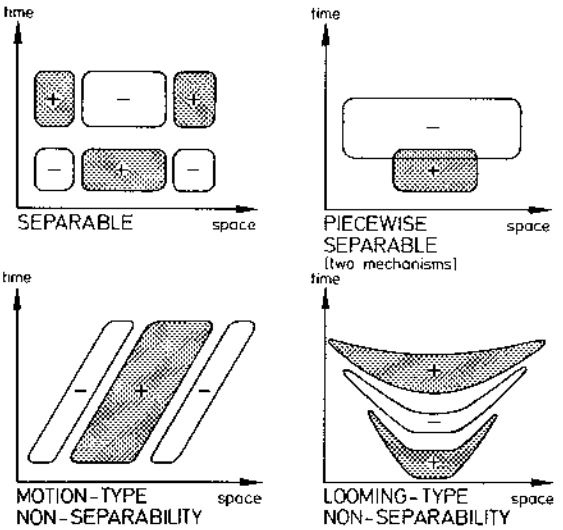

Fig. 8. Different types of spatio-temporal separability and non-separability [30]. Piecewise separability has been found for retinal ganglion cells [33], which reflect the basic center-surround organization. Spatio-temporal orientation or *motion-type* non-separability has been reported for cortical simple cells [79]. The cells from our recordings with mixed on-off discharge regions (complex-like cells) resemble those of both the *motion-type* and the *looming-type* (cf. Figs. 6 and 7).

end-stopping sensitivity, respectively. Each tuning curve in the sequence describes the actual selectivity of a cell at that moment. In this way, we avoid the temporal average that is usually done when compiling conventional tuning curves that uses a measure of maximal spike rate.

We distinguished two basically different types of responses (Fig. 9). Types Ia and Ib are the most intriguing, comprising more than 50% of our sample of area 17 neurons. Their selectivity to different orientations is clearly time dependent. Following on-off stimulation with flashed bars of light presented at different orientations, these neurons exhibit an initial state of brisk excitation that does not exhibit a selectivity for any orientations. After this initial stage, orientation selectivity evolves, indicated by a high level of selectivity for a given orientation. Types Ia and Ib differ in that type Ib changes its selected orientation over time. Type II neurons resemble most closely the conventional classification, in which selectivity is expressed without time dependence. However, type II neurons were found in only one-quarter of our sample. The time dependence of RF properties as seen in types Ia and Ib has not only been observed for orientation tuning, but also for hypercomplexity [46]. It is noteworthy that in all cases **selectivity evolves from an early state of non-selectivity**. Selectivity during the initial period of excitation and development of activity into an unspecific state was never observed [47].

These findings raise two important questions that will be treated in Section 6. One aspect deals with the obvious notion that states of maximal activity should not correlate with expression of high level of selectivity, which questions a simple model

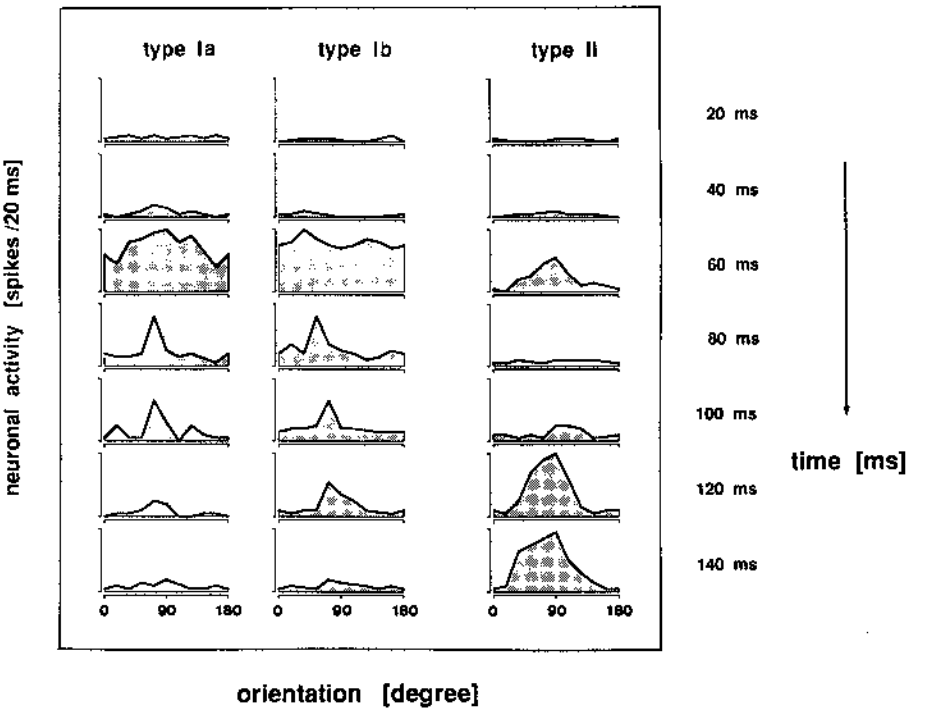

Fig. 9. Sequences of orientation tuning curves of the two different response types found in area 17, illustrating *dynamic orientation selectivity*. Time step 20 ms. Stimulus was a bar of light, flickered at 0.4 Hz and set at different orientations. Abscissa: stimulus orientation in deg., ordinate: number of spikes elicited during each 20-ms time step. Type Ia is selective after a previous state of non-selectivity excitation; type Ib is similar to type Ia, but changes its selectivity over time; type II is selective without time dependence. The latter corresponds to a conventional type of orientation selective cell.

representing stimulus information in terms of maximal or average spike counts. Secondly, we attempt to outline a theory on RFs that makes use of the observation that high level of selectivity evolves *delayed* after an initial state of stimulus-invariant excitation.

4.3. *Temporal Interference Patterns of Non-separable Spatio-temporal RFs During Processing of Moving Stimuli*

In all of the experimental findings discussed so far, RFs were analysed with stationary stimuli that were flashed on and off. This method was used because the time course of stimulation can be controlled and monitored with high precision. Even more importantly, under these conditions there can be no confounding of intrinsic response dynamics and those of the stimulus. These experiments revealed not only the highly structured response pattern, but also that RFs are composed of a set of multiple 'processing submodalities' (*ProcSubs*) that is temporally independent, i.e. the time course of excitation and inhibition is different. In terms of temporal

modulation of response pattern, this means that each location or each *ProcSubs*, respectively, may oscillate with a somewhat different frequency.

One of the important conclusions related to the temporal structure was its implication for interference patterns between intrinsic and extrinsic (i.e. stimulus-related) dynamics. This argument has considerable implications for the processing of moving stimuli.

Considering biotope and environmental conditions, there is little doubt that moving stimuli are more adequate stimuli for the visual system than stationary flashed ones. It may be tempting to try to predict neuronal response to moving stimuli using the knowledge of RF organization based on analysis with stationary signals. So far, successful predictions can be made only in neurons with separable RF organization. However, considering an RF organization such as that described above, in which each location displays a temporal behavior of its own, it is clear that, when stimuli are moving across such RFs, a very complex response pattern may emerge. One should expect a strong interaction between neighboring *ProcSubs* that will depend on stimulus speed, i.e. a temporal sequence in which adjacent *ProcSubs* are activated. Depending on the temporal properties of each *ProcSubs*, there will be suppression or facilitation of a response. The input history will interact with the internal temporal organization. Moreover, this interaction should not exclusively depend on stimulus speed, but also on the set of *ProcSubs* actually utilized. Which *ProcSubs* are involved first depends on the direction of motion and on the stimulus shape (see Fig. 10). What the model predicts is called ***mutual stimulus dependency*** [48]. In the case of ***mutual stimulus dependency***, alteration of stimulus parameters affects RF properties determined with a given set of stimuli. For example, the shape of the orientation tuning of a cell determined with an oriented stimulus of a given length moving at a given speed in a given direction is supposed to be modified when one of the stimulus parameters, such as speed, direction and length (or all of them), is changed.

4.3.1. *A dynamic model of RF organization accounts for mutual stimulus dependency – computer simulations*

The hypothesis described above was tested by computer simulations, in which the effect of systematic variation of several important parameters that are characteristic for individual *ProcSubs* was studied [49]. The tested parameters were the number of *ProcSubs* involved, the time course of excitation and inhibition of each *ProcSubs*, and their spatial arrangement within RFs. As the simulations were intended for investigating the putative influence of the internal RF dynamics, spatial interactions were not considered [50].

The simulations indicated that relatively small numbers of *ProcSubs* can generate the above-described mutual dependency of RF characteristics on stimulus parameters such as speed, direction, orientation and length, provided that there are sufficient differences in the time course of the *ProcSubs* involved. These effects were even more pronounced when an asymmetric spatial arrangement of the *ProcSubs* within RFs was introduced. Increasing the number of *ProcSubs* affects the sensitivity to different stimulus shapes rather than speed dependence. Direction selectivity revealed highest sensitivity to changes in internal RF organization. It should be

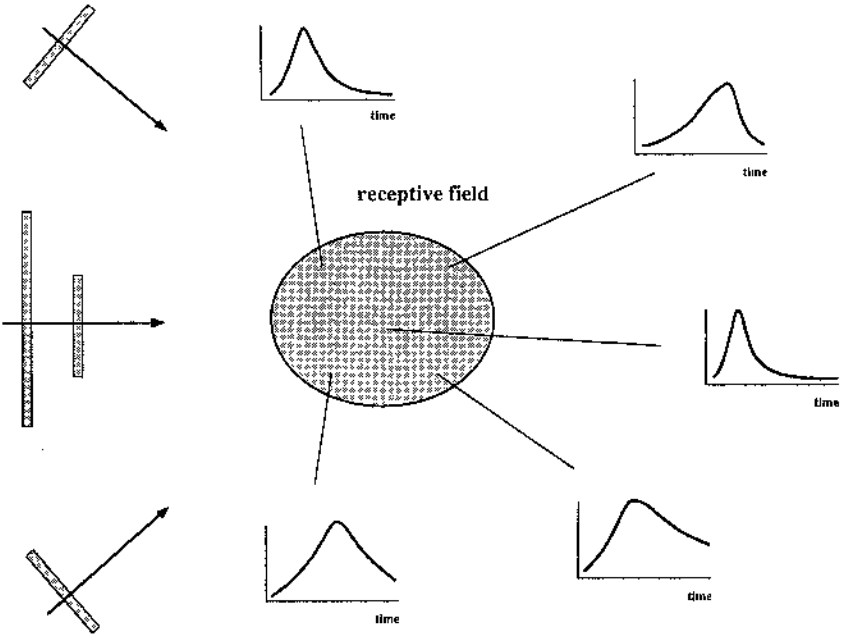

Fig. 10. Schema of receptive field (RF) organization that consists of a number of single 'processing submodalities' (*ProcSubs*) that all differ in their time course. If stimuli are moving across such an RF type (shown are four different stimuli differing in their orientation, length and direction of motion), the overall response depends on the interaction of adjacent *ProcSubs* and is thus supposed to reveal dependency on speed, direction and stimulus shape such as orientation and length.

stressed that all these effects that suggest the existence of what has been called *mutual stimulus dependency* are exclusively due to the temporal properties of RF organization.

4.3.2. *Experimental results revealing mutual stimulus dependencies: stimulus discrimination vs. stimulus representation*

Using conventional electrophysiological methods, the tuning properties of single cells in areas 17, 18 and 19 were investigated using a multidimensional stimulus set. Variation of stimulus parameters such as orientation or length was interpreted as changing stimulus shape [51]. Under this assumption, tuning curves were calculated for different speeds and directions of moving stimuli presented with different orientations and lengths (Fig. 11). The experimental data fully confirmed the predictions of the simulations as summarized in Fig. 11. Expression of stimulus selectivity can be extremely speed dependent. However, this dependency is also a function of direction of stimulus motion. On the whole, orientation tuning was somewhat more robust than hypercomplexity (end-stopping). However, while in the example of Fig. 11, the overall preferred orientation is not affected, the half-width of the tuning doubles at high stimulus speeds. In terms of orientation discrimination, this

might indicate severe loss of orientation selectivity. Speed dependence for different types of stimuli was observed in 50% to 70% of neurons from areas 17, 18 and 19 [52].

It should be noted that when more complex stimuli such as moving textured backgrounds were introduced, even more complex response patterns were observed that were not predictable from responses to moving bars of light presented without background. Again, direction selectivity is most sensitive to introduction to complex stimuli [53]. It is well known that considerable parts *outside the classical RF boundaries* are responsible for mediating such effects [54]. It seems conceivable that including the dynamic properties of remote locations outside the classical RFs will lead to a more complex response repertoire that is in full agreement with the assumption of context-bound representation of stimulus in the discharge of cortical cells [55].

In conclusion, so far **the experimental data revealed little support for stimulus-invariant discrimination** abilities, because the tuning characteristics of many neurons are alterable when further stimulus parameters are changed simultaneously. In contrast, they are best described in terms of *stimulus representation.* Under the described conditions, i.e. testing the mutual dependencies for a large number of stimulus parameters, RFs are **time and stimulus** dependent. While this behavior is difficult to explain in terms of the Hubel and Wiesel RF types, the simulations have shown that such behavior can easily be generated and even quantitatively predicted by a dynamic model of RF organization, which is based on differences in time course of excitation and inhibition for different locations within RFs. In other words, mutual stimulus dependency is due to temporal interference between intrinsic and stimulus-related dynamics.

5. Dynamic Aspects of Information Processing

5.1. *Evidence for the Use of a Time Code*

Conventional tuning curves are compiled by plotting a given measure of neuronal activity against variations of stimulus parameter. In most cases, the maximal spike rate as obtained from post-stimulus time histograms (PSTHs) is used. However, as can be seen from the sequences of tuning curves (Fig. 9), maximal excitation can be completely stimulus invariant, whereas high level of selectivity occurs delayed at an activity level far below that of the initial state [46]. This finding supports the view that high level of selectivity is not always linked to measures of maximal spike count. Assuming such a relationship in the case of time dependence of RF properties may result in misrepresentation of selectivity of cortical neurons.

A very similar observation was made in the case of evaluation of RF size, in which maximal activation was also not correlated with RF size. A comparison of the time course for both spike rate and receptive field size revealed that there was no simple, linear relationship between maximal spike rate and receptive field size. Rather, the correlation between both variables was time dependent [46].

This observation of independence of high level of selectivity and spike count measures is compatible with the initially described finding that measures of response amplitude and response latency are usually not correlated (see Section 2.1). We interpret the lack of or the weak association between temporal parameters and

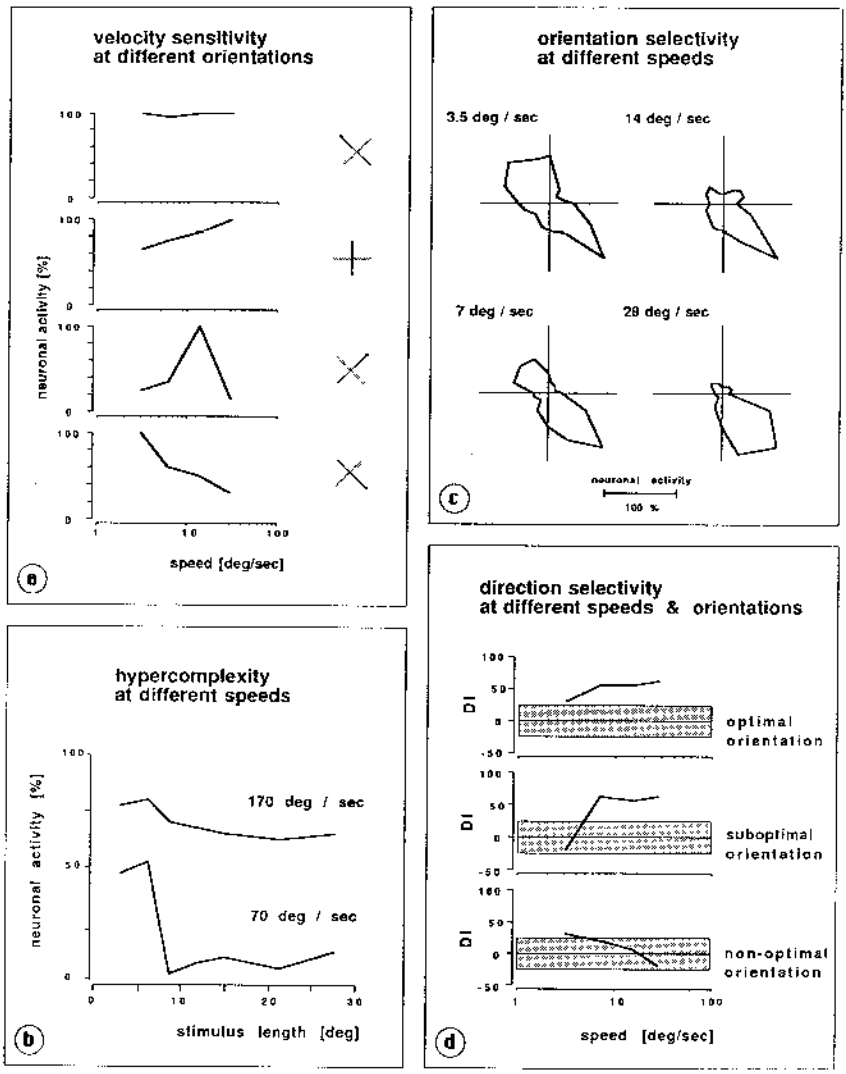

Fig. 11. Tuning curves obtained from electrophysiological experiments, illustrating various types of mutual stimulus dependency. (a) *Velocity sensitivity* for an area 17 cell measured at four different orientations. Optimal velocity or preferred range of speed can be considerably different for the same cell, when velocity tuning is tested at different orientations of the stimulus. (b) *Hypercomplexity* for an area 18 cell measured at two different speeds. Distinct inhibition of response seen during elongation of stimulus at low speed nearly disappears when the cell is tested with higher speed, indicating loss of hypercomplex properties. (c) *Orientation tuning* for an area 17 cell measured at four different speeds. Polar plots. Increasing speed is associated with considerable broadening of tuning half-width. (d) *Direction selectivity* for an area 17 cell measured at four different speeds and for optimal, sub-optimal and non-optimal orientations. DI is an arbitrary index of direction selectivity for two directions, separated by 180 deg. (preferred response − non-preferred response/preferred response × 100); positive values indicate preference for 0° direction, negative values indicate preference for 180° direction. Zero means that the cell is not direction selective. There is a clear speed dependence of DI, which is, however, a function of orientation.

measures of maximal spike count as an indication of the biological significance of a time code, in which temporal modulation of neuronal responses carries crucial information [56].

The fact that temporal modulation of response takes place over a range of about 500 ms argues in favor of the existence of two important time scales, a short, spike-to-spike time scale in the millisecond range (interspike intervals) and a second, much longer, peak-to-peak time scale in the range of tenths of seconds (interpeak intervals) that might correspond with what has been called *psychological time scale* (Fig. 12).

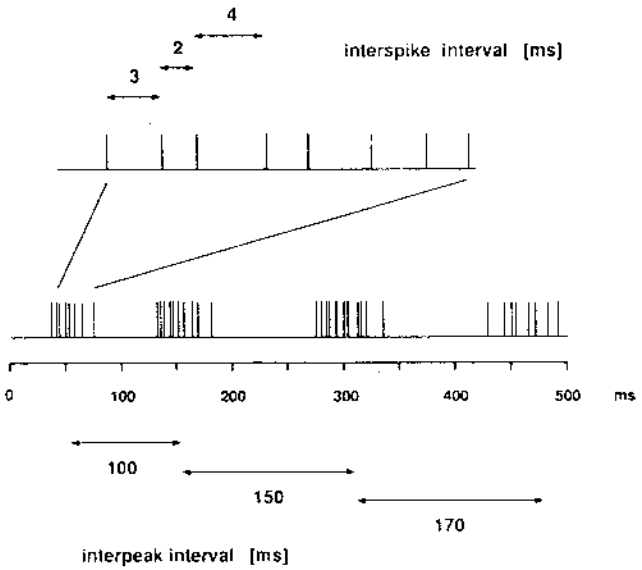

Fig. 12. Schematic illustration of a short and a long time scale, based on short interspike intervals (range 1–20 ms) and interpeak intervals (range 50–500 ms), which might correspond to the so-called *psychological* time scale.

The functional significance of time dependence of RF properties is possibly reflected in human reaction time measurements. It is well established that simple detection of stimuli can be performed within the shortest range of reaction times (about 200 ms), whereas recognition and discrimination of even simple geometric pattern leads to considerable lengthening in reaction times to the range of 400 to 500 ms. The initial state of excitation seen in the sequences of tuning curves might thus reflect that the appearance of a stimulus has just been recognized. Stimulus evaluation, however, takes a significantly longer time, which is reflected in the fact that high level of selectivity in neuronal response occurs at a much later state [57].

5.2. *Evidence for Positive Feedback*

As shown in Section 4.2, cells that showed time dependence of RF properties reach maximal high level of selectivity after an initial non-selective state of exci-

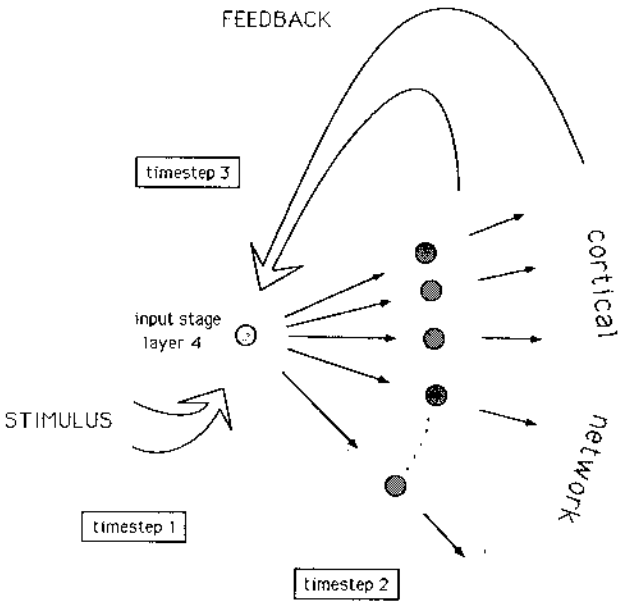

Fig. 13. Schematic illustration of the proposed feedback system.

tation. Moreover, the activity level of the initial response state was in most cases above that containing high level of selectivity. We argue that this behavior can most appropriately be explained in terms of positive feedback mechanisms. According to this assumption, the first state of excitation obtained after onset of stimulation is the initial trigger, elicited by the visual stimuli that activate the underlying cortical network. During this initial state, the activity is distributed across the entire system (Fig. 13). Reverberating activity provides information that contributes to an increasing state of high level selectivity of the local circuitry. As these processes need time, we observe evolution of selectivity over a considerable amount of time [58]. In this view, selectivity evolves over time by feedback processes that consist of multiple iterative steps, thus sculpturing selectivity (cf. Section 1.2). This assumption is in agreement with the basic properties of an *average cortical neuroanatomy*, including its vertical lamination, average axonal and dendritic domains and intrinsic feedback loops via pyramidal cell axon collaterals, all providing the requisite net-ware background. As has been described in the Introduction, all of these constraints were incorporated in the computer model of cortical architecture and supported the notion of time dependence of RF organization [59].

Further experimental evidence for the existence of iterative algorithms implemented in cortical processing was provided by analyzing the latency distribution following photic stimulation [60]: if excitation is indeed distributed throughout such a network consisting of multiple feedback loops, one should be able to trace the course of excitation at different spatial and temporal locations across the proposed iterative process. Both the considerable time delay between the cortical layers

as well as the wide scatter of visual latencies can be interpreted as a snapshot of the dynamics of the excitation distribution due to iterative steps [61].

5.3. *Evidence for Parallel Processing across Different Hierarchical Levels*

So far, we have restricted our discussion on issues related to dynamic properties of RF organization and to the time course of information processing performed by single neurons or small groups of neurons within a given cortical area. Here, we discuss some implications that arise for *interareal* interactions. The fact of a distinct temporal modulation of responses that outlasts some 500 ms counteracts the assumption of neural responses as a short event. Based on our experimental data, we reconstructed a *mean average response* to ERF-stimulation in the form of *cumulative PSTHs* (Fig. 14) for each substrate we investigated so far (LGN, areas 17, 18 and 19, PMLS, and area 7). In addition, we utilized the available data for neurons in monkey inferotemporal cortex (IT) [62].

It is a striking feature of the *cumulative PSTHs* that differences in latency to the first peak of excitation are small (Fig. 14). This is especially true for neurons of PMLS, area 7 and IT. Obviously, **there is no time for any type of sequential processing within the different stages of the visual system, provided that sequential means that a subsequent stage is waiting until the end of the entire response of a preceding stage.** Whereas areas 17, 18 and 19 of the cat predominantly process information in parallel by receiving independent inputs, areas PMLS, 7 and IT markedly differ in their level of processing. Several more input stages are involved regarding their thalamocortical connections, which should lead to longer time delays of response in comparison to those of area 17, 18 or 19 (cf. Fig. 2). However, the distribution of latencies of the former areas suggests that neurons in each of these areas independently start their processing. One has to assume a continuous interaction between all stages that already takes place during the very first state of excitation and continues during the complete temporal modulation of response. This is also true for cells of the A/A_1 lamina of the LGN and area 17, which show a considerable temporal overlap in response. Accordingly, there is no true preprocessing, but interaction between different levels is better described in terms of *temporally distributed processes* [63]. It therefore seems conceivable that there is also a strong time dependence of neuronal cooperativity of thalamocortical as well as corticocortical interactions. Obviously, due to the ongoing changing conditions in the outside world (i.e. stimulus space), this interaction hardly ever reaches steady state conditions. Similar to what has been said for *intracortical* feedback loops [60], this *interareal* time-dependent interaction could be a functional substrate for positive feedback acting *beyond* areal borders throughout the entire visual system and, therefore, extends the possible range during which neuronal cooperativity can take place to up to 500 ms.

6. On the Origin of the Temporal Structure

What is the origin of the temporal structure of neuron response? We will utilize several different lines of evidence that make it unlikely that this temporal structure is associated with thalamic oscillatory processes.

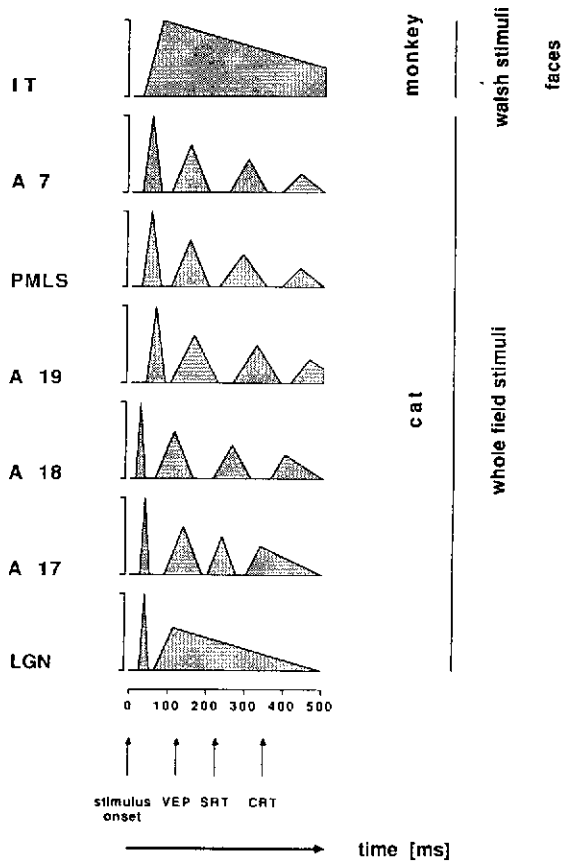

Fig. 14. Cumulative PSTHs constructed on the basis of mean values of the parameters describing the oscillatory response pattern. Data for monkey IT according to [62]. All the data for cat obtained with ERF-stimulation, IT data obtained with Walsh stimuli. The time axis is scaled using some average values for visual evoked potentials (VEP), simple reaction times (SRT) and choice reaction times (CRT). There are little differences in onset of response even for areas of an advanced level classified according to their number of input stages. The temporal modulation of response therefore considerably extends the possible range in which neuronal cooperativity can take place to up to several hundred milliseconds, and provides a substrate for parallel processing beyond areal borders.

Firstly, our recordings in A/A_1 laminae of the cat LGN under identical conditions (types of stimulation, anesthesia) revealed a total lack of the described temporal response structure in geniculate neurons. Secondly, simultaneous recordings with several independent microelectrodes revealed fundamental differences between the temporal structures of neurons recorded with separations between 0.5 and several mm. This argues against the possibility that the temporal structure in the response is merely a reflection of a global state of cortical or subcortical excitation. The described stimulus-dependent alterations of the temporal pattern are also in-

compatible with the assumption of a coupling to known EEG pattern as these alterations occurred within several minutes during which the overall state did not change. Finally, it should be noted that the range of the low-frequency oscillations overlaps the frequency range of many EEG patterns.

Another line of evidence is derived from experiments in which the temporal structure was recorded under different anesthetic conditions of barbiturate narcosis [64]. Only during low level of barbiturate anesthesia was there an optimal expression of the described low-frequency oscillation. Switching to deep level of anesthesia succeedingly slowed down the oscillatory response and finally abolished the temporal structure completely. However, neither the amplitude nor the latency of the first peak of excitation following tactile stimulation was affected. While this type of anesthesia is not directly comparable to that used in the cat experiments [65], these findings indicate that the temporal structure will not be found under deep anesthesia which, on the other hand, is known to give rise to profound thalamic oscillations [66]. The remarkable robustness of the first peak of excitation following stimulation is fully compatible with the assumption of feedback mechanisms (Fig. 13). In this view, the first peak of excitation is due to the first, direct stimulus-triggered afferent input. A lack of a profound temporal structure is then interpreted as poor operation of the network, a situation that might be met under deep anesthesia.

Recent experiments on slices of rat somatosensory cortex have revealed that pyramidal neurons in layer 5 showed intrinsic cellular oscillation in the range of 5 to 12 Hz that could be induced by a brief trigger such as intracellular current pulses [67].

In an alternative interpretation, we attempted to explain the temporal structure in terms of feedback mechanisms. How much the oscillatory components of cellular origin are an intricate part is not clear. One could think of a combined action consisting of inherent, cellular dynamics acting synergetically on the dynamics of the cortical network, thus promoting the described temporal pattern.

7. General Outline of a Theory of RF Organization

Based on what has been argued so far on the implications of temporal behavior, time dependence and feedback for RFs, we will outline a general hypothesis on dynamic RF organization.

We start with neuroanatomical observations on average dendritic field dimension as found in cat and monkey striate cortex. According to various authors, the diameter of dendritic fields do not exceed 200 to 400 microns [68]. There is also agreement that the average RF size in area 17 subserving foveal vision is about 1 to 2 deg. visual angle. Utilizing the available data on retinotopic mapping studies [69], one can recalculate cortical surface in terms of visual field parameters. Taking for granted that 1 mm^2 cortex represents 1 to 2 $deg.^2$, then the observed dendritic fields cover at least 0.2 to 0.5 $deg.^2$ [for more details, see 16]. However, as stated above, the observable, average RF size is 1 to 2 deg., for which we introduce the term *apparent RF size*.

Now we have to recall that the apparent RF size is due to considerable temporal averaging. The *dynamic receptive field size* is illustrated in the sequences of contour planes which provide detailed information about RF size at every moment after

stimulation. As can be seen from Figs. 6 and 7, the smallest extent of RFs was most frequently observed during the initial state of excitation. This is equivalent to the initial state of excitation that lacks selectivity when stimulus parameters such as orientation or length were varied. Based on what has been argued with respect to positive feedback, the smallest RF dimensions seen during this initial state are the expression of the first, direct stimulus-triggered activity. Indeed, RF size at this time is about 0.5 deg.^{2} or less. We therefore suggest that this state and only this is mediated directly by the underlying dendritic fields. In this case, during the first state of excitation, we obtain an optimal match between measured dendritic field dimensions and apparent RF size (cf. Fig. 13). In addition, this state lacks high level of selectivity. Both observations are compatible with the assumption that the underlying dendritic field is responsible for this part of the response. Next, the contributions from positive feedback become apparent, i.e. the non-local network is operating and acts on the cell under investigation. It is in this state that we observe high level of selectivity and expansion of RF diameters or motion of RF location (both lead to the apparent RF size which is normally measured with hand-plotting or with quantitative averaging techniques). Accordingly, both apparent RF size and high level of selectivity are considerably dynamic in nature and may be assumed to be based on both the underlying dendritic field organization *and* on the organization of a distributed network. This explains time dependence of RF organization and the mismatch between apparent RF size and dendritic field diameter. It also explains that high level of selectivity is always reached after a previous unselective state [70].

In this view, inhibition plays a relatively unspecific role: high level of selectivity is not determined by inhibitory processes alone, but arises from multiple iterations within a system of positive feedback. However, systems consisting of abundant positive feedback, such as cortical networks, require very meticulous control in order to maintain a stable operation. We therefore suggest that the well-documented inhibitory action is primarily used to stabilize the positive feedback system. Under these assumptions, blocking of inhibition would result in excessive excitation and loss of high level of selectivity due to an abnormal state of the entire positive feedback system. Interestingly, based on results from intracellular recording experiments, the concept of a rather unspecific role of cortical inhibition has been advocated [71]. Accordingly, inhibition has to act in a far more subtle way than might be imagined and excitatory connections are far more important than supposed.

8. Further Relationships to Temporal Aspects of Brain Function and Apparent Questions

Only a few aspects possibly related to the described temporal structure are discussed in the following.

We described RF dynamics in the range of hundredths to tenths of seconds. There is an interesting link to dynamics in the minute-range that stems from observations of reorganizational capacities of sensory maps. Representation of skin in somatosensory areas has been shown to be alterable by use [72]. Significant representational changes were demonstrated after only several minutes of intracortical microstimulation (ICMS) [73]. As to the underlying mechanisms of this reorgani-

zation of cortical representations, it has been suggested that input selection occurs by cooperation among groups of neurons. These groups have to be regarded as dynamic, i.e. group constitution is subject to continuous remodeling. The anatomical projections are believed to provide an extended, rather unspecific input repertoire that is selected from in the generation and remodeling of sensory maps. Similar to what we have described so far for RF organization in visual cortices, the generation of functional maps has been ascribed to the actions of the entire network instead of direct, dendritic field mediated effects.

Ongoing changes of the functional connectivity are the subject of an extensive investigation, in which correlated firing patterns are analyzed. Examination of simulated spike trains has indicated that dynamic firing correlation can be caused either by changes in connectivity strengths or by the dynamics of a large interconnected network [74]. Inspection of multineuron recordings of real neurons from different areas of brains of higher mammals under numerous conditions revealed in fact dramatic changes of correlated firing patterns that occurred at time scales comparable to that described here [74].

A corresponding observation was made during the reorganization of cortical skin representation which was paralleled by a dramatic increase in correlated activity. This alteration of correlated firing patterns was interpreted as a modification of neural assembly interaction, which was recorded even for pairs of neurons separated by up to 1 mm [75]. Usually, broadly peaked correlograms were found with a half-width of about 20 ms that were always centered around tau=0. It was concluded that the broadly peaked correlograms can best be explained not in terms of direct connections, but in terms of positively, but loosely coupled neurons that share some common input sources. According to this view, intracortical microstimulation changes the state of small neuron assemblies by changing the intrinsic temporal discharge pattern.

As to synaptic plasticity, there is general agreement that simultaneity of events trigger changes of synaptic efficiency. However, the effective time scale of simultaneity is not clear. Simultaneity can be restricted to single action potentials, an extreme view, as in this case the probability for simultaneity might be dramatically reduced. If simultaneity is defined in terms of the temporal structure described in this paper, the requirements for simultaneity are much easier to fulfill.

A crucial (and easily testable) topic is the notion of interference. As shown, it has implications for the question of how moving stimuli are processed in terms of underlying RF organization. Also, it is crucial for experiments dealing with repetition rates, or more generally, timing or temporal sequencing [76].

The predictive power of the notion of interference was validated in experiments in which the repetition rate of visual stimuli was systematically shifted close to the range of the temporal structure in both single-cell experiments as well as in psychophysical experiments [77]. Indeed, in both types of experiments distinct oscillatory breaks of the response amplitude occurred at repetition rates at which interference could be expected due to the intrinsic oscillations.

At a more general level, we believe that the temporal structure seems optimally adapted for dealing with an environment that is in itself essentially dynamic. As already stated in the Introduction, the entire structure and procedure of seeing provides an additional substrate that is basically dynamic. The dynamics are rep-

resented by a well-defined sequence of operations such as fixation, accommodation, or eye movements. It therefore appears reasonable to analyze such an environment in terms of elementary events rather than spatial features [78].

This brief inventory of putative liaisons is far from exhaustive. Many of the aspects briefly touched above can, however, be easily transformed into predictions and experimentally testable questions.

As mentioned at the beginning, this temporal structure seems not at all to be restricted to the visual cortex, but is common in somatosensory and auditory cortices as well [21]. It therefore appears reasonable to guide further experiments by the assumption of a general dynamic strategy of information processing. Further questions are listed without intending priority:

- To what degree is the described temporal structure subject to environmental (stimulus-dependent) or systemic changes?
- Is there an absolute temporal scaling in that certain aspects are processed in a fixed sequence?
- Is there an association between the temporal structure and certain processes within the structure and procedure of seeing? The same question holds for a possible association with elementary events or psychophysical correlates.
- Is it possible to find a global level of description in terms of dynamic patterns that accounts for the obvious synchronizing effect of *ERF-stimulation* versus *subfield-stimulation*? Moreover, using this approach, mutual relationships with other frequency bands can be analysed systematically.

It remains to be seen whether the temporal structure represents an evolutionary adaptation to the dynamics of the structure of seeing as well as to the dynamics of the environment, whether exclusively visual or, as what we have suggested, generally applicable to cortical neural processing.

9. Perspectives – Anything is Temporal

We have described a temporal structure of neuron response following on-off stimulation which consists of damped oscillations in the range of 10 Hz. What are the impacts of this temporal structure on classic concepts such as RFs? How is the temporal structure linked to fundamental problems of processing and coding of information? Figuratively, anything is temporal. In this scenario, a temporal structure emerging during the first 500 ms after onset of stimulation plays the key role. Clearly, that means that temporal averaging is no longer reasonable. Temporal averaging will erase the temporal structure from the observer. Therefore, we introduced descriptions in terms of *dynamic RF properties*, which were illustrated by temporal sequences of RF descriptors.

Receptive fields are considered the basic elements for information processing. However, the original idea of feature detectors has lost its attraction. There is increasing evidence from several laboratories that the concept of RFs has to be extended or reformulated (at present, there seems to be no coherent, generally accepted conceptual standard).

Our data showing that cortical RFs are characterized by non-separability of their spatial and temporal behavior provided additional support for this view. Non-separability, of course, implies a negative definition: RFs *cannot* be described by

a simple cascade of spatial and temporal filters. The notion of non-separability predicts time and stimulus dependence of RFs which could be experimentally verified. Based on these observations, we have introduced the contrasting concepts of *stimulus discrimination* vs. *stimulus representation*. What is still missing, however, is a new conceptual framework of RFs. This becomes even more evident as more complicated types of stimulation are used, such as moving background. Background effects described so far are clearly mediated by regions 'outside the classical RF', a term already requiring revision of the old concept.

Our demonstration that cortical neuron response is not a short event but lasts over some 300 to 500 ms, suggests that under normal conditions the visual system will never operate in a true steady state. The observed temporal structure may be ascribed to the intrinsic dynamic properties of these neurons as it was obtained under conditions that let the system reach steady state. This implies ongoing interactions between the intrinsic temporal structure of the neurons and the dynamics of the stimulus. For example, stimulus repetition faster than 1 Hz must elicit interference between the intrinsic temporal structure and the stimulus dynamics which is referred to in the notion of *temporal interference patterns*. This long lasting intrinsic temporal structure also mediates contextual interaction based upon spatial cues (i.e. stimulus dependence). This is possible because the temporal interaction depends not only on the speed of the stimulus and its direction, i.e. the temporal sequence, in which adjacent 'processing submodalities' (*ProcSubs*) are activated, but also on which set of the *ProcSubs* is actually utilized. The selection of sets is largely determined by parameters describing the overall shape of the stimulus, such as its orientation or length, thus resulting in an overall 'mutual stimulus dependency'.

The observation of *dynamic RF properties* and their time and stimulus dependence provide a strong argument that stimulus information is indeed processed during this temporal structure, indicating that stimulus information is mapped onto the entire temporal structure of the spike train. To restate, in the case of temporal encoding of information, temporal averaging of neural responses will not preserve such encoded information. Simplistic measures, such as maximal or average firing rate, are then not sufficient for understanding the messages transmitted. This is consistent with our finding of a lack of correlation between the points in time where firing rate is maximal and the occurrence of high level of selectivity. Interestingly, the length of the temporally modulated (oscillatory) response, which we suppose is the substrate for this type of temporal encoding, links the short, 'neuronal', interspike interval time scale to the much longer psychological time scale in the range of tens of seconds.

Finally, in a more general sense, we believe that the temporal structure of the type described in this paper is optimally adapted for dealing with an environment that is itself essentially dynamic. As entire stabilized images fade after several seconds, genuinely stationary stimuli might be viewed as artificial. Consequently, the environment must be analyzed in terms of elementary events rather than spatial features, an assumption that should be incorporated into new dynamic RF concepts.

Admittedly, there are a number of open questions. It remains unclear how the striking difference in temporal structure between *ERF-stimulation* and *subfield-stimulation* comes about. One might postulate a synchronizing effect acting across the entire RF. Moreover, are there general rules relating an idiosyncratic temporal

structure to the type of stimulus used? Also, the significance of layer-specific and area-specific temporal patterns is not understood at present. We are left with the certainty, however, that any conclusive conceptual framework of cortical information processing must take into account the striking temporal structure of neuron response.

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[45] C. H. Anderson and D. C. van Essen, *Proc. Natl. Acad. Sci. USA* **84**, 6297 (1987); D. C. van Essen and C. H. Anderson, in *Computational Neuroscience*, ed. by E. Schwartz (MIT Press, Cambridge, Massachusetts) in press; D. C. van Essen and C. H. Anderson, in *Introduction to Neural and Electronic Networks*, ed. by S. F. Zornetzer, J. L. Davies and C. Lau (Academic Press, Orlando) in press.

[46] H. R. O. Dinse, K. Krüger and J. Best, in *Neuronal Cooperativity*, ed. by J. Krüger (Springer, Berlin) in press.

[47] There is some discrepancy between the results on time dependence of orientation selectivity as reported here and recent experiments which failed to demonstrate it: G. A. Orban and R. Vogels, *Neurosci. Abstr.* **15**, 324 (1989); Y. Trotter, S. J. Thorpe, S. Celebrini and A. Pouget, *Neurosci. Abstr.* **15**, 1056 (1989); G. Orban, personal communication; S. Thorpe, personal communication. However, both groups used flashed gratings instead of single bars which differ concisely in the extent of the visual field that is stimulated. It seems conceivable that feedback mechanisms are highly sensitive to the global state that is altered when only very small parts of the cortex are active (single bar paradigm) or large portions of it are activated (grating paradigm). It could in fact be shown that introduction of large background stimuli that stimulate the entire visual field indeed alter the temporal pattern of neuronal response: H. R. O. Dinse and J. Best, *Brain Res.*, submitted. Moreover, using single bar stimuli, the Soviet group has reported considerable dynamic changes of orientation tuning that are comparable to those reported here: I. A. Shevelev and G. A. Sharaev, *Neurofisiologia* **13**, 451 (1981); N. A. Lazareva, R. V. Novikova, A. S. Tikhomirov and I. A. Shevelev, *Neurofisiologia* **18**, 805 (1986); I. A. Shevelev, R. V. Novikova, N. A. Lazareva, A. S. Tikhomirov and G. A. Sharaev, *Sensornje Sistemje* **1**, 184 (1987); I. A. Shevelev, A. Lazareva and A. S. Tikhomirov, *Sensornje Sistemje* 1, 309 (1987); I. A. Shevelev, *Sensornje Sistemje* **1**, 73 (1987). Interestingly, dynamic changes of RFs in owl's auditory system were recently reported by H. Wagner, *Eur. J. Neurosci.* **2**, 949 (1990).

[48] Obviously, in this model possible nonlinear interactions between the different 'processing submodalities' are not considered. It seems conceivable that including nonlinear interaction makes both the simulations and their results more complex, which is not intended at this moment.

[49] H. R. O. Dinse, in *Dynamic and Plasticity in Neuronal Systems*, ed. by N. Elsner and W. Singer (Thieme Verlag, Stuttgart, 1989) p. 358; H. R. O. Dinse, in preparation.

[50] In the simulations, a 5 by 5 matrix of subfields was used. The time course of excitation and inhibition of each subfield was adapted to fit the experimental data. The overall response to moving stimuli was calculated by linear superposition in successive time steps. The duration of the single time steps was varied to account for different stimulus speeds. The selection of subfields that contributed to the overall response depended on the shape and the direction of the stimulus.

[51] H. R. O. Dinse, in *Brain – Perception – Cognition*, ed. by N. Elsner and G. Roth (Thieme Verlag, Stuttgart, 1990) p. 244.

[52] So far, only few data are available that show mutual stimulus dependencies: P. Hammond and J. Reck, *Neurosci. Lett.* **19**, 309 (1980); H. R. O. Dinse and W. von Seelen, *Biol. Cybern.* **41**, 59 (1981); P. Hammond and I. M. E. Shorrocks, *J. Physiol. (Lond.)* **382**, 174P (1987); F. Wörgötter and U. T. Eysel, *Exp. Brain Res.* **76**, 307 (1989); K. Krüger and H. R. O. Dinse, *Visual Neurosci.*, submitted.

[53] P. Hammond and J. Reck, *Neurosci. Lett.* **19**, 309 (1980); P. Hammond and A. T. Smith, *J. Physiol. (Lond)* **342**, 35 (1983); J. Allman, F. Miezin and E. L. McGuiness, *Perception* **14**, 105 (1985); G. A. Orban, B. Gulyas and R. Vogels, *J. Neurophysiol.* **57**, 1792 (1987); H. R. O. Dinse and K. Krüger, *Soc. Neurosci. Abstr.* **13**, 1624 (1987);

K. Krüger and H. R. O. Dinse, *Soc. Neurosci. Abstr.* **14**, 602 (1988); L. Lagae, B. Gulyas, S. Raiguel and G. A. Orban, *Neurosci. Abstr.* **14**, 457 (1988); J. Allman, F. Miezin and E. L. McGuiness, in *Signal and Sense, NRP*, in press; H. R. O. Dinse, *Informationsverarbeitung im visuellen System der Katze. Neuronale Grundlagen* (Thieme Verlag, Stuttgart, 1989); J. M. Crook, *Exp. Brain Res.* **90**, 545 (1990); H. R. O. Dinse and K. Krüger, *Exp. Brain Res.* **82**, 107 (1990); K. Krüger and H. R. O. Dinse, *Visual Neurosci.*, submitted.

[54] M. von Grünau and B. J. Frost, *Exp. Brain Res.* **49**, 84 (1983); J. Allman, F. Miezin and E. L. McGuiness, *Perception* **14**, 105 (1985); H. R. O. Dinse and K. Krüger, *Soc. Neurosci. Abstr.* **13**, 1624 (1987); J. Allman, F. Miezin and E. L. McGuiness, in *Signal and Sense, NRP*, in press.

[55] H. R. O. Dinse and J. Best, *Brain Res.*, submitted.

[56] A similar conclusion was reached by L. Optican and B. Richmond, who were able to demonstrate by means of principal component analysis of the waveforms of the temporal modulation elicited by an orthogonal set of complex geometrical patterns (Walsh stimuli) that the properties of modulation can carry a considerable amount of information independent from maximal spike count: B. J. Richmond, L. M. Optican, M. Podell and H. Spitzer, *J. Neurophysiol.* **57**, 132 (1987); B. J. Richmond and L. M. Optican, *J. Neurophysiol.* **57**, 147 (1987); L. M. Optican and B. J. Richmond, *J. Neurophysiol.* **57**, 162 (1987); B. J. Richmond, L. M. Optican and H. Spitzer, *J. Neurophysiol.* **64**, 351 (1990); B. J. Richmond and L. M. Optican, *J. Neurophysiol.* **64**, 370 (1990). See also R. Eckhorn, O. J. Grüsser, J. Kröller, K. Pellnitz and B. Pöpel, *Biol. Cybern.* **22**, 49 (1976); more recently, the importance of temporal spike train patterns was shown by J. Krüger and J. D. Becker, in *Parallel Processing in Neural Systems and Computers*, ed. by R. Eckmiller, G. Hartmann and G. Hauske (Elsevier, Amsterdam, 1990) p. 121.

[57] We are fully aware that pointing out a possible significance of temporal encoding of information does by no means prove that it is in fact utilized by the nervous system.

[58] Intracellular recordings have revealed time constants of the neuronal membrane in the range of 10 to 20 ms, which is far longer than the transmission time from one neuron to the next which is only about 1 to 2 ms: K. A. C. Martin, *Q. J. Exp. Physiol.* **73**, 637 (1988); R. J. Douglas, K. A. C. Martin and D. Whitteridge, *Nature* **332**, 642 (1988).

[59] G. Krone, H. A. Mallot, G. Palm and A. Schüz, *Proc. R. Soc. Lond.* **B226**, 421 (1986). For details of an analytic approach to feedback systems, see W. von Seelen, H. A. Mallot and F. Giannakopoulos, *Biol. Cybern.* **56**, 37 (1987); H. A. Mallot and W. von Seelen, in *Visuomotor Coordination: Amphibians, Comparisons, Models, and Robots*, ed. by J. P. Ewert and M. Arbib (Plenum, New York, 1989) p. 357.

[60] J. Best, S. Reuss and H. R. O. Dinse, *Brain Res.* **385**, 356 (1986); H. R. O. Dinse and J. Best, *Brain Res.*, submitted. Similar laminar specific distributions of latencies were obtained for rat SI (primary somatosensory cortex) by H. R. O. Dinse and M. M. Merzenich, unpublished.

[61] It should be noted that the observed lamina-specific distribution does not match with the reported termination of x-, y- and w-input and thus cannot be explained in terms of the afferent input pattern: J. Best, S. Reuss and H. R. O. Dinse, *Brain Res.* **385**, 356 (1986); see also [58].

[62] B. J. Richmond, L. M. Optican, M. Podell and H. Spitzer, *J. Neurophysiol.* **57**, 132 (1987). Interestingly, the latencies of IT neurons responding selectively to faces are within the upper range set by neurons from the areas receiving direct thalamic input.

[63] One could argue that the fastest neurons in a preceding stage cooperate with the slowest of a subsequent stage. However, such an overlap can be constructed for only a small set of neurons, neglecting the major part of the cell sample.

[64] H. R. O. Dinse and G. H. Recanzone, unpublished. These experiments were performed in rat somatosensory cortex. Comparable to stationary flashed visual stimuli, brief tappings applied via a Chubback tactile stimulator were used. Recently, similar results were obtained in rat somatosensory cortex under urethane anesthesia.

[65] In the described cat experiments, animals were artificially ventilated with a mixture of nitrous oxide (70%) and oxygen (30%), thus maintaining a weak state of anesthesia.

[66] M. Steriade and R. R. Llinas, *Physiol. Rev.* **68**, 649 (1988).

[67] B. W. Connors and M. J. Gutnick, *Trends Neurosci.* **13**, 99 (1990); L. R. Silva, Y. Amitai and B. W. Connors, *Science*, in press.

[68] J. S. Lund, *J. Comp. Neurol.* **147**, 455 (1973); E. G. Jones, in *The Neurosciences. Third Study Program*, ed. by F. O. Schmitt and F. G. Worden (MIT Press, Cambridge, Massachusetts, 1974) p. 215; J. S. Lund, G. H. Henry, C. L. MacQueen and A. R. Harvey, *J. Comp. Neurol.* **184**, 599 (1979).

[69] R. J. Tusa, L. A. Palmer and A. C. Rosenquist, in *Cortical Sensory Organization II*, ed. by C. N. Woolsey (Humana Press, New York, 1981) p. 1.

[70] In addition, it overcomes the still open controversial question of to what extent anisotropic organized dendritic fields are necessary to generate the sharp tuning as seen in electrophysiological measurements. According to the hypothesis outlined in this section, a weakly biased input would be sufficient to produce a high level of selectivity on the basis of intracortical feedback mechanisms during successive iterative steps.

[71] K. A. C. Martin, *Q. J. Exp. Physiol.* **73**, 637 (1988); R. J. Douglas, K. A. C. Martin and D. Whitteridge, *Nature* **332**, 642 (1988); K. A. C. Martin, personal communication.

[72] M. M. Merzenich, T. Allard, W. M. Jenkins and G. Recanzone, in *Neural Networks. Structure and Models*, ed. by W. von Seelen, G. Shaw and U. M. Leinhos (VCH, Weinheim, 1988) p. 285; M. M. Merzenich, G. Recanzone, W. M. Jenkins, T. Allard and R. J. Nudo, in *Neurobiology of Neocortex. Dahlem Konferenzen 1988*, ed. by P. Rakic and W. Singer (Wiley, 1988) p. 41; G. H. Recanzone, W. M. Jenkins, G. T. Hradek, C. E. Schreiner, K. A. Grajski and M. M. Merzenich, *Neurosci. Abstr.* **15**, 1223 (1989).

[73] The method of ICMS has been reported to produce changes in topographic representations that are comparable in extent to those found after behavioral training by G. Recanzone and M. M. Merzenich, *Soc. Neurosci. Abstr.* **14**, 223 (1988); H. R. O. Dinse and M. M. Merzenich, *Soc. Neurosci. Abstr.* **15**, 1223 (1989); H. R. O. Dinse, G. H. Recanzone and M. M. Merzenich, in *Parallel Processing in Neural Systems and Computers*, ed. by R. Eckmiller, G. Hartmann and G. Hauske (Elsevier, Amsterdam, 1990).

[74] G. L. Gerstein, P. Bedenbaugh and A. M. H. J. Aertsen, *IEEE* **36**, 4 (1989); A. M. H. J. Aertsen, G. L. Gerstein, M. K. Habib and G. Palm, *J. Neurophysiol.* **61**, 900 (1989); A. Aertsen, T. Bonhoeffer and J. Krüger, in *Physics of Cognitive Processes*, ed. by E. R. Caianiello (World Scientific, Singapore, 1987) p. 1.

[75] H. R. O. Dinse and M. M. Merzenich, *Soc. Neurosci. Abstr.* **15**, 1223 (1989); H. R. O. Dinse, G. H. Recanzone and M. M. Merzenich, in *Parallel Processing in Neural Systems and Computers*, ed. by R. Eckmiller, G. Hartmann and G. Hauske (Elsevier, Amsterdam, 1990) p. 65.

[76] G. L. Shaw and V. S. Ramachandran, *Perception* **11**, 491 (1982); L. Brothers and G. L. Shaw, in *Models of Brain Function*, ed. by R. M. J. Cotterill (Cambridge Univ. Press, 1989) p. 285; G. L. Shaw, P. C. Rinaldi and J. C. Pearson, *Exp. Neurol.* **79**, 293 (1983); J. J. Hopfield and D. W. Tank, in *Neural Models of Plasticity – Experimental and Theoretical Approaches*, ed. by J. H. Byrne and W. O. Berry (Academic Press, San Diego, 1989) p. 363; T. J. Watanabe, T. J. Gawne, B. J. Richmond and L. A. Optican, *Neurosci. Abstr.* **15**, 1054 (1989); E. Pöpel, E. Ruhnau, K. Schill and N. von

Steinbüchel, in *Synergetics of Cognition*, ed. by H. Haken and M. Stadler (Springer, Berlin, 1990) p. 144.

[77] H. R. O. Dinse, unpublished; in the psychophysical experiments, thresholds for intensity of a masking pattern were determined as a function of the repetition rate of a briefly flashed stimulus: H. R. O. Dinse and J. Best, unpublished. See also G. L. Shaw and V. S. Ramachandran, *Perception* **11**, 491 (1982).

[78] There are several theories of cortical information processing that rely on oscillations of the type we report here. For example, the 'trion model' of cortical organization is based on temporal oscillations in the range of 50 to 100 ms, which the authors believe represents a significant clock-like temporal scale of cortical information processing: G. L. Shaw, D. J. Silverman and J. C. Pearson, *Proc. Natl. Acad. Sci. USA* **82**, 2364 (1985); G. L. Shaw, D. J. Silverman and J. C. Pearson, in *Brain Theory*, ed. by G. Palm and A. M. H. J. Aertsen (Springer, New York, 1986) p. 177; G. L. Shaw, D. J. Silverman and J. C. Pearson, in *Systems with Learning and Memory Abilities*, ed. by J. Delacour and J. C. S. Levy (Elsevier, Amsterdam, 1988) p. 411.

[79] J. McLean, S. Raab and L. Palmer, *Soc. Neurosci. Abstr.* **13**, 1623 (1987).