

From Attention to Goal-Directed Behavior

Francisco Aboitiz • Diego Cosmelli
Editors

From Attention to Goal-Directed Behavior

Neurodynamical, Methodological
and Clinical Trends

 Springer

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Contents

Part I Attentional Networks: Basic Mechanisms and Methodological Issues

1 Neuronal Signatures of Selective Attention – Synchronization and Gain Modulation as Mechanisms for Selective Sensory Information Processing.....	3
C. Bosman and T. Womelsdorf	
2 Intracortical Recordings During Attentional Tasks	29
J.-P. Lachaux and T. Ossandón	
3 The Spatiotemporal Dynamics of Visual-Spatial Attention.....	51
S.J. Luck	
4 Attention and Neurodynamical Correlates of Natural Vision	67
P.E. Maldonado, J.P. Ossandón, and F.J. Flores	
5 Attending to the Stream of Consciousness – A Methodological Challenge	83
D. Cosmelli	
6 Crossmodal Attention – The Contribution of Event-Related-Potential Studies.....	105
R. Ortega and V. López	
7 Measuring and Modulating Hemispheric Attention.....	125
A. Hill, A. Barnea, K. Herzberg, A. Rassis-Ariel, S. Rotem, Y. Meltzer, Y.H. Li, and E. Zaidel	

8 A Connectionist Perspective on Attentional Effects in Neurodynamics Data	145
O. David	
Part II From Attention to Behavioral Control	
9 From Goals to Habits – A View from the Network.....	165
J.M. Hurtado	
10 Dynamics of a Neuromodulator – I. The Role of Dopaminergic Signaling in Goal-Directed Behavior	187
F. Aboitiz	
11 Dynamics of a Neuromodulator – II. Dopaminergic Balance and Cognition.....	205
F. Aboitiz	
Part III Clinical and Developmental Issues	
12 Prefrontal Cortex and Control of Behavior – Evidence from Neuropsychological Studies	231
A. Slachevsky, P. Reyes, G. Rojas, and J.R. Silva	
13 The Maturation of Cognitive Control and the Adolescent Brain	249
B. Luna	
14 Electrophysiological and Genetic Markers of Attention Deficit–Hyperactivity Disorder: Boundary Conditions for Normal Attentional Processing and Behavioral Control.....	275
X. Carrasco, M. Henríquez, F. Zamorano, P. Rothhammer, F. Daiber, and F. Aboitiz	
15 The Aberrant Connectivity Hypothesis in Schizophrenia.....	301
P.A. Gaspar, C. Bosman, S. Ruiz, and F. Aboitiz	
Index.....	325

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Introduction

Attention is a key psychological construct in the understanding of human cognition, and the target of enormous efforts to elucidate its physiological mechanisms, as the wealth of literature—both primary and secondary—attests (for recent compilations see Itti, Rees, & Tsotsos, 2005; Paletta & Rome, 2008; Posner, 2004). But in addition to asking what attention actually is, decomposing and analyzing its varieties, or delimiting its neurobiological mechanisms and effects, in this volume we want to explore attention somewhat differently. We believe that a full-fledged theory of attention must consider its workings in the context of motivated, goal-directed, and environmentally constrained organisms.

That attention is related to goal-directed behavior is not news. What the contributions to this volume do suggest, however, is the existence of fundamental links between attention and two key processes that are crucial for *adapted* conduct: goal-directed behavior and cognitive control. Importantly, they show that these relations can be explored at multiple levels, including neurodynamical, neurochemical, evolutionary, and clinical aspects, and that in doing so multiple methodological challenges arise that are worth considering and pursuing. The reader will find here, therefore, a selection of contributions that range from basic mechanisms of attention at the neuronal level to developmental aspects of cognitive control and its impairments. Another trend that will become evident is that, in different ways, the authors stress the need to understand these issues as they unfold in natural behavior (both healthy and pathological), thus arguing for a more ecological approach to these questions.

An interesting dichotomy emerges from the reading of the chapters compiled here. Attention as a complex process seems to stand in the middle of the two somewhat opposing forces mentioned above: motivated, goal-directed behavior and cognitive control. While the former is necessary for the exploration of the world in search for reward, the latter is critical to restrain and tune action so that predicted outcome can be accurately gauged against potential risks. Attention indeed faces both ways: it is endogenously driven and exogenously called upon, and the balance of the two extremes appears crucial for survival. In other words, beneath these three themes—attention, goal-directed behavior, and cognitive control—lies the unifying thread of a precarious but fundamental equilibrium that is characteristic of animal life: the tension between self-motivated behavior and world-constrained opportunities for action. Both extremes are at work in adapted behavior. Importantly, a functional attentional system is critical to ensure that we can navigate an unpredictable world while keeping in accordance with experience-dependent goals, yet allowing for behavioral novelty through spontaneous exploration. As several of the authors show, unbalance in any of these three processes will inevitably lead to departures from what we usually understand as “normal” or “healthy” behavior. Interestingly,

while sometimes this unbalance can be catastrophic, on other occasions it can result in the expression of alternative cognitive strategies that might even have a positive evolutionary value.

These considerations push us to propose the underlying thesis of this book: It is necessary to tackle the study of attention in the ecological context of motivated beings, while taking into consideration, from the very start, the variety of relations and intertwinement that exist with goal-directed behavior and cognitive control. We believe that, far from obscuring the object of study, this strategy holds the potential of making common mechanisms and complementarities appear—or begin to be intuited—for the benefit of a more comprehensive view of cognition. Moreover, we suggest that this can be done with the aid of numerous methodological advances that have been developed in the last few years, some of which are explicitly reviewed by our contributors.

Several concrete lines of inquiry seem to open up from here: It is evident that neurophysiological mechanisms of attention, goal-directed behavior, and cognitive control are not exhausted by “hot spots” of activity in the brain: dynamic neural connectivity, both at the functional and at the effective, anatomical level is critical; neurotransmitter “wet” dynamics are likewise a fundamental biological mechanism that cannot be disregarded; evolutionary and developmental processes are necessary to understand any supposedly stereotyped (mature) form of cognitive activity; clinical investigations of pathological conditions offer a unique window into how different cognitive processes interact and are interdependent or isolatable; finally, the ecological context cannot be sacrificed for the alleged benefit of analytical clarity because it obscures the way any given process is related to actual—adapted, flexible—behavior.

In the following paragraphs we provide a brief synopsis of the different contributions to this volume. We hope the reader will enjoy the diversity of approaches presented here; we invite him or her to look for the many (not so) hidden connections that have the potential of priming novel perspectives and empirical approaches to these rather fundamental issues of human cognition.

Attentional Networks: Basic Mechanisms and Methodological Issues

Conrado Bosman and *Thilo Womelsdorf* (Chap. 1) open this book with an in-depth analysis of how two basic mechanisms of attentional modulation of sensory response can proceed: selective gain of sensory spiking and selective synchronization within local neuronal groups. Bosman and Womelsdorf, however, transcend the traditional opposition that has been established between these two candidate mechanisms. They show how both can act in concert and in complement to bring about what they consider the ultimate consequence of attentional modulation: the selective gain control that underlies enhanced sensory representations. In this context, Bosman and Womelsdorf discuss three main themes: the importance of oscillatory

activity and how phase relations between active neuronal groups are crucial for selection through rhythmic behavior; the relation between bottom-up and top-down mechanisms and how these might proceed through different frequency bands (especially in the gamma and beta range); and, finally, the importance of inhibitory networks for the establishment of gamma-band oscillatory activity and their role in bringing about effective gain modulation.

Jean-Philippe Lachaux and *Tomás Ossandón* (Chap. 2) present a review of one of the most rapidly growing domains of inquiry into the brain mechanisms underlying cognition in general and attention in particular: intracortical recordings in humans. They highlight the relevance it has had to demonstrate actual cortical oscillatory activity in the gamma band and precise synchronization among distant populations in the human brain. This chapter converges and agrees with several conclusions that Bosman and Womelsdorf put forth, such as the importance of the gamma band in selective attention. However, the approach here is different, with stress on the functional role synchronization might have in selective attention, as well as the methodological challenges that imply dealing with this question in human beings at the mesoscopic level. Lachaux and Ossandón present several examples in visual perception, attention to reading and to memory that show complex intracortical responses in the gamma band. Interestingly, they discuss the functional importance of the dynamic balance between synchronization and desynchronization in this frequency band. Finally they present the dynamical spectral imaging approach developed by their group, whereby ongoing spectral decompositions of actual brain signals can be obtained during attentional, or other, cognitive tasks.

Steven Luck (Chap. 3) proposes a highly original perspective in his chapter on the spatiotemporal dynamics of visual–spatial attention. He discusses the importance of understanding how attentional mechanisms are at play during actual fixation, a much neglected aspect in the study of attention at work in natural conditions (see also Chap. 4 by Maldonado et al.). Luck describes in detail the relation and dynamic interplay between covert attention and eye movements. In contrast to the traditional approach of studying covert attention by isolating it from the act of fixating, Luck argues that such shifts to peripheral regions of visual space and eye movements are intertwined at least on two functionally relevant levels: covert shifts of attention facilitate the ulterior foveation of regions that are likely to be relevant sources of information; consequently, covert attention is then critical to adjust dynamically around the foveated target so that distracting objects get effectively filtered out. The author highlights in his review the necessity to consider visual attention in a more ecological setting, yet shows how this is possible without losing the analytical detail that traditional approaches have provided.

Pedro Maldonado et al. (Chap. 4) tackle a complex issue in their contribution: the problem of natural vision. They challenge the classical receptive field notion by showing the importance of contextual, dynamical modulation in goal-directed behavior that dominates when animals find themselves in natural complex settings. Through a detailed analysis of the structure of natural images and the related neuronal responses, they argue that traditional receptive field explanations cannot

account for the response of visual neurons in these conditions. Consequently, Maldonado et al. stress the notion of “active vision” where goal-oriented behavior and environmental relevance meet, therefore questioning the traditional top-down/bottom-up divide. In this context they argue for the need for an ecological approach to the study of attention, where the natural exploratory behavior of the organism is taken into account from the beginning.

In line with the call for a consideration of the more ecological aspects of attention, *Diego Cosmelli* (Chap. 5) undertakes a quite neglected theme in cognitive neuroscience: the ongoing stream of conscious experience. Cosmelli argues that a full-fledged theory of attention will have to consider attentional shifts as they take place during mind-wandering, internal discourse, and in general the restless movement of our focus of interest which characterizes our intimate daily experience. Drawing from the phenomenological tradition, he proposes that in addition to the traditional endogenous-voluntary/exogenous-reflexive distinction, the spontaneous nature of attentional shifts be considered a type in its own right – and studied accordingly. Cosmelli suggests starting from the foundations provided by traditional experimental psychology paradigms that target aspects such as vigilance changes and the process of attentional orienting. He then explores the recent reappraisal of stimulus-independent cognition and the default mode of brain function, and the opportunity these developments represent for a concerted approach to studying the workings of attention in the stream of consciousness.

In their chapter, *Rodrigo Ortega* and *Vladimir López* (Chap. 6) survey mechanisms of cross-modal integration and attention. This process is crucial for associating predicting stimuli or behavioral actions with outcomes, something on which our everyday behavior strongly relies. Contrary to early concepts of modular sensory processing, recent evidence using event-related potentials strongly indicates that stimuli presented in one modality may influence processing in other modalities. This mechanism may be crucial for establishing associations between different conditioned and unconditioned stimuli in everyday behavior.

Considering the conflicting findings of electrophysiological studies in brain lateralization, *Andrew Hill* et al. (Chap. 7) describe an experiment in which subjects are trained with an EEG biofeedback protocol, with electrodes located either at lateralized or at midline sites in the scalp. Subjects were assessed for attentional skills using the Lateralized Attentional Network Test, before and after the training procedure. They found that training with left-hemisphere electrodes improved attention in the right hemisphere and, vice versa, training in the right hemisphere improved attention in the left hemisphere. This suggests the existence of a contralaterally organized meta-cognitive control system. This work indicates that besides being lateralized, attentional networks are strongly dependent on behavior and on the valuation of behavioral outcomes.

In one of the most methodologically inclined chapters of this book, *Olivier David* (Chap. 8) presents the dynamic causal modeling framework and how it can be highly beneficial for the study of attentional networks. As David shows, this approach to brain imaging is founded on explicit prior probability distributions regarding brain function that take into consideration biophysical constraints. As

David suggests this hypothesis-driven approach allows for testing the validity of different neuropsychological models of attention through the study of event-related activity. This allows one to evaluate effective connectivity during cognitive paradigms, therefore producing a network picture that is beyond classical inverse-problem approaches. After introducing the basic mathematical concepts, David presents two examples from his own work to illustrate the framework: an emotional attention paradigm and a classic auditory oddball.

From Attention to Behavioral Control

In his contribution, *José Hurtado* (Chap. 9) deals with the contrast between goal-oriented and routine behaviors. He reviews the structural basis for a fronto-supervisory/posterior-sensorimotor dichotomy and how this might relate to the way executive attention comes into play when novel behavior must be deployed. Hurtado discusses two related concepts. Drawing from the representational properties of sensorimotor neuronal assemblies, he shows how intracortical high-order assemblies can act as “pointers” on low-level sensory assemblies to bias routine behavior. On the other hand, he presents the “scaffolding hypothesis,” whereby the frontal system can match actions and their outcomes – and therefore their putative reward value – for the system. This is a clear instance of the frontoposterior dichotomy that implies a large network through which frontal (supervisory) systems recruit sensorimotor (procedural) ensembles to enact behavioral novelty. In turn, the sensorimotor–basal ganglia loop can stabilize behavioral sequences that are good predictors of reward through modulation of the corticothalamic system.

Francisco Aboitiz (Chaps. 10, 11) reviews the dopaminergic mechanisms of behavioral control and cognitive function. Dopamine regulates behavior and cognition at multiple levels, from behavioral activation, stimulus reward associations, and reward predictions to modulation of attentional mechanisms, working memory, and in general executive function. Aboitiz proposes an evolutionary framework to unify this complex signaling mechanism, which started from a simple system to invigorate behavior and acquired more complex functions as the capacity to associate predicting stimuli to reward or punishment became increasingly sophisticated, and predicting stimuli became increasingly separated in time and space from outcomes. In this context, cognitive and attentional function can be seen as subsidiary mechanisms of the elaboration and increasing complexity of goal-directed behavior.

Clinical and Developmental Issues

Andrea Slachevsky et al. (Chap. 12) review the neuroanatomy and functions of the human frontal lobe, mainly on the basis of analyses of brain-damaged patients. They highlight the mosaic nature of frontal lobe architecture, which corresponds to

specific behavioral and cognitive subprocesses, in the final instance all related to behavioral control. Thus, frontal lobe function is far from being a strictly unitary process, but rather corresponds to a complex set of functions that concur to generate appropriate behavior according to contextual information, and allows the individual to modify behavior to obtain reward when it is not directly accessible.

Beatriz Luna (Chap. 13) describes brain maturation mechanisms during adolescence, placing strong emphasis on cognitive mechanisms of behavioral control that are proposed to be refined via myelination and synaptic pruning mechanisms. Cognitive development studies indicate that adolescence is characterized by improvements in existing abilities, including the speed and capacity of information processing, and in the ability to have consistent cognitive control of behavior. Temporoparietal association and prefrontal cortices, involved in sensorimotor integration mechanisms and crucial for control mechanisms, mature during this important period.

Ximena Carrasco et al. (Chap. 14) discuss the evidence for electrophysiological and genetic alterations in attention deficit–hyperactivity disorder (ADHD), and the emergent trend to assess genetically based variability in neurodynamical patterns using ADHD as a model. These authors pose the questions of whether ADHD reflects a variant within the spectrum of phenotypic variability more than a specific morbid condition, and that perhaps more than an attention deficit condition, ADHD relates to suboptimal function of behavioral control mechanisms.

Pablo Gaspar et al. (Chap. 15) analyze the operation of cognitive networks in schizophrenia. A current interpretation of the schizophrenic condition is that it reflects a disconnection pattern in neural networks involved in cognitive and emotional processes. Gaspar et al. expand this idea to the concept of “aberrant connectivity,” highlighting imaging evidence that indicates that, in addition to decreased functional connectivity in some functions, there may be domains of abnormally increased connectivity. Overall, this evidence points to a generalized dysfunction in the mechanisms linking sensory stimuli, behavioral mechanisms, and valuation of behavioral outcomes.

References

- Itti, L., Rees, G., & Tsotsos, J. (2005). *Neurobiology of attention*: Elsevier.
- Paletta, L., & Rome (Eds.). (2008). *Attention in Cognitive Systems. Theories and Systems from an Interdisciplinary Viewpoint: 4th International Workshop on Attention in Cognitive Systems, WAPCV 2007 Hyderabad, India, January 2007, Revised Selected Papers*: Springer.
- Posner, M. I. (Ed.). (2004). *Cognitive Neuroscience of Attention*. New York: The Guilford Press.

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Part I
Attentional Networks: Basic Mechanisms
and Methodological Issues

Chapter 1

Neuronal Signatures of Selective Attention – Synchronization and Gain Modulation as Mechanisms for Selective Sensory Information Processing

C. Bosman and T. Womelsdorf

Abstract Voluntary attention selectively enhances the influence of neuronal responses conveying information about relevant sensory attributes. This attentional modulation of sensory responses reflects selective gain changes of sensory spiking response and is accompanied by selective synchronization of those neuronal responses within a local neuronal group which convey information about the attended visual input. While these empirical signatures of selective attention in visual cortex are derived from different levels of analysis (single neurons vs. neuronal groups), they provide complementary insights into the selective modulation of sensory processing in the brain: neurons which are tuned to the spatial and featural attributes of the attended sensory inputs are those which most strongly synchronize within a local neuronal group, while likewise showing the strongest gain change of their spiking response. Both of these neuronal consequences of attention enhance the signal-to-noise ratio for the attended information, but their different roles for selective neuronal processing have not been reconciled. Here, we propose that rhythmic synchronization is the key mechanism underlying the selective gain control within sensory cortex during attentional processing. We derive this hypothesis from computational studies and from insights into the physiological mechanisms that impose synchronized oscillatory activity within neuronal groups. In summary, voluntary attention appears to recruit rhythmic neuronal activity to establish a selective gain pattern within visual cortex to ultimately enhance the representation of the attended sensory information.

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Introduction

Voluntary “top-down” attention is the key mechanism to select relevant subsets of sensory information among the multitude of environmental inputs that our sensors receive at any moment in time. Attentional selection ensures that our brain’s limited processing resources are focused on behaviorally relevant input, while irrelevant and distracting sensory information is suppressed. The functional consequences of such prioritization of relevant inputs are manifold: Attended sensory information is processed more rapidly and accurately and with higher spatial resolution and sensitivity for fine changes, while nonattended information appears lower in contrast and is sometimes not perceived at all (Carrasco, Ling, & Read, 2004; Simons & Rensink, 2005).

These behavioral consequences of selective attention originate in highly selective changes of neuronal activity that evolve rapidly and span all levels of cortical information processing, from single neurons to local groups of neurons and integrated network interactions among distant neuronal groups. The dynamic restructuring of neuronal activity during selective attentional processing may be best illustrated by briefly surveying the response modulations as they evolve during typical attentional paradigms: These tasks typically begin with an instructional cue at the start of a trial or block of trials. The cue informs the subject about which stimulus attribute and/or motor output is behaviorally relevant and thus triggers voluntary attention to covertly shift toward the respective information. A critical prerequisite for attentional paradigms is that there are always alternative stimuli available within a trial, but that attention is covertly directed to only subsets of these stimuli.

On the basis of variants of this task design, neurons in various areas have been shown to change their firing pattern with a short delay following the cue. The top-down information about the behaviorally relevant visual field location can be read out as soon as 150 ms following cue onset from response changes of neurons in prefrontal cortex, the frontal eye field, intraparietal sulcus, and the superior colliculus (Buschman & Miller, 2007; Everling, Tinsley, Gaffan, & Duncan, 2002; Gottlieb, Kusunoki, & Goldberg, 1998; Ignashchenkova, Dicke, Haarmer, & Thier, 2004; Inoue & Mikami, 2007; McPeck & Keller, 2004; Muller, Philiastides, & Newsome, 2005; Thompson, Biscoe, & Sato, 2005; Tomita, Ohbayashi, Nakahara, Hasegawa, & Miyashita, 1999). Thus, top-down information is available in the response patterns in a distributed neuronal circuitry. These top-down signals have been shown to directly influence downstream neurons in sensory cortices (Armstrong & Moore, 2007; Johnston, Levin, Koval, & Everling, 2007; Miller & D’Esposito, 2005). The top-down influence is thereby highly selective in enhancing and suppressing response strength and response synchronization of neurons activated by the attended stimulus (Gilbert & Sigman, 2007; Maunsell & Treue, 2006; Reynolds & Chelazzi, 2004; Womelsdorf & Fries, 2007). For example, the dynamical interplay of top-down information and attentional response modulation can be seen already in the earliest visual cortical processing stages (Khayat, Spekreijse, & Roelfsema, 2006), revealing an early attentional routing of sensory information transfer.

Dynamic top-down control of neuronal responsiveness in sensory areas is at the heart of attentional processing (Fries, Nikolic, & Singer, 2007; Gilbert & Sigman, 2007). It essentially shows that selective processing is accomplished by flexible changes of the interaction pattern among neurons conveying top-down information and neurons controlling behavioral and processing sensory inputs: Attention determines which of the anatomically possible connections are made efficient, while neuronal connections conveying irrelevant information are rendered ineffective. Although the mechanisms underlying selective changes in effective neuronal communication across cortical areas are of critical importance for attentional processing, only a few studies have investigated them directly (Buschman & Miller, 2007; Saalman, Pigarev, & Vidyasagar, 2007; Womelsdorf et al., 2007). These studies generally point toward a critical role of rhythmic synchronization of neuronal responses to sharpen and stabilize communication between those neuronal groups processing relevant information. However, in contrast to the analysis of neuronal interactions, the most detailed characteristics of attentional modulation has been gathered on the basis of analysis of single neuron responses in isolated areas (Reynolds & Chelazzi, 2004; Treue, 2001). One major insight following these studies is that top-down information is imposing a highly selective gain change on neuronal responses in sensory cortices. Attentional gain enhances the responses of neurons, which convey information about the attended stimulus feature, and suppresses the influence of neurons tuned to stimulus attributes opposite to those of the attended feature, with negligible effects on neurons not tuned to the attended attribute (Martinez Trujillo & Treue, 2004; Treue & Martinez Trujillo, 1999).

This brief overview illustrates that there are two basic attentional signatures which evolve from different levels of analysis: Attentional response modulation of single neurons is best described as gain change, while attentional effects at the level of neuronal groups and interactions among them appear to critically rely on mechanisms of selective synchronization. In the following we will argue that results from both levels of analysis provide a common window on basic properties of neuronal circuitry. Consideration of recent empirical and theoretical insights about the physiological origins and functional relevance of rhythmic synchronization within neuronal circuitry, strongly suggests that mechanisms underlying selective response synchronization are likely the key to understanding selective sensory processing (Fries, 2005; Womelsdorf & Fries, 2007).

Principle Characteristics of Synchronization Relevant for Selective Attention

The last paragraph conclusion is inferred from various recent findings demonstrating the functional relevance of rhythmic synchronization and basic neuronal and network properties, which render rhythmic activity particularly suited to rapidly establish and sustain selective patterns of neuronal synchronization. Among these

core findings are five main aspects, which will be briefly listed discussed and followed up in the subsequent sections of this review:

1. Firstly, synchronization of neuronal responses in various cortical regions has been shown to convey stimulus-specific information. In other words, the degree of synchronization within a local neuronal group is tuned to particular stimulus parameters so that changes in the strength of synchronization convey information about the relative weighting of these input parameters to upstream neurons. The degree of synchronization not only follows basic input properties such as stimulus contrast or coherence of motion signals (Henrie & Shapley, 2005; Lee, Simpson, Logothetis, & Rainer, 2005; Siegel, Donner, Oostenveld, Fries, & Engel, 2006), but is likewise tuned to stimulus orientation and spatial frequency (Frien, Eckhorn, Bauer, Woelbern, & Gabriel, 2000; Gray & Singer, 1989; Kayser & Konig, 2004; Kreiter & Singer, 1996; Siegel & Konig, 2003), the speed and direction of visual motion (Liu & Newsome, 2006), the spatial motor intentions and movement directions (Scherberger & Andersen, 2007; Scherberger, Jarvis, & Andersen, 2005), and objects defined by complex feature combinations (Kraskov, Quiroga, Reddy, Fried, & Koch, 2007; Kreiman et al., 2006).
2. Secondly, synchronization is modulated by selective attention (Womelsdorf & Fries, 2007). In particular, attending to one of two visual stimuli or to searching for particular stimulus features within the visual field induces selective synchronization among those neurons activated by the attended stimulus feature (Bichot, Rossi, & Desimone, 2005; Buschman & Miller, 2007; Fries, Reynolds, Rorie, & Desimone, 2001). The strength of synchronization thereby allows one to predict how efficient the attended stimulus is processed and how it is related to the perceptual accuracy during a shape discrimination task (Taylor, Mandon, Freiwald, & Kreiter, 2005; Womelsdorf, Fries, Mitra, & Desimone, 2006). Thus, synchronization carries information about which spatial location or stimulus feature is behaviorally relevant.
3. Thirdly, synchronization of neuronal inputs is a powerful mean to increase the response gain of the postsynaptic, “receiving” target neurons and could thus underlie the gain modulation during selective attentional processing (Fellous, Rudolph, Destexhe, & Sejnowski, 2003; Salinas & Sejnowski, 2001; Tiesinga, 2005). In particular, already moderate amounts of input synchronization can change the spiking response of a neuron manifold and enhance neuronal excitability. Notably, increases in the average input rate alone and in the absence of synchronization do not automatically increase response strength due to active synaptic mechanisms such as synaptic depression, which can actually lead to enhanced spiking thresholds and thus decreased spiking output of neurons (Tsodyks & Markram, 1997; Wespataat, Tennykeit, & Singer, 2004). Moreover, enhanced spiking probability is promoted by rhythmic fluctuations at the postsynaptic membrane, with enhanced excitability periods corresponding to periods of maximum depolarization. Taken together, the described impact of synchronous inputs and the neuronal preference to generate spikes at time windows, or particular phases, of the rhythmic membrane fluctuations complements each other. They provide powerful mechanisms to control neuronal sensitivity and

responsiveness and could thus underlie selective gain modulation during attentional processing.

4. The fourth key feature of neuronal synchronization pertains to its spatial and temporal selectivity. How are the subsets of neuronal connections that convey information about attended information made more effective, while connections conveying irrelevant information are rendered less effective? Recent empirical and modeling studies suggest that the critical key component for such a selective routing is the control of the phase of rhythmic synchronization of neuronal activity (Buia & Tiesinga, 2006; Fries, 2005; Fries et al., 2007; Mishra, Fellous, & Sejnowski, 2006; Schoffelen, Oostenveld, & Fries, 2005; Womelsdorf et al., 2007). Aligning the phase of rhythmic activity between neuronal groups promotes mutual interactions, because the time windows of excitability overlap. In contrast, neuronal groups that synchronize at random phase or at antiphase are less likely to influence each other. Such phase-dependency of neuronal interactions shows a high spatial and temporal resolution. In a recent study the pattern of neuronal interactions could be predicted by the phase of rhythmic synchronization between groups that were as close as $600\mu\text{m}$ from each other (Womelsdorf et al., 2007). The generality of the mechanism described is highlighted by the fact that the same phase dependency predicted interaction patterns among distant groups of neurons from different cortical areas (Womelsdorf et al., 2007). Thus, rhythmic synchronization can be highly selective in determining the interaction patterns between groups of neurons and spans broad spatial scales. Thus, attentional top-down control could recruit these mechanisms to achieve neuronal coupling that is selective in time and space.
5. The fifth critical aspect of the hypothesized role of selective synchronization for attentional processes is its feasible implementation in neuronal circuitry. Importantly, recent computational studies have reproduced the neurophysiologically observed attentional gain changes on neuronal responses with model architectures, which explicitly acknowledge the complex interplay of inhibitory and excitatory neurons and the synaptic characteristics of spike generation (Bartos, Vida, & Jonas, 2007). Rhythmic synchronization emerges spontaneously in neuronal populations when excitatory drive diverges onto inhibitory interneurons, which then feed back their inhibition onto the excitatory cells. The inhibitory feedback thereby gates the excitatory activity by imposing synchronized inhibition onto their activity (Bartos et al., 2007; Borgers, Epstein, & Kopell, 2005; Whittington, Traub, Kopell, Ermentrout, & Buhl, 2000). Based on variations of this architecture, recent studies succeeded in reproducing the empirically observed attentional effects by inducing small biases of the phase of ongoing inhibitory synchronization (Mishra et al., 2006; Tiesinga, 2005; Tiesinga, Fellous, Salinas, Jose, & Sejnowski, 2004). Modulating the phase and precision of inhibitory synchronization in neuronal networks selectively facilitated the influence of groups of excitatory neurons that convey information about the attended information. Thus, modeling studies demonstrate in detail how (and potentially at which site) attention could act upon neuronal circuitry to rapidly establish, sustain, and switch between selective representations of the behaviorally

relevant information by considering the rich interplay of inhibitory and excitatory neuronal activity.

Taken together, the five aspects of selective synchronization described suggest that it is a pivotal mechanism that is invoked during selective attentional processing. The following sections will survey empirical evidence supporting this conclusion. We will begin by reviewing recent insights of attentional modulation within local neuronal groups and between groups of neurons from distant cortical areas. Later sections will outline in more detail the role of inhibitory circuitry in imposing gain changes in cortical neurons and groups of neurons.

Attention Affects Neurons Tuned Toward the Attended Stimulus Attribute

Top-down attention modulates the responses of neurons in all sensory areas studied so far (Maunsell & Cook, 2002). Studies from the past two decades have revealed various key characteristics of this selective response modulation. First, response modulation can proceed not only on spatially selected information (spatial attention), but can likewise be based on information of behaviorally relevant features (e.g., motion vs. color), and on parameters within a particular feature space (e.g., upward vs. downward motion directions, or red vs. green color) (Maunsell & Treue, 2006; Reynolds & Chelazzi, 2004). The general conclusion from studies of space-based and feature-based attention is that attention enhances the responsiveness of those neurons which are tuned for the attended stimulus attribute. This is most convincingly demonstrated for spatial attention, where attention typically enhances response strength and selective synchronization only of those neurons which overlap the spatial focus of attention, i.e., which prefer the spatial attribute of the attended stimulus (Connor, Preddie, Gallant, & Van Essen, 1997; Fries et al., 2001; Taylor et al., 2005; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006; Womelsdorf, Fries et al., 2006). Similar to the spatial domain, attention in “feature space” to the color of a stimulus enhances responses of neurons in color-selective areas, while attention to the motion direction of an otherwise identical stimulus results in the strongest modulation in motion-selective areas, like such as the middle temporal (MT) area in the parietal cortex (Hopf et al., 2006; McMains, Fehd, Emmanouil, & Kastner, 2007; Schoenfeld et al., 2007).

Importantly, within a functionally specialized visual area such as area MT, attentional modulation reveals that attention not only enhances responses, but also suppresses responses of those neurons which are tuned toward features opposite to those of the attended stimulus attribute (Fig. 1.1). This finding has given rise to the feature-similarity gain hypothesis of attention (Treue & Martinez Trujillo, 1999), which holds that top-down information about the behaviorally relevant stimulus attribute imposes a unique gain factor on neuronal responses in sensory cortices. The strength and sign of attentional enhancement/suppression will thereby depend on the overlap of a single neuron’s tuning preferences and the attended feature.

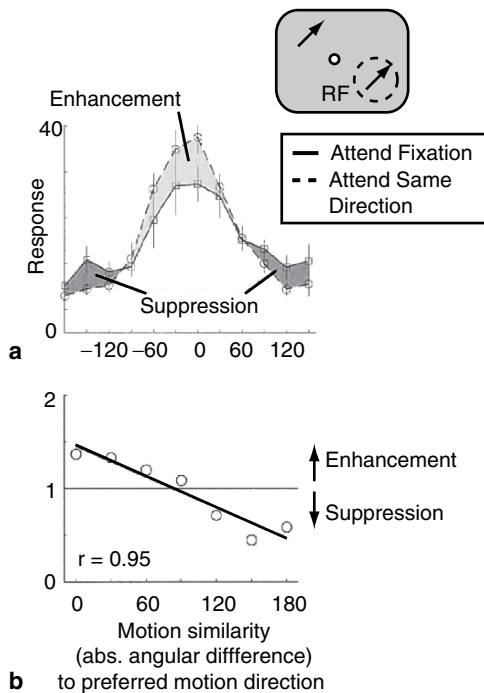


Fig. 1.1 Attention enhances and suppresses neuronal responses depending on the overlap of the attended stimulus feature (here, motion direction) and the tuning preference of single neurons in macaque middle temporal (MT) area. **(a)** The relation of average neuronal firing rate (y-axis) of a neuron to stimuli of different directions of motion (x-axis, arrows in the inset illustrate stimulus locations). The solid line shows the tuning curve of the neuron when the monkey attended the fixation spot (the white circle in the inset). The dashed line shows the response to identical motion stimuli within the neuronal receptive field (RF) when the monkey attended a second motion stimulus in the hemifield opposite the RF. The two stimuli (within and outside the RF) always moved in the same direction. The graph illustrates that attending to the preferred motion direction (here, 0°) enhances neuronal responses, while attending to antipreferred motion directions (here, 180°) suppresses the response. **(b)** Average result across the population of area MT neurons illustrating that the attentional effect (y-axis) varies as a function of the similarity of the attended motion direction with the feature preference of the neurons. (Adapted from Martinez-Trujillo & Treue 2004)

Recent evidence has demonstrated that the feature-similarity rule cannot only be traced back to firing rates, but is likewise evident in changes of response synchronization (Bichot et al., 2005). Attention to a particular feature selectively synchronized the responses of those sensory neurons which are tuned to the attended feature. To show this Bichot et al. (2005), recorded neuronal spiking responses and local field potentials (LFPs) in macaque visual area V4 while monkeys searched in multistimulus displays for a target stimulus defined either by color, shape, or both. When monkeys searched, e.g., for a red stimulus by shifting their gaze across stimuli on the display, the receptive fields of the recorded neurons could either encompass

nontarget stimuli (e.g., of blue color), or the (red) target stimulus prior to the time when the monkey detected the target. The authors found that neurons synchronized to the LFP more strongly in response to their preferred stimulus feature when it was the attended search target feature rather than a distracter feature. Notably, the observed modulation depended on the overlap of feature preference and attended feature and was independent of the spatial location of attention. This feature-based modulation was also evident during a conjunction search task involving targets which were defined by two features: When monkeys searched for a target stimulus with a particular orientation and color (e.g., a red horizontal bar), neurons with tuning preference to one of these features synchronized their responses more strongly (Bichot et al., 2005). This enhancement was observed not only in response to the color-shape-defined conjunction target, but also in response to distracters sharing one feature with the target (e.g., red color). This finding is not only capable of explaining the increased difficulty and search times during conjunction versus simple search tasks. It also suggests that attention modulates neuronal synchronization in visual cortex gradually, and not according to a strict all-or-nothing principle as a function of the overlap of the neurons' tuning preference and the attended stimulus feature (Womelsdorf & Fries, 2007).

Attention Imposes a Gain Pattern on Sensory Neurons

The effects of attention on neuronal responses described generally reflect a modulation of the input–output relation of neuronal activity, which can be formalized as gain modulation. Existing evidence suggests, that selective attention utilizes a gain control mechanism that (1) enhances neuronal sensitivity to synaptic inputs and (2) can likewise act on the normalization stage of neuronal response functions and thereby reflect response, or output, gain control. These different scenarios emerge from the few studies which have investigated a broad range of input values during selective attention.

The most compelling evidence showing that attention imposes a multiplicative response gain arises from its effects on the tuning functions in extrastriate visual cortex in areas of the ventral, temporal, as well as the dorsal, parietal processing pathway. In particular, multiplicative scaling of tuning functions has been demonstrated for direction of motion in area MT of the macaque monkey, and for orientation tuning curves in area V4 (McAdams & Maunsell, 1999; Treue & Martinez Trujillo, 1999). For example, neurons in area MT respond to stimuli moving in varying directions of motion, with a gradual, bell-shaped response profile peaking at their preferred direction of motion. Attending to that preferred direction of motion outside the receptive field causes the tuning function to be scaled up multiplicatively, while attending to the antipreferred direction of motion causes the tuning function to be scaled down (Martinez Trujillo & Treue, 2004; Treue & Martinez Trujillo, 1999). This finding demonstrates that attention does not sharpen basic feature selectivity at the single-neuron level, i.e., by narrowing the range of motion directions that elicit

responses, but rather by a change in the gain of the neuronal response. Importantly though, the multiplicative gain modulation of single-neuron responses translates into strongly enhanced feature selectivity of the population response of modulated neurons in area MT: Neurons with a tuning preference close to the attended direction of motion enhance their contribution to the population response profile, while neurons with preferences away from the attended feature reduce their contribution (Martinez Trujillo & Treue, 2004)

In addition to multiplicative gain modulation of featural input to a cortical neuron, attention interacts with other input, or bottom-up, aspects of visual stimuli. In particular, attention has been demonstrated to interact with the luminance contrast of the attended stimulus to effectively increase the effective contrast of the attended stimuli (Martinez Trujillo & Treue, 2002; Reynolds, Pasternak, & Desimone, 2000; Williford & Maunsell, 2006). Visual cortical neurons typically respond to stimuli of increasing contrast with a sigmoidal contrast-response function. Attention modulates this input–output function of cortical neurons by changing the gain of the input in various ways. Early studies suggested that attention modulated particularly stimuli of intermediate contrasts (Martinez Trujillo & Treue, 2002; Reynolds et al., 2000), which is evident in a leftward shift of the contrast-response function (“contrast gain”). A more recent study revealed a more complicated gain pattern across neurons, with response modulation of a larger proportion of neurons reflecting a rather constant gain factor modulating responses along the whole contrast-response function (“response gain”), or with an additional general increase of response strength (“activity gain”) (Williford & Maunsell, 2006). Interestingly, a recent attention experiment based on human scalp recordings from visual cortex in response to flickering stimuli likewise suggests that attention boosts the amplitude of the steady-state population response even at highest contrasts and thus reflects response-gain modulation rather than a nonlinear contrast gain control (Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007).

The findings surveyed demonstrate that the firing rate output of single neurons constrains which gain-control mechanism, or combination of mechanisms, provides adequate descriptions of the working principles of attention at that level of processing. The following sections will extend this level to include interactions among groups of neurons, by surveying evidence of selective synchronization during selective attentional processing across cortical areas, before the last sections describe the mechanistic aspects of gain control through rhythmic activity in inhibitory networks.

Attention Invokes Selective Long-Range Synchronization Between Cortical Areas

The evidence for attentional effects outlined following the feature-similarity principle and acting according to gain-control mechanisms were restricted to neuronal responses to local groups of neurons within functionally specialized sensory cortices. Few studies have gone beyond single-area recordings to reveal a more comprehensive picture

of how gain-modulated neuronal responses at one level of the processing pathways affect and mutually interact with neuronal groups in other areas, which are likewise known to be attentionally modulated. Importantly, as insinuated in the “Introduction,” selective interareal communication is the major characteristic of selective attention. Top-down information from higher-order frontal and parietal areas impinges on sensory cortex recruiting selective subsets of neuronal groups in distributed, functionally specialized visual areas. Similarly, distributed neuronal groups in sensory cortices need to be functionally linked according to the behavioral demands. Recent studies have begun to provide critical evidence that such a dynamic interareal communication between neuronal groups is likely mechanistically subserved by selective phase synchronization (Womelsdorf et al., 2007). In particular, neuronal groups were shown to strongly interact at those time periods when they precisely synchronized their rhythmic activity. At the same time, epoch interactions were reduced, or rendered negligible to neuronal groups, which were active at random phases or out of phase (Fig. 1.2a). These findings strongly support the notion that selective neuronal communication is critically promoted by selective synchronization (Fries, 2005). Selective synchronization could therefore be utilized by attention to dynamically link subsets of distributed neuronal groups conveying behaviorally relevant information (Womelsdorf & Fries, 2007).

Existing evidence supports this proposed role for selective long-range synchronization during attentional processing (Buschman & Miller, 2007; Saalmann et al., 2007; Schoffelen et al., 2005). Knowledge from earlier studies of awake cats demonstrated that nonselective states of expectancy of a behaviorally relevant stimulus (in, e.g., “go/no-go tasks”) increase interareal beta-frequency synchronization among visual cortical and premotor regions (Roelfsema, Engel, König, & Singer, 1997; von Stein, Chiang, & König, 2000) and between thalamic and early visual cortical regions (Wrobel, Ghazaryan, Bekisz, Bogdan, & Kaminski, 2007).

Recent studies have critically extended these findings by showing that frontoparietal and intraparietal interactions are accompanied by synchronization at high beta frequencies (20–35 Hz) during task epochs requiring searching for and selecting behavioral relevant visual stimuli (Buschman & Miller, 2007; Saalmann et al., 2007). Figure 1.2b illustrates findings from a visual search task requiring monkeys to detect a search target that is salient and pops out among distracting stimuli (“bottom-up search”), or that is nonsalient by sharing features with distracting stimuli (Buschman & Miller, 2007). In contrast to bottom-up salient targets, the nonsalient target stimuli were detected more slowly, indicating that they require attentive search through the stimuli in the display before they are successfully detected (“top-down search”). Paralleling the difference in behavioral demands, the authors found a selective synchronization pattern among the LFPs in frontal and parietal cortex. While attentive “top-down search” enhanced specifically rhythmic synchronization at 20–35 Hz compared with the “bottom-up” search, the stimulus-driven “bottom-up” search enhanced interareal synchronization at higher frequencies (Fig. 1.2b). The pattern of results is

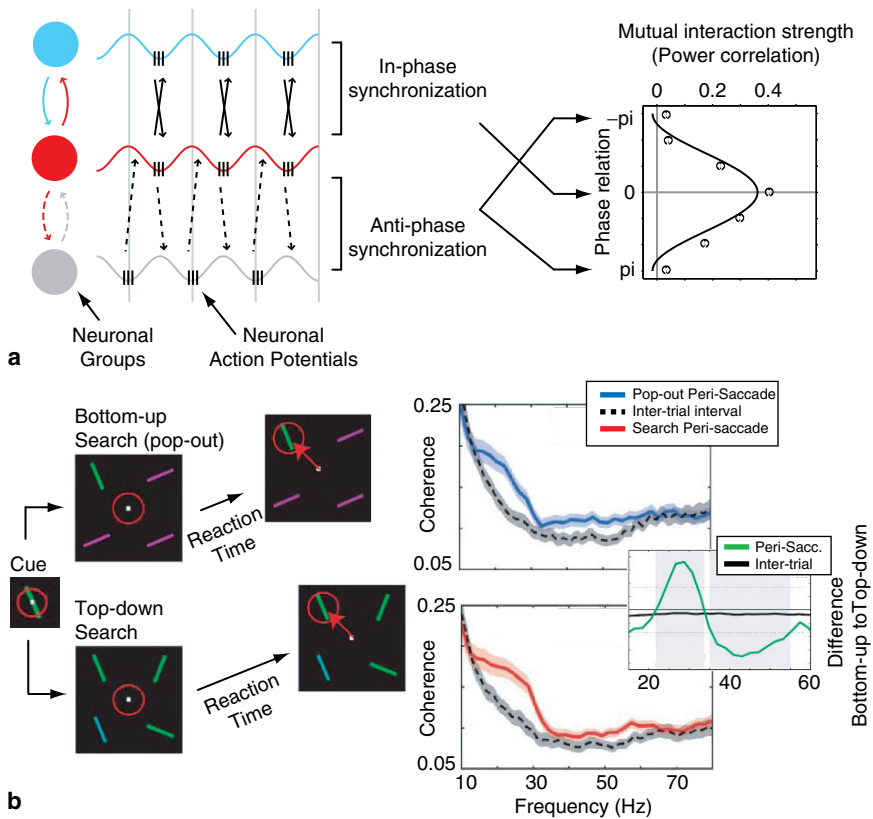


Fig. 1.2 Precise synchronization of rhythmic activities between neuronal groups determines the strength of their mutual interactions and is modulated by attention. **(a)** Rhythmic activity (local field potential oscillations with spikes at the troughs) of three neuronal groups (*circles*). Time windows of maximum excitability are either aligned in-phase (red and blue group) or are not aligned (red and grey group, here illustrated as groups with antiphase synchronization). The plot on the *right* shows increasing mutual interactions (*upper axis*, correlation of the power of the local field potential and the spiking response of the neuronal groups) during a period of in-phase synchronization and lower ones otherwise. **(b)** *Left panels* sketch the visual search tasks used by Buschman & Miller (2007). A cue instructed monkeys about the orientation and color of a bar that was the later search target in a multistimulus display during a bottom-up search task (both target color and orientation were unique) and during a top-down search task (target shared color or orientation with distracting stimuli). Monkeys covertly attended the multistimulus array and made a saccade to the target stimulus position as soon as they found it. The authors measured the coherence of the local field potential activity of neuronal groups in frontal cortex and the lateral intraparietal area. The line plots on the *right* show the coherence (*y-axis*) for different frequency bands (*x-axis*) in the bottom-up and top-down tasks, along with the coherence difference across tasks (*green line in inset*). The results show that attentional demand modulated long-range coherence at different frequency bands (relative to an intertrial baseline epoch) among the distant cortical sites. **((a)** Adapted from Womelsdorf et al., 2007. **(b)** Adapted from Buschman & Miller, 2007)

most likely due to differences in task demands in both search modes and was unaffected by differences in reaction times, suggesting that interareal communication during top-down attentional control and bottom-up feedforward signaling is conveyed through rhythmic synchronization at different frequencies.

Importantly, the neurophysiological evidence surveyed on interareal synchronization during selective sensory processing is paralleled by a variety of human EEG and MEG studies, demonstrating a modulation of beta- and gamma-frequency oscillations and phase synchronization during tasks requiring selective attention, working memory, and speeded reaction times (Aboitiz, Lopez, & Montiel, 2003; Engel, Fries, & Singer, 2001; Jensen, Kaiser, & Lachaux, 2007; Varela, Lachaux, Rodriguez, & Martinerie, 2001; Womelsdorf & Fries, 2007). In this context, gamma-band synchronization appears to be mechanistically relevant to modulate visual cortex activity during visual attention. This modulation has relevant behavioral consequences. Thus, the understanding of the emergence of gamma-band phase synchronization within and across neuronal groups and its putative relation with changes in the gain of local circuits of neurons could provide insights into the mechanisms underlying selective attentional modulation in visual cortex. The following section will focus on these mechanisms that allow neuronal groups to rhythmically synchronize their activity. In that sense, it has been well studied that inhibitory interneuron networks have a prominent role in the generation of gamma oscillations, imposing a transient and recurrent inhibition to the excitatory drive of principal cells (Bartos et al., 2007; Jefferys, Traub, & Whittington, 1996). The next section will describe several models that can reproduce the observed changes in neuronal gain during visual attention, based on the dynamic interaction of inhibitory and excitatory neurons, by inducing small biases of the phase of ongoing inhibitory synchronization that restructures the balance of excitatory and inhibitory network interactions (Borgers et al., 2005; Mishra et al., 2006; Tiesinga et al., 2004; Tiesinga & Sejnowski, 2004).

Mechanisms of Attention

Selective Synchronization Via Inhibitory Networks

Oscillatory synchronization at gamma-band frequencies (30–90 Hz) appears to be a ubiquitous phenomenon; however, there is no single mechanism that accounts for the emergence of neuronal gamma-synchronized oscillations. At least two mechanisms have been suggested: (1) the spiking activity of fast rhythmic bursting (FRB) cells (also called “chattering cells”), which have been found mainly in neocortical regions, and (2) the activity of inhibitory interneurons, whose impact on network rhythms has been largely studied in hippocampal slices. We will briefly refer to both mechanisms.

FRB neurons comprise a unique class of cortical neurons that, during depolarization, intrinsically generate bursts of high-frequency action potentials (350–700 Hz),

with interburst frequencies in the gamma-band range (Gray & McCormick, 1996; Nowak, Azouz, Sanchez-Vives, Gray, & McCormick, 2003). This type of cell has been described in visual cortex (Gray & McCormick, 1996), but also in sensory-motor and association cortices (Steriade, Timofeev, Durmuller, & Grenier, 1998). Early work by Gray and McCormick (1996) found stimulus-evoked gamma-frequency burst generated by FRB cells in the cat visual cortex. On the basis of these findings, Gray and McCormick (1996) have postulated that FRB cells acts as pacemakers, imposing a particular LFP modulation in the range of the gamma-band frequency on neighboring pyramidal cells. Anatomically, FRB has been found in intermediate layers of the neocortex (2/3 layer) (Gray & McCormick, 1996), but also in layer 5 or layer 6 (Steriade et al., 1998). Layer 6 receives strong input connections from the thalamus. In addition, FRB cells present profuse axonal projections to different types of neurons, including other FRB cells (Cunningham et al., 2004; Gray & McCormick, 1996; Steriade et al., 1998). Both findings strongly suggest that FRB cells may contact many postsynaptic targets, thus amplifying and distributing inputs from thalamic regions (Cardin, Palmer, & Contreras, 2005). On the basis of these findings, it has been suggested that FRB cells, rather than functioning as pacemakers of gamma-frequency oscillations, could act as a part of a corticothalamic network that on one hand facilitates the generation of corticothalamocortical oscillatory loops (Cardin et al., 2005; Castelo-Branco, Neuenschwander, & Singer, 1998), and also distributes rhythmic gamma-band activity (possibly generated by inhibitory interneuron networks) to the other types of neurons in the neocortex (Cunningham et al., 2004; Takekawa, Aoyagi, & Fukai, 2007).

In addition to FRB-cell-mediated gamma-band oscillation, inhibitory interneurons have been implicated in generating and sustaining robust neuronal oscillatory activity. Inhibitory interneurons are highly heterogeneous, differing in their morphology, expression of molecular markers, anatomical location, and physiological properties (Bartos et al., 2007; Freund & Buzsaki, 1996; McBain & Fisahn, 2001). Interneurons can be broadly classified according to their pattern of spike discharge into fast-spiking (FS) and non-fast-spiking neurons. Basket cells are FS parvalbumin neurons owing to the expression of the calcium binding protein parvalbumin. These cells play an important role in the generation of gamma-band oscillations (Bartos et al., 2007; Galarreta & Hestrin, 2001a; Hajos et al., 2004; Hestrin & Galarreta, 2005; McBain & Fisahn, 2001). FS parvalbumin neurons are abundant in the cortex (approximately 20% of all inhibitory interneurons) (Freund & Buzsaki, 1996). Their particular morphology and extensive dendritic and axonic arborizations reflect an extensive network of mutually connected inhibitory neurons (Buzsaki, Kaila, & Raichle, 2007; McBain & Fisahn, 2001). Importantly, FS neurons target perisomatic region of principal neurons. This inhibition controls the timing of spike discharges of the targeted principal neurons with respect to the rhythm imposed by the inhibitory interneuron network (Buzsaki et al., 2007; Cobb, Buhl, Halasy, Paulsen, & Somogyi, 1995). Similar to what has been proposed for FRB cells, inhibitory interneuron networks could act as pacemakers, imposing a timing signal by successive windows of inhibition over groups of principal neurons which are thereby