

Abnormal Gamma Oscillations in *N*-Methyl-D-Aspartate Receptor Hypofunction Models of Schizophrenia

Monika P. Jadi, M. Margarita Behrens, and Terrence J. Sejnowski

ABSTRACT

N-methyl-D-aspartate receptor (NMDAR) hypofunction in parvalbumin-expressing (PV+) inhibitory neurons (INs) may contribute to symptoms in patients with schizophrenia (SZ). This hypothesis was inspired by studies in humans involving NMDAR antagonists that trigger SZ symptoms. Animal models of SZ using neuropharmacology and genetic knockouts have successfully replicated some of the key observations in human subjects involving alteration of gamma band oscillations (GBO) observed in electroencephalography and magnetoencephalography signals. However, it remains to be seen if NMDAR hypofunction in PV+ neurons is fundamental to the phenotype observed in these models. In this review, we discuss some of the key computational models of GBO and their predictions in the context of NMDAR hypofunction in INs. While PV+ INs have been the main focus of SZ studies in animal models, we also discuss the implications of NMDAR hypofunction in other types of INs using computational models for GBO modulation in the visual cortex.

Keywords: Computational models, Gamma oscillations, Inhibition, NMDA hypofunction, Parvalbumin, Schizophrenia
<http://dx.doi.org/10.1016/j.biopsych.2015.07.005>

Schizophrenia (SZ) is a mental disorder that afflicts about 1% of the population and is manifested as mild or debilitating episodes of hallucinations and delusions and cognitive deficits. Sensory-triggered hallucinations, disordered thoughts, and delusions are termed positive symptoms and respond better to medication. Social withdrawal, lack of motivation and flat expressions form the negative symptoms and respond poorly to medication. Alterations in fundamental brain processes of perception as well as executive function are thought to underlie these outcomes in SZ patients (1,2). Unlike conditions such as Alzheimer's disease (3), schizophrenia does not involve major neuronal degeneration, although subtle deficits in certain neuronal populations have been described (4–6) [but see (7)]. Before clinical assessment, schizophrenia thus remains a difficult to detect and poorly understood brain disorder.

Diagnostically, several functional and behavioral measures using electroencephalography (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging are being developed to identify the SZ population from control subjects. For example, sustained oscillations in these signals, which reflect coordinated activity of neural populations, are identified as an increase in power in a narrow band of frequency and are compared between control and SZ patients in terms of both their strength/amplitude/power and frequency. The narrow band power is compared in various behavioral states: stimulus or task-driven state when the subject is actively processing a stimulus and/or performing a cognitive task and baseline or resting at other times

(Supplement). Since resting state in rodents is ill defined, we refer to both as baseline in the review of animal models. The stimulus/task-driven power is compared both in terms of its evoked component as well as induced (2) (Supplemental Figure S1 and text in the Supplement). This review focuses mainly on observations of induced narrow band power in the gamma range (30–80 Hz), commonly referred to as gamma band oscillations (GBOs); GBOs are of interest because they have been implicated in synchronization of neural ensembles during working memory, feature binding, dynamic routing of information, and attention (8,9). The review first summarizes the observations on GBO abnormalities in patients and the related data in a class of animal models of SZ. It then discusses several computational models of induced GBOs for mechanistic insights. Finally, the review discusses the implications of recent findings about the microstructure of the local cortical inhibitory circuits for the computational models and ultimately the animal models of the disease.

ABNORMAL GBO IN SCHIZOPHRENIA PATIENTS

Abnormalities in the strength of GBO power in EEG and MEG have been consistently observed in studies with SZ patients (2,10). GBO power has been reported to be both higher and lower compared with control subjects, depending on the task and brain state.

Task Dependence

GBOs are reduced in SZ patients during sensory processing and working memory (2,11–14) [but see (15,16)]. In addition, the severity of the positive or negative symptoms covaries with alteration of GBO power: a pattern of enhanced GBOs emerges in patients with more severe positive symptoms (11,15,17,18), but a clear pattern does not emerge in cases where GBOs are reduced in SZ patients (15,16). The differences that are reported are significant for groups but have low predictive power on individuals.

Brain-State Dependence

GBO modification in SZ patients depends on the brain state during which activity is monitored. GBOs are weakened during sensory processing across multiple modalities (12,15,18,19). For the same group of patients, GBO activity was higher than control subjects before presentation of sensory stimulation (20) (Figure 1A) or baseline but lower during sensory processing or stimulus-driven state (17) (Figure 1B). It should be noted that the increase of baseline GBOs was significant only at 40 Hz, the frequency of the steady-state stimulation. In addition, the increase was not significant across all electrodes (Figure 1A). However, others studies have reported a decrease in baseline GBOs (21). Reconciling GBO changes across studies will require separating the effect in stimulus-locked or evoked EEG signal versus induced part of the signal (22). Each component reflects different aspects of information processing in the cortex: evoked GBOs reflect bottom-up sensory transmission, whereas induced GBOs represent the emergent dynamics within cortical networks.

ANIMAL MODELS OF SZ

The development of animal models has been confined to measurable symptoms of the disease such as altered sensory processing, locomotion, and social behavior. These models have explored several hypotheses about deficits in specific neurotransmission systems that could form the basis of the modified neural processing in SZ patients. The dopamine system has been implicated because antipsychotic drugs target mainly dopamine D2 receptors (23,24). However, results have suggested that glutamate might also be involved (25); low doses of ketamine or phencyclidine, antagonists for glutamate receptor *N*-methyl-D-aspartate (NMDA), produce a

syndrome similar to a psychotic episode in healthy humans (26–34). The main mechanism behind the psychotic effects of these antagonists is thought to be the disinhibition of excitatory circuits in the brain (35–37). Postmortem studies in the prefrontal cortex in SZ patients, on the other hand, have shown deficits in the neurotransmitter gamma-aminobutyric acid (GABA) that is released by a majority of inhibitory interneurons (INs) in the brain (1,38–42).

These findings have inspired the hypothesis that disruption of NMDA receptor (NMDAR) neurotransmission in INs leads to abnormalities in the GABA neurotransmission machinery in SZ. Indeed, postmortem evidence in the anterior cingulate cortex suggests that the density of GABAergic INs that express the NMDAR subunit NR2A is decreased in SZ patients in general (43); in particular, the glutamatergic innervation of subsets of GABAergic cells might be differentially altered (44). This has been recently explored in both pharmacologic and genetic animal studies (Supplement). In addition to behavioral performance, changes in GBOs have been observed during baseline and tasks in surface EEG recordings as well as local field potentials (LFP), a surface-localized depth EEG using penetration microelectrodes.

ABNORMAL GBO IN ANIMAL MODELS OF NMDAR HYPOFUNCTION

Abnormal GBOs are observed in pharmacologic as well as genetic NMDAR hypofunction models of SZ (45,46), which are summarized in the following text.

Pharmacologic Models

In vitro, acute treatment with ketamine, a nonspecific NMDAR antagonist, decreases the strength of kainate-induced GBOs in medial entorhinal cortex (47). However, the same treatment increases the kainate-induced GBO in the primary auditory cortex (48). In vivo, chronic treatment with NMDAR antagonists reduces the strength of hippocampal GBO activity (49). However, acute systemic treatment with NMDAR antagonists causes a significant increase in GBO power in the hippocampus and frontal cortex both before and during stimulus processing (49–52). Increase in baseline GBO power in vivo in response to acute treatment with several NMDAR antagonists has been seen in multiple studies in rodents (53–60). Pharmacologic models thus demonstrate a mixed dependence of GBOs on brain state, as well as frequency and duration of

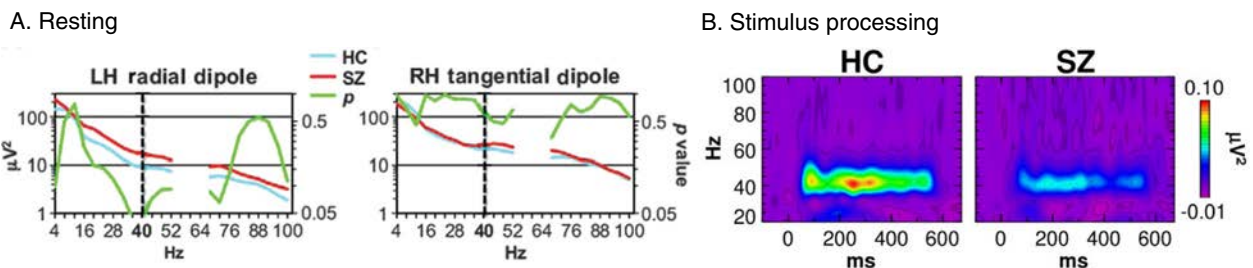


Figure 1. Brain-state dependent modulation of gamma band oscillations in schizophrenia (SZ). Electroencephalography (EEG) signals recorded during resting state (A) and stimulus-processing (B) states in SZ patients and healthy controls (HC). Stimulus-processing state data were recorded during periodic auditory stimulation at 20 Hz. (A) Time-averaged power in different frequency bands in the EEG signal (blue and red). Also shown is the *p* value (green). (B) Power in different frequency bands in the EEG signal as a function of time. LH, left hemisphere; RH, right hemisphere. [Adapted with permission from Spencer *et al.* (17) and Spencer (20).]

drug treatment; the latter requires careful further investigation since differences in this factor can translate to immediate (GABAergic disinhibition) versus long-term (compensatory homeostatic mechanisms) modification of the cortical network with unique downstream effects on GBOs.

Genetic Models

In addition to several SZ-like symptoms, genetic models show abnormalities in GBO power in a brain-state dependent manner (Figure 2). In models involving genetic ablation of NMDARs in parvalbumin-expressing (PV+) INs, increased

GBO power is observed in the baseline LFPs recorded from awake behaving mice in both the neocortex (61) and the hippocampus (62). The increase in power is broadband but is shown to be statistically significant in the gamma range of frequencies. In the same model, stimulus-processing state GBOs induced by optogenetic stimulation have reduced power as compared with control mice (61). In other models involving hypofunction of NMDARs in GABAergic INs that is not restricted to the PV+ and occurs earlier in development, the baseline LFPs also show a broadband increase in power (63). At the same time, the stimulus-processing state GBOs

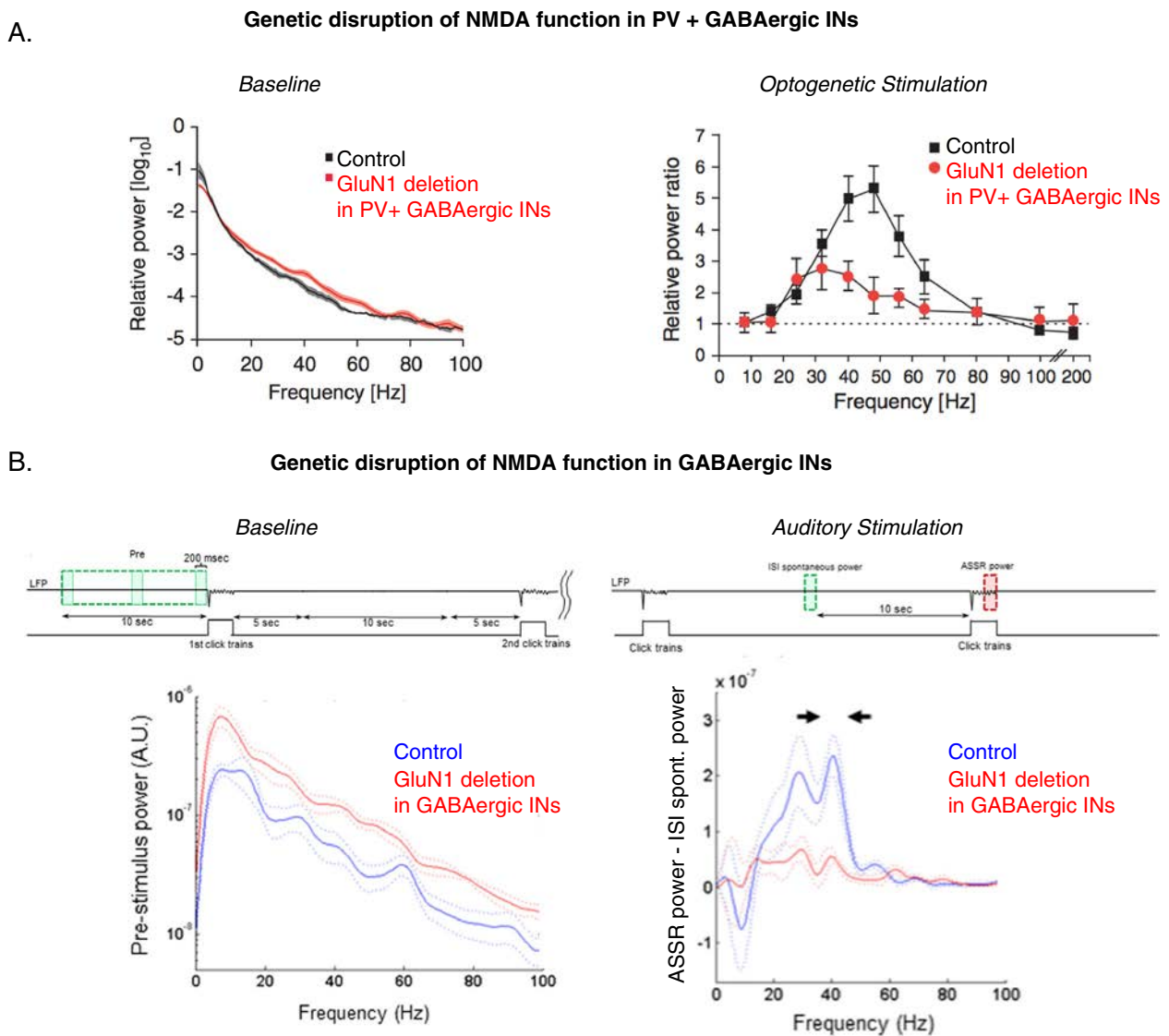


Figure 2. Gamma band oscillation alteration in genetic *N*-methyl-D-aspartate receptor (NMDAR) hypofunction models of schizophrenia. **(A)** Power in different frequency bands in the electroencephalography signal recorded from anesthetized control mice (black) and those with deletion of GluN1 subunit of NMDARs in parvalbumin-expressing (PV+) gamma-aminobutyric acid (GABA)ergic neurons (red). Left: Baseline. Right: Stimulus-processing state. [Adapted with permission from Carlen *et al.* (61).] **(B)** Power difference in different frequency bands in the EEG signal recorded from control mice (blue) and those with deletion of GluN1 subunit of NMDARs targeting all GABAergic neurons (red). Left: Baseline. Right: Stimulus-processing state. [Adapted with permission from Nakao and Nakazawa (63).] ASSR, auditory steady-state response; IN, inhibitory interneuron; ISI, interspike interval; LFP, local field potential.

Table 1. Computational Models of GBO

Model	NO-ING	NO-PING	D-ING	D-PING	ISN-PING	SR-ING	SR-PING
GBO Mechanism	Spike synchronization of neuronal oscillators in an I-I network	Spike synchronization of neuronal oscillators in an E-I network	Oscillation in firing rates induced by conduction delays in an I-I network	Oscillation in firing rates induced by conduction delays in an E-I network	Oscillation in firing rates induced by inhibition-stabilized network connectivity regimen in an E-I network	Stochastic resonance—noise induced sustenance of damped oscillations in an I-I network	Stochastic resonance in an E-I network
Firing Pattern	[e.g., (84–87)] Regular	[e.g., (70,72,88)] Regular	[e.g., (93,94)] Irregular	[e.g., (93,94)] Irregular	[e.g., (81–83)] Irregular	[e.g., (112)] Irregular	[e.g., (113–116)] Irregular
GBO Frequency Determinant	Decay time constants of IPSCs	Decay time constants of IPSCs	Delays in synaptic transmission	Delays in synaptic transmission Decay time constants for IPSCs and EPSCs	Connection strength of E-E, E-I, I-E, and I-I Decay time constants for IPSCs and EPSCs	Decay time constants for IPSCs	Decay time constants for IPSCs (113) Connection strength of E-E, E-I, I-E, and I-I Decay time constants for IPSCs and EPSCs (114–116)
GBO Power Determinant	Excitation to INs	Excitation to INs	Excitation to INs and ENS	Excitation to INs and ENS	Excitation to INs	Noise level in network activity and/or input	Noise level in network activity and/or input

D-ING, delay-based-interneuron network gamma; D-PING, delay-based-pyramidal-interneuron network gamma; E, excitatory; EN, excitatory neuron; EPSC, excitatory postsynaptic current; GBO, gamma band oscillation; I, inhibitory; IN, inhibitory interneuron; IPSC, inhibitory postsynaptic current; ISN-PING, inhibition-stabilized network-pyramidal-interneuron network gamma; NO-ING, neural oscillator based-interneuron network gamma; NO-PING, neural oscillator based-pyramidal-interneuron network gamma; SR-ING, stochastic resonance-pyramidal-interneuron network gamma; SR-PING, stochastic resonance-pyramidal-interneuron network gamma.

show a decrease in response to auditory stimulation. In general, the genetic models show a consistent dependence of GBOs on brain states. One proposed hypothesis for the reduced GBO during sensory processing in both humans and rodent models is that the increased GBO power during baseline period causes a ceiling effect, preventing further GBO recruitment during cognitive tasks (20,64). However, in the genetic model of NMDAR hypofunction in GABAergic INs not restricted to PV+ (63), the baseline GBO power in the period between repeated presentations of auditory stimuli does not show any change from control animals; thus, the ceiling effect does not explain the entire data set and requires further investigation in terms of differences in the brain state between the two protocols. A separate definition of baseline versus resting state in the animal models would be a step in the direction of reconciliation of the data. Caution also needs to be exercised while comparing human and animal studies; GBOs in most animal models are analyzed in LFPs, while human studies involve EEG or MEG (Supplement).

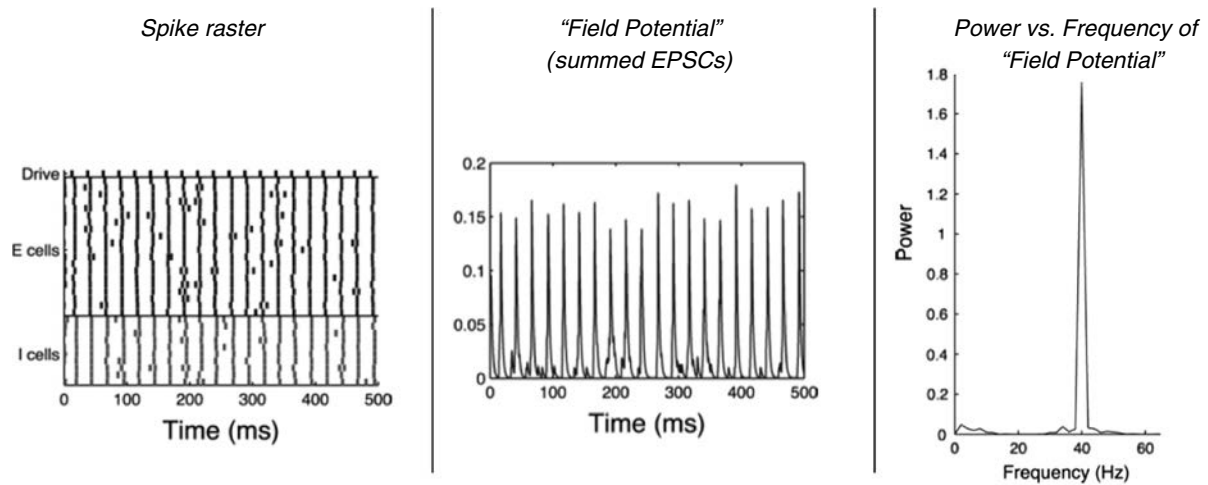
Several hypotheses have been proposed regarding the mechanisms underlying the GBO alterations in both the SZ patients and animal models (2,10). GABAergic INs are crucial to the generation of oscillations in the cortical population activity and PV+ INs are considered a major contributor to the generation of GBOs (65–68). However, unraveling the mechanism of GBO modification in SZ, even for the animal models, is challenging due to at least two key reasons: imprecise understanding of the action of NMDAR antagonists in the pharmacologic model and the effects of homeostatic mechanisms during development in the genetic models (Supplement). Given these complex issues, computational modeling of GBOs is an invaluable tool to explore the various hypotheses regarding the changes in networks that not only modify the GBO but also ultimately lead to SZ symptoms. GBO computational models have been broadly categorized as those involving IN-IN interactions, also termed interneuron network gamma (ING), or those involving pyramidal neuron-IN interactions, termed pyramidal-interneuron network gamma (PING) (Supplemental Figure S2). They can be further categorized based on the underlying mechanisms and their unique predictions (Table 1). While these models have been previously reviewed in great detail (66), we discuss some of the most relevant ones in the context of the data considered in this review.

COMPUTATIONAL MODELS OF GBO MODULATION

Modeling the Increase in Baseline GBOs

Baseline activity in animal models of NMDAR hypofunction shows a moderate to robust increase in GBO power. Since this is also observed in the genetic knockout model of NMDARs in the PV+ INs, altered PV+ inhibition in the cortical network could have a key role in this effect. This hypothesis was explored in a computational model (61) that is based on the GBO mechanism of synchronization of neural oscillators, which we term here as neural oscillator based-ING or neural oscillator based-PING (Table 1) (69–73). The modified cortical circuit in the NMDAR receptor knockout mice was captured as decreased excitability of fast spiking INs in the computational

A. NO-PING type GBO model



B. Simulation of NMDA hypofunction in the NO-PING GBO model

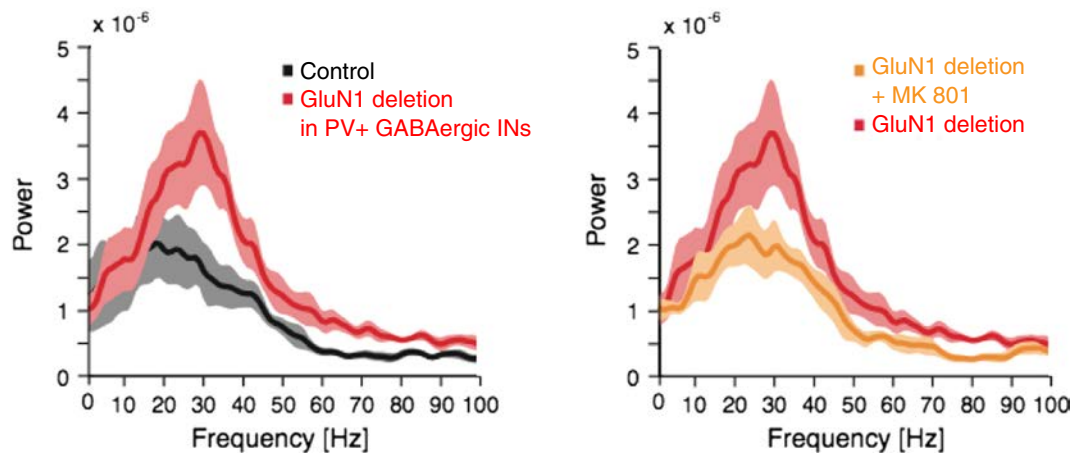


Figure 3. Computational models of changes in baseline gamma band oscillations (GBOs). **(A)** Spike rasters and local field potentials in the neural oscillator-pyramidal inhibitory neuron network gamma (NO-PING) model. Adapted with permission from (73). **(B)** Simulation of *N*-methyl-D-aspartate (NMDA) receptor hypofunction in parvalbumin-expressing (PV+) inhibitory interneurons (INs) by reducing excitability of INs in the NO-PING model shown in **(A)** Adapted with permission from (61). E, excitatory; EPSC, excitatory postsynaptic current; GABA, gamma-aminobutyric acid; I, inhibitory.

model (61) (Figure 3A). In the presence of noisy background activity, this modification to the model resulted in reduced spontaneous activity in the PV+ INs during minimal (baseline period) excitation, resulting in increased synchronous activity of excitatory population. Since reduced excitability of the model INs required more synchronized excitation to activate them, it resulted in more synchronous inhibition at gamma frequency and hence an enhancement of GBOs (Figure 3B). Other models exhibited stronger GBOs with weakened excitatory (E) to inhibitory (I) connections as a result of NMDAR hypofunction in an E-I network (74,75).

However, these computational models conflict with the observation that in at least one animal model of NMDAR hypofunction, disinhibition of cortical excitatory neurons is accompanied by reduced neuronal synchrony (76). It should, however, be noted that in this animal model, the hypofunction

was not limited to PV+ neurons in the cortex. In addition, as was pointed out earlier, the alterations in NMDAR function in the different animal models occur at different points during development; thus, it is not clear how comparable the different animal models are in terms of the GBO observations. A recent in vivo study revealed that cortical disinhibition achieved by MK-801, an NMDAR antagonist, caused an increase in GBO power but a reduced synchronization in the firing of action potentials in the medial prefrontal cortex of free-moving rats (60). While INs have been shown to be more sensitive to NMDAR antagonists (77), a broad range of cortical INs are expected to be affected in these experiments (60), similar to the genetic knockout model of Belforte *et al.* (76). This suggests the possibility that the increase in baseline GBO power in the animal models of cortical NMDAR hypofunction could also reflect a robust increase in synaptic inputs due to

disinhibition and not a true increase in synchronization of neural activity, as seen in the computational models (61,70,71,73). Finally, a key issue with the models of GBOs that are based on synchronization of neuronal oscillators is that they show a narrow distribution of interspike intervals (ISIs), whereas experimental data from cortex and the hippocampus suggest a broad distribution of ISIs during GBOs (78–80).

We recently explored the modulation of GBO power and frequency in a special case of the Wilson and Cowan (81) oscillation model based on an inhibition-stabilized PING model with superlinear inhibition (82,83). The strong inhibition in this model stabilizes the positive feedback in the population of pyramidal cells. This model replicated a range of observations on GBO modulation in the primate visual cortex (82). The model predicted rate-level oscillations, rather than spike to spike, with a broad distribution of ISIs. In this regimen, the power of GBOs in the model is proportional to the ratio of stimulation to the local excitatory and inhibitory neurons, other factors remaining relatively unchanged; if this ratio increases, power in GBOs increases (82,83). The model predicts an increase in the GBO strength if the key effect of NMDAR hypofunction is captured as reduction in the excitability of INs (83). However, the model predicts a decrease in the GBO strength if the key effect of NMDAR hypofunction is captured as a selective decrease in the strength of excitatory connections to the INs (83).

Finally, it is not known how the cortical circuit reorganizes through compensatory mechanisms in the genetic knockout models. This makes it difficult to accurately model the effects of genetic knockout of NMDARs in PV+ neurons in this as well as other computational models, especially since the alteration occurs at different developmental time points in different animal models. A clean way to test the computational models would be acute suppression of NMDARs selectively in PV+ neurons (thus allowing the circuits to develop normally), which could be a possibility in the future.

Modeling the Decrease in GBOs During Stimulus Processing

As discussed above, several studies in SZ patients and rodent models of NMDAR hypofunction demonstrate a reduction in GBO strength during sensory stimulus processing (Figures 1, 2). An underlying cause is thought to be the reduced excitability of PV+ INs, which are crucial to GBO generation. Most computational models show sensitivity of GBO strength to the excitability of INs (Table 1) and predict weaker gamma in response to reduced excitability, such as through NMDAR hypofunction in the INs. Here, we discuss the specific predictions of different computational models and how they might be tested in the future.

Computational models based on synchronization of integrate-and-fire type neurons, which we group and term here as neural oscillator based-ING or neural oscillator based-PING (70,72,84–88) (Table 1), predict unsustainable GBOs when the drive to inhibitory neurons through NMDAR hypofunction is sufficiently reduced. Other models of PING-type GBOs exhibit similarly synchronous firing with Hodgkin-Huxley type spiking mechanisms in INs (74,88,89). One such model predicts stronger GBOs with reduced feedback excitation to INs from the local E neurons (74), while another predicts

weaker GBOs with reduced feedforward excitation to INs (88). Since reduced excitability of INs affects both feedforward and feedback coupling to PV+, it remains to be seen how these effects interact in a computational model of NMDAR hypofunction. One prediction is that GBOs could either decrease or increase when the local network is strongly driven by the stimulus, depending on the balance of feedforward versus feedback excitation to INs. Computational modeling, anatomical evidence, and in vitro experiments, as well as those using knockout mice, show that gap junctions between GABAergic INs can facilitate GBOs, specifically the ING type (90–92). While gap junctions are an important mechanism for synchronizing neuronal activity, the evidence for their disruption in GABAergic neurons in SZ is not clear. We have thus limited this review to examining the connection between oscillatory disruption observed in SZ patients and disruption in chemical synaptic function.

Oscillations in networks can also arise from a mechanism that does not rely on synchronization of individual neural oscillators. In such models, the oscillations are not spike-to-spike but are observable in the firing rates (93,94). The mechanism relies on communication delays such as axonal conduction delays and synaptic transmission; the frequency of oscillations is sensitive to these delays. GBO strength in these models, which we term here as delay-based ING or delay-based PING, depends on the drive to the INs; they predict weakened oscillations with reduced drive. This would predict weakened GBOs with NMDAR hypofunction in the INs. However, in computational models involving both α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA)- and NMDA-mediated excitatory conductances, GBOs have been shown to be sensitive to mostly AMPA-mediated (and not NMDA-mediated) excitation (93). The high sensitivity of GBOs to AMPA receptor hypofunction is explained by the need of fast excitation to IN to sustain oscillations in the computational models of GBO; AMPA sensitivity of GBOs has also been experimentally demonstrated in animal models with genetic modification of AMPA receptors in PV+ GABAergic neurons (95).

The inhibition-stabilized PING model captures a range of observations on GBO modulation in the primate visual cortex (82,83). If a modification of relative stimulation to local E-I population results in an increase in the net firing rates in the network, it predicts a decrease in GBO power (Figure 4A). When NMDAR hypofunction is modeled as selective decrease in excitation to PV+ neurons that relieves the net inhibition in the local network, the model predicts a decrease in GBO power, as is also observed in the genetic models (61) (Figure 4B). However, a recent study with selective NMDAR ablation in pyramidal neurons in the cortex and hippocampus also infers a reduction in GBO power (96). While the study reports an increase in the excitability of pyramidal neurons in the animal model, it is not clear if this translates to an increase in spiking response to stimulation. If it does, the computational model provides a mechanism for the observed decrease in GBO power.

Finally, computational models have several limitations in their ability to shed light on underlying mechanisms. They do not address the effects of the cellular/molecular consequences of chronic NMDAR antagonist treatment or ablation of NMDARs in early life or the extent to which NMDARs or other receptors are blocked in non-PV+ IN types. Acute NMDAR

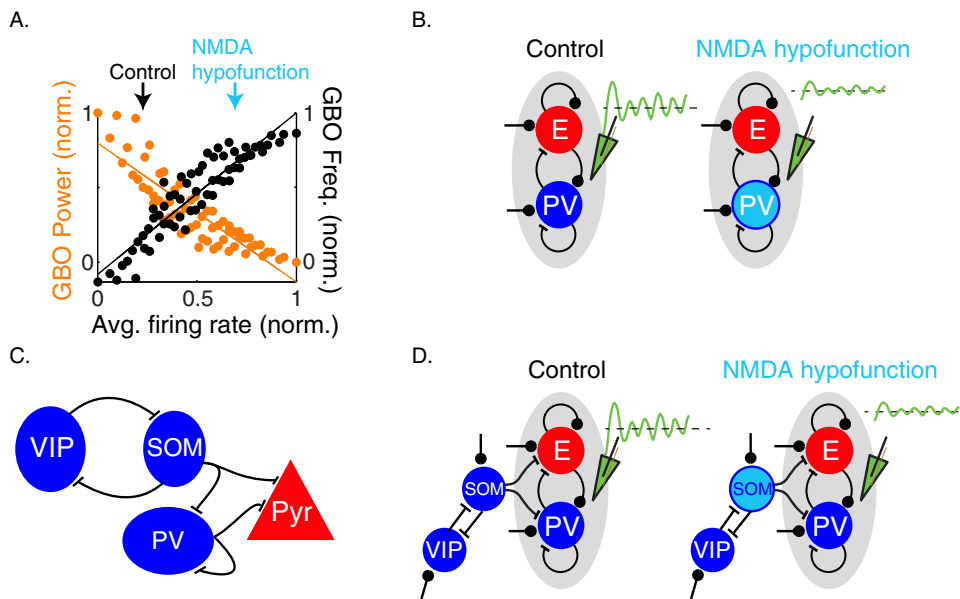


Figure 4. Stimulus-induced gamma band oscillations (GBOs) due to N-methyl-D-aspartate (NMDA) receptor (NMDAR) hypofunction in an inhibition-stabilized gamma (ISN-PING) model. **(A)** Covariation of average spiking activity and GBO power and frequency in an ISN-PING model. The arrows indicate how GBO power changes in response to changes in the activity of PING network. The variations in activity level and GBO properties are plotted in response to changes in the excitatory drive to the PING network, such as in the case of NMDAR hypofunction. **(B)** NMDAR hypofunction in parvalbumin-expressing (PV+) inhibitory interneurons (INs) modeled as reduced excitation predicts disinhibition and weaker GBO in the model. **(C)** Local inhibition circuit in the cortex (97–99). PV+ INs inhibit each other as well as excitatory neurons. Somatostatin positive (SOM+) INs inhibit both PV+ INs and excitatory pyramidal (Pyr) neurons. Vasoactive intestinal polypeptide immunopositive (VIP+) INs disinhibit excitatory neurons by inhibiting SOM+ INs. **(D)** The ISN-PING model predicts reduced power of stimulus-induced GBO if NMDAR hypofunction in SOM+ INs relieves inhibition of both excitatory neurons and PV+ INs such that the average activity is increased in the network. Avg., average; E, excitatory; Freq., frequency; norm., normalized. [Adapted with permission from Jadi and Sejnowski (82).]

rons. Vasoactive intestinal polypeptide immunopositive (VIP+) INs disinhibit excitatory neurons by inhibiting SOM+ INs. **(D)** The ISN-PING model predicts reduced power of stimulus-induced GBO if NMDAR hypofunction in SOM+ INs relieves inhibition of both excitatory neurons and PV+ INs such that the average activity is increased in the network. Avg., average; E, excitatory; Freq., frequency; norm., normalized. [Adapted with permission from Jadi and Sejnowski (82).]

blockade in adulthood is probably the best understood case in terms of likely cellular changes, with the most potential for successful exploration (computational and otherwise) of modulation of GBOs and other network behavior. In addition to more precise characterization of the effect of NMDA hypofunction, predicting the circuit-level disinhibitory effect will involve taking into consideration the additional complexities of connections between the different IN types found in the cortex and hippocampus; some of these have been recently revealed to provide disinhibition to the excitatory neurons. Future efforts in computational modeling will necessitate the evaluation of these disinhibitory mechanisms.

MECHANISMS OF CORTICAL DISINHIBITION

The reciprocal interaction between the pyramidal neurons and the PV+ INs is the core of the feedback circuit that generates GBOs using the PING mechanism. Inputs to this circuit include thalamo-cortical projections, lateral interactions from neighboring columns, and feedback from other areas. Additional cortical circuits involving non-PV+ INs modulate the gain of the network and the overall level of activity. For example, a series of studies using optogenetic techniques have uncovered a disinhibitory circuit involving somatostatin positive (SOM+) and vasoactive intestinal polypeptide immunopositive INs (97–99) (Figure 4C). In multiple cortical areas in the mouse, SOM+ INs target both pyramidal and PV+ INs, but silencing SOM+ INs increases the overall excitatory activity in the cortex (100). Integrating these details in different computational models will have unique predictions (Figure 4D; Supplement). The predictions related to disinhibition in the cortex due to NMDAR hypofunction in non-PV+ IN types have not been explicitly tested in animal models, but in the final section, we briefly discuss the

literature that supports a role for alterations in non-PV+ IN types in causing GBO alterations seen in SZ.

NMDAR HYPOFUNCTION IN NON-PV+ NEURONS: POSTMORTEM STUDIES

Several lines of experimental evidence suggest that hypofunction of NMDARs is more robust in INs than pyramidal neurons (22,77,101) [but see (102)]. Alteration in neurochemical markers of GABA transmission is most prominent in PV+ INs in response to NMDAR hypofunction in the adult cortex (103). However, postmortem studies show that not all classes of cortical INs are affected equally in SZ patients (39,41,42,104). Significant expression deficits in messenger RNAs (mRNAs) associated with GABAergic neurons, including mRNAs of the neuropeptides SOM, Y, and cholecystokinins, have been detected in postmortem prefrontal cortical tissues of SZ subjects (39). In hippocampal tissue of SZ subjects, a reduction in the number of PV+ and SOM+ interneurons and the level of PV+, SOM+, and glutamic acid decarboxylase mRNA expression has been reported (105) (Figure 5A). On the other hand, the levels of calretinin (an interneuron cell-type marker, like PV and SOM, of cortical GABAergic interneurons) are largely unaffected (6,39,106). The deficits also show specificity along the cortical laminae; in postmortem studies in prefrontal cortical tissue, SOM mRNA expression is significantly reduced in layers 2 to superficial layer 6 in SZ patients (41) (Figure 5B). Amalgamation of several postmortem studies suggest that SZ patients show alteration of SOM+ inhibitory neurotransmission to the apical dendrites of pyramidal neurons whose cell bodies are present in the deep layers of the dorsolateral prefrontal cortex (38,107).

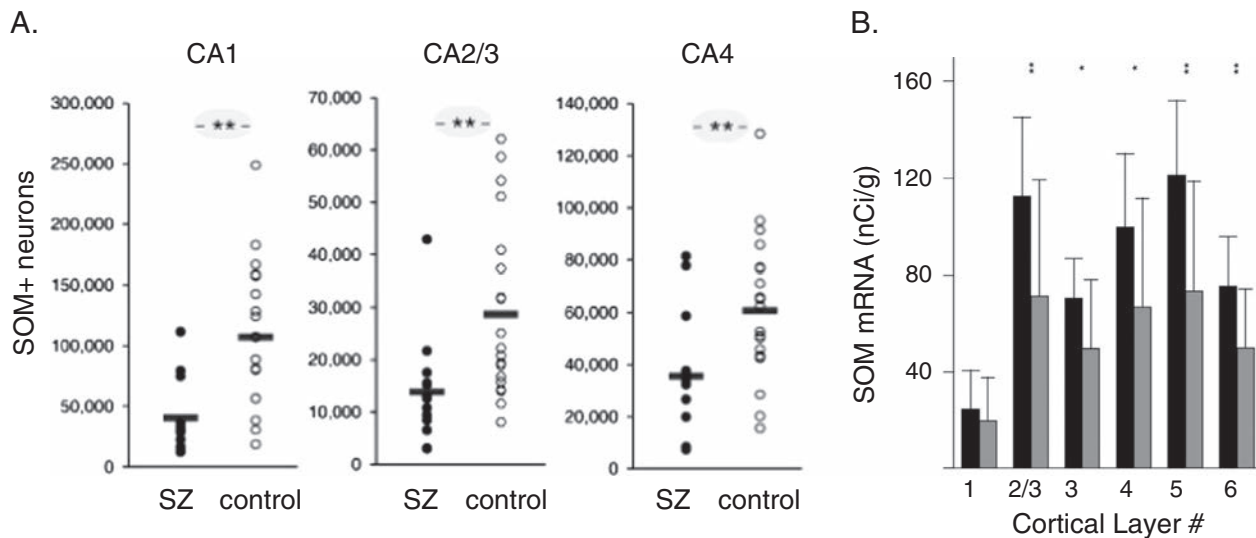


Figure 5. Alteration of non-parvalbumin-expressing inhibition in schizophrenia (SZ). **(A)** Immunohistochemical estimate of somatostatin positive (SOM+) neurons in the hippocampus in postmortem SZ subjects (closed circle) and control subjects (open circles) (105). **(B)** Laminar expression of the messenger RNAs (mRNAs) for SOM in dorsolateral prefrontal cortex in postmortem SZ subjects. Mean film optical density for mRNA expression in each cortical layer between comparison and schizophrenia groups. CA, cornu ammonis. [Adapted with permission from Morris *et al.* (41).]

NMDAR HYPOFUNCTION IN NON-PV+ NEURONS: NEUROPHARMACOLOGY AND COMPUTATIONAL MODELS

In a recent EEG study in rats, several NMDAR antagonists showed nonmonotonic dose-response effects on cortical GBO power (108). A recent computational study demonstrated that NMDAR manipulation in a single IN population can give rise to a nonmonotonic U-shaped dependence of stimulus-induced GBO on NMDAR efficacy (109). On the other hand, at least two local IN populations with either low or high sensitivity to NMDAR antagonists are crucial to the conceptual model proposed for GBO modulation in response to NMDAR antagonists (108). While PV+ INs are implicated in the GBO generating population (67,68), the involvement of subpopulations of PV+ INs with differential sensitivity to NMDAR antagonists or even non-PV+ classes of INs is a possibility (110). In addition to deficits in the GABAergic system itself, there are other modulators of inhibition that could play a role in the deficits observed in the disease and need further consideration (Supplement).

CONCLUSIONS AND FUTURE DIRECTIONS

We have examined the empirical data and computational models that support the hypothesis that NMDAR hypofunction in inhibitory neurons, specifically the PV+ ones, may contribute to the observed GBO abnormalities and ultimately the symptoms in patients with SZ. However, possible contribution of other inhibitory systems cannot be ruled out. NMDAR hypofunction in non-PV+ cortical INs, such as SOM+ INs, that exert inhibitory control on cortical activity may also be involved; this finds support in postmortem studies. In addition, recent characterization of SOM+ INs in the rodent somatosensory cortex suggests that they provide differential inhibition

to excitatory neurons as well as PV+ INs in a cortical layer specific manner (111). How the dysregulation of this subsystem influences the dynamics of the mature cortical circuit both in terms of GBO and otherwise is an important question. In summary, studies focused on the developmental aspects of the complex inhibitory/disinhibitory systems will help elucidate how and when its dysfunction leads to the permanent alterations in cortical circuitry responsible for the observed changes in oscillatory activity in schizophrenia.

ACKNOWLEDGMENTS AND DISCLOSURES

MPJ was supported by National Institute of Mental Health Grant No. T32MH020002, National Eye Institute Grant No. K99 EY025026, and the Swartz Foundation. MMB was supported by National Institute of Mental Health Grant Nos. MH091407 and MH094670. TJS was supported by Howard Hughes Medical Institute.

The authors report no biomedical financial interests or potential conflicts of interest.

ARTICLE INFORMATION

From the Howard Hughes Medical Institute (MPJ, MMB, TJS), The Salk Institute for Biological Studies; and Division of Biological Sciences (MPJ, TJS), University of California at San Diego, La Jolla, California.

Address correspondence to Monika P. Jadi, Ph.D., The Salk Institute for Biological Studies, 10010 N Torrey Pines Rd, San Diego, CA 92037; E-mail: jadi@salk.edu.

Received Dec 10, 2014; revised Jun 3, 2015; accepted Jul 7, 2015.

Supplementary material cited in this article is available online at <http://dx.doi.org/10.1016/j.biopsych.2015.07.005>.

REFERENCES

- Lewis DA, Hashimoto T, Volk DW (2005): Cortical inhibitory neurons and schizophrenia. *Nat Rev Neurosci* 6:312–324.
- Uhlhaas PJ, Singer W (2010): Abnormal neural oscillations and synchrony in schizophrenia. *Nat Rev Neurosci* 11:100–113.

3. Wenk GL (2003): Neuropathologic changes in Alzheimer's disease. *J Clin Psychiatry* 64(suppl 9):7–10.
4. Akbarian S, Kim JJ, Potkin SG, Hagman JO, Tafazzoli A, Bunney WE Jr, Jones EG (1995): Gene expression for glutamic acid decarboxylase is reduced without loss of neurons in prefrontal cortex of schizophrenics. *Arch Gen Psychiatry* 52:258–266.
5. Volk DW, Austin MC, Pierri JN, Sampson AR, Lewis DA (2000): Decreased glutamic acid decarboxylase67 messenger RNA expression in a subset of prefrontal cortical gamma-aminobutyric acid neurons in subjects with schizophrenia. *Arch Gen Psychiatry* 57: 237–245.
6. Woo TU, Whitehead RE, Melchitzky DS, Lewis DA (1998): A subclass of prefrontal gamma-aminobutyric acid axon terminals are selectively altered in schizophrenia. *Proc Natl Acad Sci U S A* 95: 5341–5346.
7. Beasley CL, Reynolds GP (1997): Parvalbumin-immunoreactive neurons are reduced in the prefrontal cortex of schizophrenics. *Schizophr Res* 24:349–355.
8. Singer W, Gray CM (1995): Visual feature integration and the temporal correlation hypothesis. *Annu Rev Neurosci* 18:555–586.
9. Salinas E, Sejnowski TJ (2001): Correlated neuronal activity and the flow of neural information. *Nat Rev Neurosci* 2:539–550.
10. Gonzalez-Burgos G, Lewis DA (2008): GABA neurons and the mechanisms of network oscillations: Implications for understanding cortical dysfunction in schizophrenia. *Schizophr Bull* 34:944–961.
11. Uhlhaas PJ, Singer W (2006): Neural synchrony in brain disorders: Relevance for cognitive dysfunctions and pathophysiology. *Neuron* 52:155–168.
12. Cho RY, Konecky RO, Carter CS (2006): Impairments in frontal cortical gamma synchrony and cognitive control in schizophrenia. *Proc Natl Acad Sci U S A* 103:19878–19883.
13. Haenschel C, Bittner RA, Waltz J, Haertling F, Wibrall M, Singer W, et al. (2009): Cortical oscillatory activity is critical for working memory as revealed by deficits in early-onset schizophrenia. *J Neurosci* 29:9481–9489.
14. Minzenberg MJ, Firl AJ, Yoon JH, Gomes GC, Reinking C, Carter CS (2010): Gamma oscillatory power is impaired during cognitive control independent of medication status in first-episode schizophrenia. *Neuropsychopharmacology* 5:2590–2599.
15. Spencer KM, Nestor PG, Perlmutter R, Niznikiewicz MA, Klump MC, Frumin M, et al. (2004): Neural synchrony indexes disordered perception and cognition in schizophrenia. *Proc Natl Acad Sci U S A* 101: 17288–17293.
16. Lee SH, Wynn JK, Green MF, Kim H, Lee KJ, Nam M, et al. (2006): Quantitative EEG and low resolution electromagnetic tomography (LORETA) imaging of patients with persistent auditory hallucinations. *Schizophr Res* 83:111–119.
17. Spencer KM, Niznikiewicz MA, Nestor PG, Shenton ME, McCarley RW (2009): Left auditory cortex gamma synchronization and auditory hallucination symptoms in schizophrenia. *BMC Neurosci* 10:85.
18. Spencer KM, Salisbury DF, Shenton ME, McCarley RW (2008): Gamma-band auditory steady-state responses are impaired in first episode psychosis. *Biol Psychiatry* 64:369–375.
19. Winterer G, Ziller M, Dorn H, Frick K, Mulert C, Wuebben Y, et al. (2000): Schizophrenia: Reduced signal-to-noise ratio and impaired phase-locking during information processing. *Clin Neurophysiol* 111: 837–849.
20. Spencer KM (2012): Baseline gamma power during auditory steady-state stimulation in schizophrenia. *Front Hum Neurosci* 5:190.
21. Rutter L, Carver FW, Holroyd T, Nadar SR, Mitchell-Francis J, Apud J, et al. (2009): Magnetoencephalographic gamma power reduction in patients with schizophrenia during resting condition. *Hum Brain Mapp* 30:3254–3264.
22. Uhlhaas PJ, Singer W (2012): Neuronal dynamics and neuropsychiatric disorders: Toward a translational paradigm for dysfunctional large-scale networks. *Neuron* 75:963–980.
23. Carlsson A, Lindqvist M (1963): Effect of chlorpromazine or haloperidol on formation of 3-methoxytyramine and normetanephrine in mouse brain. *Acta Pharmacol Toxicol (Copenh)* 20:140–144.
24. Seeman P, Lee T, Chau-Wong M, Wong K (1976): Antipsychotic drug doses and neuroleptic/dopamine receptors. *Nature* 261: 717–719.
25. Kellendonk C, Simpson EH, Polan HJ, Malleret G, Vronskaia S, Winiger V, et al. (2006): Transient and selective overexpression of dopamine D2 receptors in the striatum causes persistent abnormalities in prefrontal cortex functioning. *Neuron* 49:603–615.
26. Coyle JT (1996): The glutamatergic dysfunction hypothesis for schizophrenia. *Harv Rev Psychiatry* 3:241–253.
27. Deutsch SI, Mastropalo J, Schwartz BL, Rosse RB, Morihisa JM (1989): A “glutamatergic hypothesis” of schizophrenia. Rationale for pharmacotherapy with glycine. *Clin Neuropharmacol* 12:1–13.
28. Javitt DC (1987): Negative schizophrenic symptomatology and the PCP (phencyclidine) model of schizophrenia. *Hillside J Clin Psychiatry* 9:12–35.
29. Lahti AC, Holcomb HH, Medoff DR, Tamminga CA (1995): Ketamine activates psychosis and alters limbic blood flow in schizophrenia. *Neuroreport* 6:869–872.
30. Olney JW, Farber NB (1995): Glutamate receptor dysfunction and schizophrenia. *Arch Gen Psychiatry* 52:998–1007.
31. Tamminga CA (1998): Schizophrenia and glutamatergic transmission. *Crit Rev Neurobiol* 12:21–36.
32. Lodge D, Anis NA (1982): Effects of phencyclidine on excitatory amino acid activation of spinal interneurons in the cat. *Eur J Pharmacol* 77:203–204.
33. Krystal JH, Karper LP, Seibyl JP, Freeman GK, Delaney R, Bremner JD, et al. (1994): Subanesthetic effects of the noncompetitive NMDA antagonist, ketamine, in humans. Psychotomimetic, perceptual, cognitive, and neuroendocrine responses. *Arch Gen Psychiatry* 51: 199–214.
34. Hong LE, Summerfelt A, Buchanan RW, O'Donnell P, Thaker GK, Weiler MA, Lahti AC (2010): Gamma and delta neural oscillations and association with clinical symptoms under subanesthetic ketamine. *Neuropsychopharmacology* 35:632–640.
35. Olney JW, Farber NB (1995): NMDA antagonists as neurotherapeutic drugs, psychotogens, neurotoxins, and research tools for studying schizophrenia. *Neuropsychopharmacology* 13:335–345.
36. Moghaddam B, Adams B, Verma A, Daly D (1997): Activation of glutamatergic neurotransmission by ketamine: A novel step in the pathway from NMDA receptor blockade to dopaminergic and cognitive disruptions associated with the prefrontal cortex. *J Neurosci* 17:2921–2927.
37. Poels EM, Kegeles LS, Kantrowitz JT, Slifstein M, Javitt DC, Lieberman JA, et al. (2014): Imaging glutamate in schizophrenia: Review of findings and implications for drug discovery. *Mol Psychiatry* 19:20–29.
38. Beneyto M, Abbott A, Hashimoto T, Lewis DA (2011): Lamina-specific alterations in cortical GABA(A) receptor subunit expression in schizophrenia. *Cereb Cortex* 21:999–1011.
39. Hashimoto T, Arion D, Unger T, Maldonado-Aviles JG, Morris HM, Volk DW, et al. (2008): Alterations in GABA-related transcriptome in the dorsolateral prefrontal cortex of subjects with schizophrenia. *Mol Psychiatry* 13:147–161.
40. Lewis DA, Hashimoto T, Morris HM (2008): Cell and receptor type-specific alterations in markers of GABA neurotransmission in the prefrontal cortex of subjects with schizophrenia. *Neurotox Res* 14: 237–248.
41. Morris HM, Hashimoto T, Lewis DA (2008): Alterations in somatostatin mRNA expression in the dorsolateral prefrontal cortex of subjects with schizophrenia or schizoaffective disorder. *Cereb Cortex* 18:1575–1587.
42. Volk DW, Matsubara T, Li S, Sengupta EJ, Georgiev D, Minabe Y, et al. (2012): Deficits in transcriptional regulators of cortical parvalbumin neurons in schizophrenia. *Am J Psychiatry* 169:1082–1091.
43. Woo TU, Walsh JP, Benes FM (2004): Density of glutamic acid decarboxylase 67 messenger RNA-containing neurons that express the N-methyl-D-aspartate receptor subunit NR2A in the anterior cingulate cortex in schizophrenia and bipolar disorder. *Arch Gen Psychiatry* 61:649–657.

44. Woo TU, Shrestha K, Lamb D, Minns MM, Benes FM (2008): N-methyl-D-aspartate receptor and calbindin-containing neurons in the anterior cingulate cortex in schizophrenia and bipolar disorder. *Biol Psychiatry* 64:803–809.
45. Pratt J, Winchester C, Dawson N, Morris B (2012): Advancing schizophrenia drug discovery: Optimizing rodent models to bridge the translational gap. *Nat Rev Drug Discov* 11:560–579.
46. Bubenikova-Valesova V, Horacek J, Vrajova M, Hoschl C (2008): Models of schizophrenia in humans and animals based on inhibition of NMDA receptors. *Neurosci Biobehav Rev* 32:1014–1023.
47. Cunningham MO, Hunt J, Middleton S, LeBeau FE, Gillies MJ, Davies CH, *et al.* (2006): Region-specific reduction in entorhinal gamma oscillations and parvalbumin-immunoreactive neurons in animal models of psychiatric illness. *J Neurosci* 26:2767–2776.
48. Roopun AK, Cunningham MO, Racca C, Alter K, Traub RD, Whittington MA (2008): Region-specific changes in gamma and beta2 rhythms in NMDA receptor dysfunction models of schizophrenia. *Schizophr Bull* 34:962–973.
49. Kittelberger K, Hur EE, Sazegar S, Keshavan V, Kocsis B (2012): Comparison of the effects of acute and chronic administration of ketamine on hippocampal oscillations: Relevance for the NMDA receptor hypofunction model of schizophrenia. *Brain Struct Funct* 217:395–409.
50. Hakami T, Jones NC, Tolmacheva EA, Gaudias J, Chaumont J, Salzberg M, *et al.* (2009): NMDA receptor hypofunction leads to generalized and persistent aberrant gamma oscillations independent of hyperlocomotion and the state of consciousness. *PLoS One* 4: e6755.
51. Pinault D (2008): N-methyl d-aspartate receptor antagonists ketamine and MK-801 induce wake-related aberrant gamma oscillations in the rat neocortex. *Biol Psychiatry* 63:730–735.
52. Lazarewicz MT, Ehrlichman RS, Maxwell CR, Gandal MJ, Finkel LH, Siegel SJ (2010): Ketamine modulates theta and gamma oscillations. *J Cogn Neurosci* 22:1452–1464.
53. Leung LW (1985): Spectral analysis of hippocampal EEG in the freely moving rat: Effects of centrally active drugs and relations to evoked potentials. *Electroencephalogr Clin Neurophysiol* 60:65–77.
54. Ma J, Leung LS (2007): The supramammillo-septal-hippocampal pathway mediates sensorimotor gating impairment and hyperlocomotion induced by MK-801 and ketamine in rats. *Psychopharmacology (Berl)* 191:961–974.
55. Ehrlichman RS, Gandal MJ, Maxwell CR, Lazarewicz MT, Finkel LH, Contreras D, *et al.* (2009): N-methyl-d-aspartic acid receptor antagonist-induced frequency oscillations in mice recreate pattern of electrophysiological deficits in schizophrenia. *Neuroscience* 158:705–712.
56. Palenicek T, Fujakova M, Brunovsky M, Balikova M, Horacek J, Gorman I, *et al.* (2011): Electroencephalographic spectral and coherence analysis of ketamine in rats: Correlation with behavioral effects and pharmacokinetics. *Neuropsychobiology* 63:202–218.
57. Kulikova SP, Tolmacheva EA, Anderson P, Gaudias J, Adams BE, Zheng T, Pinault D (2012): Opposite effects of ketamine and deep brain stimulation on rat thalamocortical information processing. *Eur J Neurosci* 36:3407–3419.
58. Wood J, Kim Y, Moghaddam B (2012): Disruption of prefrontal cortex large scale neuronal activity by different classes of psychotomimetic drugs. *J Neurosci* 32:3022–3031.
59. Caixeta FV, Cornelio AM, Scheffer-Teixeira R, Ribeiro S, Tort AB (2013): Ketamine alters oscillatory coupling in the hippocampus. *Sci Rep* 3:2348.
60. Molina LA, Skelin I, Gruber AJ (2014): Acute NMDA receptor antagonism disrupts synchronization of action potential firing in rat prefrontal cortex. *PLoS One* 9:e85842.
61. Carlen M, Meletis K, Siegle JH, Cardin JA, Futai K, Vierling-Claassen D, *et al.* (2012): A critical role for NMDA receptors in parvalbumin interneurons for gamma rhythm induction and behavior. *Mol Psychiatry* 17:537–548.
62. Korotkova T, Fuchs EC, Ponomarenko A, von Engelhardt J, Monyer H (2010): NMDA receptor ablation on parvalbumin-positive interneurons impairs hippocampal synchrony, spatial representations, and working memory. *Neuron* 68:557–569.
63. Nakao K, Nakazawa K (2014): Brain state-dependent abnormal LFP activity in the auditory cortex of a schizophrenia mouse model. *Front Neurosci* 8:168.
64. McNally JM, McCarley RW, Brown RE (2013): Chronic ketamine reduces the peak frequency of gamma oscillations in mouse prefrontal cortex *ex vivo*. *Front Psychiatry* 4:106.
65. Buzsáki G, Chrobak JJ (1995): Temporal structure in spatially organized neuronal ensembles: A role for interneuronal networks. *Curr Opin Neurobiol* 5:504–510.
66. Buzsaki G, Wang XJ (2012): Mechanisms of gamma oscillations. *Annu Rev Neurosci* 35:203–225.
67. Cardin JA, Carlén M, Meletis K, Knoblich U, Zhang F, Deisseroth K, *et al.* (2009): Driving fast-spiking cells induces gamma rhythm and controls sensory responses. *Nature* 459:663–667.
68. Sohal VS, Zhang F, Yizhar O, Deisseroth K (2009): Parvalbumin neurons and gamma rhythms enhance cortical circuit performance. *Nature* 459:698–702.
69. Hansel D, Mato G, Meunier C (1993): Clustering and slow switching in globally coupled phase oscillators. *Phys Rev E Stat Phys Plasmas Fluids Relat Interdiscip Topics* 48:3470–3477.
70. Borgers C, Kopell N (2003): Synchronization in networks of excitatory and inhibitory neurons with sparse, random connectivity. *Neural Comput* 15:509–538.
71. Börgers C, Epstein S, Kopell NJ (2005): Background gamma rhythmicity and attention in cortical local circuits: A computational study. *Proc Natl Acad Sci U S A* 102:7002–7007.
72. Ermentrout GB, Kopell N (1998): Fine structure of neural spiking and synchronization in the presence of conduction delays. *Proc Natl Acad Sci U S A* 95:1259–1264.
73. Vierling-Claassen D, Siekmeier P, Stufflebeam S, Kopell N (2008): Modeling GABA alterations in schizophrenia: A link between impaired inhibition and altered gamma and beta range auditory entrainment. *J Neurophysiol* 99:2656–2671.
74. Volman V, Behrens MM, Sejnowski TJ (2011): Downregulation of parvalbumin at cortical GABA synapses reduces network gamma oscillatory activity. *J Neurosci* 31:18137–18148.
75. Spencer KM (2009): The functional consequences of cortical circuit abnormalities on gamma oscillations in schizophrenia: Insights from computational modeling. *Front Hum Neurosci* 3:33.
76. Belforte JE, Zsiros V, Sklar ER, Jiang Z, Yu G, Li Y, *et al.* (2010): Postnatal NMDA receptor ablation in corticolimbic interneurons confers schizophrenia-like phenotypes. *Nat Neurosci* 13:76–83.
77. Homayoun H, Moghaddam B (2007): NMDA receptor hypofunction produces opposite effects on prefrontal cortex interneurons and pyramidal neurons. *J Neurosci* 27:11496–11500.
78. Staley KJ (2007): Neurons skip a beat during fast ripples. *Neuron* 55: 828–830.
79. Nikolic D, Hausler S, Singer W, Maass W (2009): Distributed fading memory for stimulus properties in the primary visual cortex. *PLoS Biol* 7:e1000260.
80. Ray S, Maunsell JHR (2010): Differences in gamma frequencies across visual cortex restrict their possible use in computation. *Neuron* 67:885–896.
81. Wilson HR, Cowan JD (1972): Excitatory and inhibitory interactions in localized populations of model neurons. *Biophys J* 12:1–24.
82. Jadi MP, Sejnowski TJ (2014): Cortical oscillations arise from contextual interactions that regulate sparse coding. *Proc Natl Acad Sci U S A* 111:6780–6785.
83. Jadi MP, Sejnowski TJ (2014): Regulating cortical oscillations in an inhibition-stabilized network. *Proc IEEE Inst Electr Electron Eng*:102.
84. Whittington MA, Traub RD, Jefferys JG (1995): Synchronized oscillations in interneuron networks driven by metabotropic glutamate receptor activation. *Nature* 373:612–615.
85. Wang XJ, Buzsáki G (1996): Gamma oscillation by synaptic inhibition in a hippocampal interneuronal network model. *J Neurosci* 16: 6402–6413.

86. Traub RD, Whittington MA, Colling SB, Buzsaki G, Jefferys JG (1996): Analysis of gamma rhythms in the rat hippocampus in vitro and in vivo. *J Physiol* 493:471–484.
87. Van Vreeswijk C, Abbott LF, Ermentrout GB (1994): When inhibition not excitation synchronizes neural firing. *J Comput Neurosci* 1: 313–321.
88. Buia C, Tiesinga P (2006): Attentional modulation of firing rate and synchrony in a model cortical network. *J Comput Neurosci* 20: 247–264.
89. Tiesinga P, Sejnowski TJ (2009): Cortical enlightenment: Are attentional gamma oscillations driven by ING or PING? *Neuron* 63: 727–732.
90. Traub RD, Kopell N, Bibbig A, Buhl EH, LeBeau FE, Whittington MA (2001): Gap junctions between interneuron dendrites can enhance synchrony of gamma oscillations in distributed networks. *J Neurosci*, 21, 9478–9486.
91. Fukuda T, Kosaka T, Singer W, Galuske RA (2006): Gap junctions among dendrites of cortical GABAergic neurons establish a dense and widespread intercolumnar network. *J Neurosci*, 26, 3434–3443.
92. Buhl DL, Harris KD, Hormuzdi SG, Monyer H, Buzsaki G (2003): Selective impairment of hippocampal gamma oscillations in connexin-36 knock-out mouse in vivo. *J Neurosci* 23:1013–1018.
93. Brunel N, Wang X-J (2003): What determines the frequency of fast network oscillations with irregular neural discharges? I. Synaptic dynamics and excitation-inhibition balance. *J Neurophysiol* 90: 415–430.
94. Geisler C, Brunel N, Wang XJ (2005): Contributions of intrinsic membrane dynamics to fast network oscillations with irregular neuronal discharges. *J Neurophysiol* 94:4344–4361.
95. Fuchs EC, Zivkovic AR, Cunningham MO, Middleton S, Lebeau FE, Bannerman DM, *et al.* (2007): Recruitment of parvalbumin-positive interneurons determines hippocampal function and associated behavior. *Neuron* 53:591–604.
96. Tatar-Leitman VM, Jutzeler CR, Suh J, Saunders JA, Billingslea EN, Morita S, *et al.* (2015): Pyramidal cell selective ablation of N-methyl-D-aspartate receptor 1 causes increase in cellular and network excitability. *Biol Psychiatry* 77:556–568.
97. Pfeffer CK, Xue M, He M, Huang ZJ, Scanziani M (2013): Inhibition of inhibition in visual cortex: The logic of connections between molecularly distinct interneurons. *Nat Neurosci* 16:1068–1076.
98. Pi HJ, Hangya B, Kvitsiani D, Sanders JI, Huang ZJ, Kepecs A (2013): Cortical interneurons that specialize in disinhibitory control. *Nature* 503:521–524.
99. Fu Y, Tucciarone JM, Espinosa JS, Sheng N, Darcy DP, Nicoll RA, *et al.* (2014): A cortical circuit for gain control by behavioral state. *Cell* 156:1139–1152.
100. Adesnik H, Bruns W, Taniguchi H, Huang ZJ, Scanziani M (2012): A neural circuit for spatial summation in visual cortex. *Nature* 490: 226–231.
101. Grunze HC, Rainnie DG, Hasselmo ME, Barkai E, Hearn EF, McCarley RW, Greene RW (1996): NMDA-dependent modulation of CA1 local circuit inhibition. *J Neurosci* 16:2034–2043.
102. Rotaru DC, Lewis DA, Gonzalez-Burgos G (2012): The role of glutamatergic inputs onto parvalbumin-positive interneurons: Relevance for schizophrenia. *Rev Neurosci* 23:97–109.
103. Behrens MM, Ali SS, Dao DN, Lucero J, Shekhtman G, Quick KL, Dugan LL (2007): Ketamine-induced loss of phenotype of fast-spiking interneurons is mediated by NADPH-oxidase. *Science* 318:1645–1647.
104. Hashimoto T, Volk DW, Eggan SM, Mimics K, Pierri JN, Sun Z, *et al.* (2003): Gene expression deficits in a subclass of GABA neurons in the prefrontal cortex of subjects with schizophrenia. *J Neurosci* 23: 6315–6326.
105. Konradi C, Yang CK, Zimmerman EI, Lohmann KM, Gresch P, Pantazopoulos H, *et al.* (2011): Hippocampal interneurons are abnormal in schizophrenia. *Schizophr Res* 131:165–173.
106. Sakai T, Oshima A, Nozaki Y, Ida I, Haga C, Akiyama H, *et al.* (2008): Changes in density of calcium-binding-protein-immunoreactive GABAergic neurons in prefrontal cortex in schizophrenia and bipolar disorder. *Neuropathology* 28:143–150.
107. Ali AB, Thomson AM (2008): Synaptic alpha 5 subunit-containing GABAA receptors mediate IPSPs elicited by dendrite-preferring cells in rat neocortex. *Cereb Cortex* 18:1260–1271.
108. Hiyoshi T, Kambe D, Karasawa J, Chaki S (2014): Differential effects of NMDA receptor antagonists at lower and higher doses on basal gamma band oscillation power in rat cortical electroencephalograms. *Neuropharmacology* 85:384–396.
109. Kirli KK, Ermentrout GB, Cho RY (2014): Computational study of NMDA conductance and cortical oscillations in schizophrenia. *Front Comput Neurosci* 8:133.
110. Buchanan KA, Blackman AV, Moreau AW, Elgar D, Costa RP, Lalanne T, *et al.* (2012): Target-specific expression of presynaptic NMDA receptors in neocortical microcircuits. *Neuron* 75:451–466.
111. Xu H, Jeong HY, Tremblay R, Rudy B (2013): Neocortical somatostatin-expressing GABAergic interneurons disinhibit the thalamorecipient layer 4. *Neuron* 77:155–167.
112. Brunel N, Hakim V (2008): Sparsely synchronized neuronal oscillations. *Chaos* 18:015113.
113. Brunel N (2000): Dynamics of sparsely connected networks of excitatory and inhibitory spiking neurons. *J Comput Neurosci* 8:183–208.
114. Kang K, Shelley M, Henrie JA, Shapley R (2010): LFP spectral peaks in V1 cortex: Network resonance and cortico-cortical feedback. *J Comput Neurosci* 29:495–507.
115. Wallace E, Benayoun M, van Drongelen W, Cowan JD (2011): Emergent oscillations in networks of stochastic spiking neurons. *PLoS One* 6:e14804.
116. Bressloff PC (2010): Metastable states and quasicycles in a stochastic Wilson-Cowan model of neuronal population dynamics. *Phys Rev E Stat Nonlin Soft Matter Phys* 82:051903.