Dual Perspectives

Dual Perspectives Companion Paper: How Close Are We to Understanding What (if Anything) γ Oscillations Do in Cortical Circuits?, by Vikaas S. Sohal

Snapshots of the Brain in Action: Local Circuit Operations through the Lens of γ Oscillations

Jessica A. Cardin

Department of Neuroscience and Kavli Institute, Yale University, New Haven, Connecticut 06520

γ oscillations (20–80 Hz) are associated with sensory processing, cognition, and memory, and focused attention in animals and humans. γ activity can arise from several neural mechanisms in the cortex and hippocampus and can vary across circuits, behavioral states, and developmental stages. γ oscillations are nonstationary, typically occurring in short bouts, and the peak frequency of this rhythm is modulated by stimulus parameters. In addition, the participation of excitatory and inhibitory neurons in the γ rhythm varies across local circuits and conditions, particularly in the cortex. Although these dynamics present a challenge to interpreting the functional role of γ oscillations, these patterns of activity emerge from synaptic interactions among excitatory and inhibitory neurons and thus provide important insight into local circuit operations.

Key words: cortex; gamma oscillation; interneuron; hippocampus; parvalbumin; rhythm

Introduction

Rhythms in the brain have provided insights into local circuit interactions (Csicsvari et al., 2003; Montgomery and Buzsáki, 2007; Cardin et al., 2009; Sohal et al., 2009) and network architecture (Berger, 1929; Contreras and Steriade, 1995; Haider et al., 2006; Steriade, 2006) and remain intriguing for their potential roles in information encoding and transmission (Fries, 2005; Fries et al., 2007; Womelsdorf et al., 2007). Considerable attention has been given to high-frequency oscillations in the 20–80 Hz, or γ, range (Jasper, 1938; Das, 1955; Bressler and Freeman, 1980) and more recently in the high γ (90–140 Hz) range (Colgin et al., 2009; Sullivan et al., 2011). γ oscillations are associated with sensory processing (Gray and Singer, 1989; Gray et al., 1990), cognition and memory (Engel et al., 2001; Harris et al., 2003; Fries, 2005; Montgomery and Buzsáki, 2007; Cabral et al., 2014), and focused attention (Tiitinen et al., 1993; Fries et al., 2001; Vidal et al., 2006) in animal models. γ activity is likewise associated with cognition and perception in humans and is compromised in human neurodevelopmental disorders, including autism (Milne et al., 2009; Peiker et al., 2015) and schizophrenia (Spencer et al., 2003, 2008a, b; Gallinat et al., 2004; Light et al., 2006).

Activity in the γ range can represent the outcome of more than one neural mechanism, either independently or in coordination. Although the observed frequency bands are approxi-

mately similar, γ activity varies across an array of species from insects to humans (Ribary et al., 1991; Eckhorn et al., 1993; Laurent et al., 1996; Nase et al., 2003) and across brain regions, including the olfactory bulb, thalamus, hippocampus, and cortex (Ghose and Freeman, 1992; Pinault and Deschênes, 1992; Steriade et al., 1993, 1996; Chrobak et al., 2000; Kay, 2015). γ oscillations are also significantly modulated in peak frequency and power across behavioral and developmental states. Further complicating interpretation, observed increases in γ-band power may sometimes represent enhanced power in a broad frequency range, more analogous to filtered noise than a true oscillation. It is therefore challenging to assign a single, definitive role for γ oscillations in brain function. However, these oscillations emerge from dynamic interactions among excitatory and inhibitory neurons and thus provide a crucial and informative real-time window into local circuit operations.

Multiple network mechanisms

γ oscillations are observed in the local field potential (LFP), which emerges as a result of spatially organized, summed current flow largely due to synaptic activity within a neural network (Mitzdorf, 1985; Barth et al., 1989; Einevoll et al., 2013). γ is the result of rhythmic synaptic output from cohorts of neurons with precise temporal relationships. However, there are varied mechanisms by which these temporal patterns occur within local neural circuits.

In the hippocampus, extensive exploration of computational and experimental models has identified multiple network mechanisms by which γ oscillations can be generated. Experimental work using pharmacological manipulations of the *in vitro* hippocampal slice preparation found that the 40 Hz-range field potential oscillations evoked under different circumstances exhibited different reliance on synaptic excitation and inhibition. γ oscillations induced by activat-

ing mGluR (Whittington et al., 1995) or kainate (Fisahn et al., 2004) receptors require GABAergic, but not glutamatergic, synaptic transmission. In contrast, oscillations induced by the cholinergic receptor agonist carbachol (Fisahn et al., 1998; Fellous and Sejnowski, 2000; Gulyás et al., 2010) or by elevated potassium levels (LeBeau et al., 2002) rely on both GABAergic and glutamatergic components. γ-band activity can thus be evoked in the hippocampal circuit by at least two network mechanisms: (1) by strongly activating interneuron-interneuron networks (I-I; sometimes referred to as interneuron network γ) (Van Vreeswijk et al., 1994; Ermentrout, 1996; Wang and Buzsáki, 1996; Bartos et al., 2002) or (2) by coactivating reciprocally connected groups of interneurons and pyramidal neurons (E-I; sometimes referred to as pyramidal interneuron network γ) (Wilson and Cowan, 1972; Ermentrout and Kopell, 1998; Whittington et al., 2000; Brunel and Wang, 2003; Traub et al., 2005; Tiesinga and Sejnowski, 2009; Whittington et al., 2011). These two key mechanisms may occur independently or in concert, but both rely on fast inhibitory synaptic transmission by GABAergic interneurons.

Although pyramidal-interneuron and interneuron-interneuron network mechanisms for γ generation have been clearly demonstrated in hippocampal circuits, pyramidal-interneuron mechanisms appear to predominate in cortex. Optogenetic activation of fast-spiking basket interneurons (Cardin et al., 2009; Sohal et al., 2009) or pyramidal neurons (Adesnik and Scanziani, 2010) in sensory cortex evokes robust γ oscillations that depend on both GABAergic and glutamatergic synaptic transmission. Indeed, spontaneous γ oscillations *in vivo* are eliminated by optogenetic suppression of interneurons (Sohal et al., 2009) and both spontaneous and optogenetically evoked cortical oscillations are abolished by application of AMPAR and NMDAR blockers (Cardin et al., 2009). Together, these data strongly suggest that coordinated activity of excitatory and inhibitory neurons is necessary for expression of cortical γ rhythms.

The canonical E-I model of γ generation requires that reciprocally connected excitatory and inhibitory cells fire at different times during the γ cycle. Consistent with this model, some work *in vitro* and in anesthetized animals has found precisely offset phase relationships between excitatory and inhibitory cortical cell firing during γ oscillations (Hasenstaub et al., 2005). In contrast, several recent studies in awake rodents found little or no average phase difference between excitatory and inhibitory cortical cells (Vinck et al., 2015b; Perrenoud et al., 2016). However, the existence of multiple populations of cortical fast-spiking interneurons with entrainment to early and late phases of γ (Vinck et al., 2015b) may indicate multiple ongoing circuit mechanisms for cortical γ generation. These might include I-I γ generation or more complex relationships among interneurons during bouts of cortical activity. The direct contribution of I-I γ oscillations to cortical rhythms remains to be experimentally demonstrated. However, interneuron-interneuron interactions may contribute to γ rhythms even under circumstances where E-I γ is generated. Indeed, fast-spiking interneurons receive rhythmic IPSPs that likely enhance their entrainment to γ rhythms by modulating spike probability (Tamás et al., 2000; Hasenstaub et al., 2005; Sohal and Huguenard, 2005; Oren et al., 2006; Salkoff et al., 2015).

Hippocampal and neocortical GABAergic interneurons are highly diverse, but several lines of evidence point to fast-spiking basket cells that coexpress the calcium binding protein parvalbumin (PV$^+$) as a key source of synaptic inhibition in the generation of γ oscillations. PV$^+$ basket cells are the most abundant type of interneuron, and they are extensively connected to each other via both chemical and electrical synapses (Cobb et al., 1997; Tamás et al., 1998, 2000; Galarreta and Hestrin, 1999; Gibson et al., 1999; Bartos et al., 2001, 2002). These interneurons also ex-

hibit a highly promiscuous reciprocal synaptic connectivity with nearby pyramidal neurons, potentially allowing them to powerfully synchronize and respond to excitatory spiking (Hofer et al., 2011; Packer and Yuste, 2011). Basket cells are capable of firing rapidly, have intrinsic resonance in the γ range, and are highly entrained to endogenous γ oscillations (Tukker et al., 2007; Klausberger and Somogyi, 2008). Extensive theoretical and computational work has suggested that the specialized synaptic and firing properties of fast-spiking interneurons promote γ oscillations (Wang and Buzsáki, 1996; Rinzel et al., 1998; Bartos et al., 2001, 2002, 2007; Börgers et al., 2008). The time course of GABA$_A$ receptor-mediated IPSPs is optimal for generating a 40 Hz oscillation cycle (Whittington et al., 1995; Wang and Buzsáki, 1996). IPSPs with rapid temporal kinetics also enforce a narrow window for postsynaptic spiking (Pouille and Scanziani, 2001; Wehr and Zador, 2003; Wilent and Contreras, 2004; Higley and Contreras, 2006; Cardin et al., 2010), enhancing the entrainment of excitatory neurons.

Relatively little is known about the roles of nonbasket interneuron populations in directly generating γ-band activity. Recent work identified two separate hippocampal γ rhythms: one at the pyramidal cell soma and one at the apical dendritic tuft. The firing of basket cells was coupled to somatic, but not dendritic γ, suggesting a possible role for other GABAergic neurons in at least one local form of γ activity (Lasztóczi and Klausberger, 2014). Intriguingly, under some circumstances, hippocampal basket cells are less strongly entrained to γ than other GABAergic populations, including bistratified cells (Tukker et al., 2007; Klausberger and Somogyi, 2008). In the cortex, PV$^+$ cells receive innervation from other interneuron populations, such as the somatostatin- and vasoactive intestinal peptide-expressing interneurons, and their firing is strongly regulated by these inputs (Cottam et al., 2013; Pfeffer et al., 2013; Pi et al., 2013). γ activity could thus also be strongly modulated by synaptic inhibition of PV$^+$ cells from multiple sources. Computational modeling of the emergence of γ oscillations from neural networks suggests that synaptic inhibition of PV$^+$ basket cells may promote the flexible expression of γ oscillations with varying frequencies (Börgers et al., 2008).

γ generators: hippocampus versus cortex
Although γ oscillations have been observed in many circuits, their properties and underlying synaptic mechanisms vary. As described above, findings from *in vitro*, *in vivo*, and computational work suggest several network mechanisms for γ generation in the hippocampus. In addition, the hippocampal-entorhinal cortex circuit comprises multiple anatomically distinct oscillation generators that produce activity in both fast and slow γ bands. Evidence from *in vivo* recordings suggests at least two independent γ current sources within the hippocampus: one in the CA3-CA1 regions and one in the dentate gyrus (Bragin et al., 1995; Csicsvari et al., 2003). CA3 pyramidal neurons entrained to the γ rhythm activate local CA3 basket cells as well as cells in CA1 (Csicsvari et al., 2003), and γ activity in CA1 depends on input from CA3 (Fisahn et al., 1998). In contrast, γ activity in the dentate gyrus depends on input from the entorhinal cortex (Bragin et al., 1995).

The hippocampal formation generates not only the canonical "40 Hz" γ rhythm but also a distinct fast γ oscillation (defined as 90–140 Hz or 65–140 Hz) (Csicsvari et al., 1999; Colgin et al., 2009; Sullivan et al., 2011; Schomburg et al., 2014; Zheng et al., 2016). γ oscillations in the medial entorhinal cortex are most prominent in the superficial layer, entrain both inhibitory and excitatory neurons, and are strongly modulated by local θ oscillations (Chrobak and Buzsáki, 1998; Cunningham et al., 2003; Quilichini et al., 2010). Entorhinal fast γ oscillations are synchro-

nized with fast γ in the hippocampal CA1, whereas slow γ activity is coherent between CA1 and CA3, suggesting a possible function for these distinct frequency bands in routing information through different networks (Colgin et al., 2009). Synaptic mechanisms underlying fast γ rhythms have been examined in much less detail than those for slow γ. Indeed, much of the mechanistic information inferred from pharmacological work *in vitro* and anesthetized recordings *in vivo* may pertain more to CA3-generated slow (30 – 80 Hz) γ than to fast (90 –140 Hz) γ, which depends on entorhinal inputs that are removed or attenuated by slicing for *in vitro* preparations and by anesthesia *in vivo*.

Rather than occurring in sustained patterns of activity, both slow and fast γ oscillations in the hippocampus are generated in short bouts, suggesting brief entrainment of subnetworks of inhibitory and excitatory neurons. Slow and fast γ activity patterns occur on different θ oscillation phases and during different behavioral epochs related to spatial exploration and memory (Colgin et al., 2009; Carr et al., 2012; Kemere et al., 2013; Bieri et al., 2014; Cabral et al., 2014; Takahashi et al., 2014; Yamamoto et al., 2014; Zheng et al., 2016). However, the frequency and amplitude of γ oscillations are not stationary, even within these short bouts. Instead, instantaneous frequency and amplitude change rapidly both *in vitro* and *in vivo* (Bragin et al., 1995; Womelsdorf et al., 2007) and are coupled to underlying fluctuations in synaptic excitation and inhibition (Atallah and Scanziani, 2009). This variation suggests that the temporally patterned interactions between excitatory and inhibitory neurons that underlie γ oscillations are transiently recruited or enhanced by ongoing events in the surrounding network. It remains unclear whether this transient recruitment is due to fluctuations in local synchrony at lower frequencies, changes in overall excitatory drive to the circuit, or another mechanism. Overall, these findings highlight not only the diversity of hippocampal γ activity patterns, but also how a detailed understanding of these oscillations has provided insight into the architecture and function of the hippocampal circuit.

γ oscillations in cortical circuits exhibit a pronounced laminar profile. γ power (30 – 80 Hz) in the LFP and γ-band synchrony among neurons are highest in supragranular layers, suggesting that densely recurrent networks in these layers may contribute to amplification of activity in this frequency band (Lund, 1988; Malach et al., 1993; Buffalo et al., 2011; Xing et al., 2012; Smith et al., 2013). In agreement with this idea, optogenetic activation of layer 2/3 pyramidal cells with a ramp stimulus generates robust γ oscillations in mouse primary visual cortex *in vivo* and *in vitro* (Adesnik and Scanziani, 2010). Evidence from laminar recordings of mouse visual cortex suggests potentially independent sites of local γ generation in superficial and deep cortical layers (Welle and Contreras, 2016). Recordings from layers 4 and 6 in primate visual cortex further indicate amplification of γ power from input to output layers (Briggs and Usrey, 2009). In turn, γ oscillations may exert different levels of control over spike timing in specific subnetworks of cortical pyramidal neurons, mediating more precise spike control in supragranular pyramidal neurons than those in deeper layers (Otte et al., 2010; Hasenstaub et al., 2016). Although the retina and lateral geniculate nucleus generate some activity in the γ range, recordings in primate and cat LGN and primary visual cortex suggest that the thalamus is not a major contributor to γ power in cortex (Castelo-Branco et al., 1998; Koepsell et al., 2009; Ito et al., 2010; Bastos et al., 2014). In contrast, recent evidence suggests that narrowband, but not broadband, γ in mouse primary visual cortex is inherited from the thalamus (Saleem et al., 2016). γ oscillations in the 20 – 80 Hz

range in cortex are thus largely cortical in origin and may result from the activity of multiple laminarly distinct generators, but γ sources may vary across species. γ power in the LFP can also be inherited from long-range corticocortical synaptic connections and can entrain local neurons (Engel et al., 1991; Roelfsema et al., 1997; Tallon-Baudry et al., 2001; Gregoriou et al., 2009). γ activity recorded in the LFP at any particular cortical site may thus emerge from a mix of local and long-range circuit operations, presenting experimental and analytical challenges to assigning underlying sources and mechanisms.

Spontaneous and evoked oscillations

Spontaneously generated and stimulus-evoked γ oscillations differ in their engagement of cortical networks. Recordings in cats and rodents highlight the different subnetworks engaged by these two forms of γ activity. Spontaneous γ is generated throughout the cortical layers and largely entrains fast-spiking, putative inhibitory interneurons (Steriade and Amzica, 1996; Steriade et al., 1996; Sukov and Barth, 1998; Welle and Contreras, 2016). In contrast, stimulus-evoked γ is primarily generated in layer 4 and supragranular layers and also entrains excitatory neurons, suggesting distinct circuit involvement (Welle and Contreras, 2016). Intracellular recordings of neurons in superficial visual cortex in awake mice reveal that PV$^+$ interneurons show strong but brief spike entrainment to γ activity in response to short epochs of correlated background synaptic input during both baseline and visual stimulus periods. In contrast, excitatory pyramidal neurons show little entrainment in the absence of a visual stimulus (Perrenoud et al., 2016). Work from primate visual cortex area V4 similarly suggests that phase-locking to spontaneous γ during baseline epochs is largely restricted to putative interneurons, whereas entrainment of putative excitatory neurons is observed upon visual stimulation (Vinck et al., 2013). In both V1 and S1 cortex of rodents, fast-spiking putative interneurons always show entrainment to γ activity, whereas regular spiking putative excitatory neurons become entrained during periods of arousal and locomotion (Vinck et al., 2015a, b). Together, these findings suggest that resonant circuits in different layers may be differentially recruited by internally and externally generated drive to the cortex.

During spontaneous UP states in prefrontal cortex *in vitro* and *in vivo*, inhibitory synaptic and spiking activity in layer 5 is locked to the γ rhythm, indicating that interneurons are entrained during spontaneous γ as observed in sensory cortex (Hasenstaub et al., 2005). However, γ activity associated with UP states also entrains the firing of layer 5 putative excitatory neurons (Hasenstaub et al., 2005; Ushimaru and Kawaguchi, 2015). Similar phase relationships between γ oscillations and both excitatory and inhibitory events have been observed during spontaneous UP states in superficial entorhinal cortex *in vitro* (Salkoff et al., 2015). This variation in observed entrainment of pyramidal cells may result from true distinctions in circuit architecture across different cortical areas, potential differences in the type of γ oscillations generated by UP states and other regimens of spontaneous activity, or differences in analytical techniques between groups.

Stimulus-induced γ in visual cortex has a broad peak in both primates (Ray and Maunsell, 2010) and rodents (Vinck et al., 2015a), consistent with observations that γ oscillations occur in transient bouts and with varying frequencies. Rather than being stationary, evoked cortical γ oscillations depend on the ongoing stimulus regimen. Repeated visual stimulation results in increased γ-band synchronization among putative cortical pyramidal neurons and interneurons, even when overall firing rates

decrease (Brunet et al., 2014). γ power likewise varies with a number of other stimulus features, as reviewed extensively by Ray and Maunsell (2015). γ frequency rises with increasing stimulus contrast and varies over cortical distance in response to stimuli with spatially variable contrast values (Ray and Maunsell, 2010). Similarly, the frequency of visually induced γ oscillations in humans changes with the velocity of stimulus motion and the eccentricity of the stimulus (Swettenham et al., 2009; van Pelt and Fries, 2013; Orekhova et al., 2015). Because the frequency of oscillations is tied to the timing of the underlying synaptic interactions between neurons, these observations suggest evolving recruitment of local circuit elements over time during periods of high external drive to the cortex.

In sum, these findings suggest that distinct subnetworks in different cortical layers not only generate γ oscillations independently but may also be recruited differentially by internally generated spontaneous activity and sensory-evoked drive to the cortex. Excitatory drive to cortical networks engages the resonant properties of local circuits, facilitating the transient engagement of local synchrony among excitatory and inhibitory neurons. The varying frequencies exhibited during these bouts of γ oscillations suggest a range of temporal dynamics in the underlying synaptic interactions, but these temporal variations still remain to be fully explored *in vivo*.

State dependence of oscillation frequencies and entrainment

γ oscillations vary significantly with behavioral state in both cortex and hippocampus, suggesting state-dependent modulation of the underlying synaptic interactions. Hippocampal γ activity increases during locomotor behavior (Buzsáki et al., 1983) and peak γ frequency increases with running speed (Ahmed and Mehta, 2012; Kemere et al., 2013). In contrast, in both visual and somatosensory cortex, the power and peak frequency of the γ oscillation increase with arousal and locomotion but appear uncorrelated with locomotion speed (Niell and Stryker, 2010; Vinck et al., 2015a, 2015b). In mouse V1, locomotion- and visual stimulus-induced γ bands demonstrate separable peak frequencies (Vinck et al., 2015a), suggesting that they may be generated through different local and long-range circuits. Locomotion-related γ oscillations have been reported to be narrow-band in frequency (Niell and Stryker, 2010; Hoy and Niell, 2015), highlighting the possible engagement of a single γ generator circuit that may rely on thalamic input (Saleem et al., 2016). Intriguingly, several recent studies found that the state-dependent γ oscillations associated with locomotion emerge over the course of development. Cortical γ oscillation power and spike-field coherence increase in a laminar pattern during the critical period in rodents (Chen et al., 2015; Hoy and Niell, 2015). This trajectory likely reflects developmental changes in the intrinsic properties of inhibitory interneurons (Doischer et al., 2008; Okaty et al., 2009; Goldberg et al., 2011) as well as critical-period changes in network connectivity (Fagiolini and Hensch, 2000; Chattopadhyaya et al., 2004; Lazarus and Huang, 2011).

γ oscillations vary not only with global arousal and motor activity, but also with attention and cognitive demand. Attention is associated with increased γ power in the LFP (Fries et al., 2001, 2008; Hauck et al., 2007), and this increased power is observed independently of ongoing cortical firing rates (Fries et al., 2001, 2008; Vinck et al., 2013). Computational work has identified potential roles for pyramidal-interneuron γ oscillations in attentional selection between stimuli (Börgers et al., 2008). In agreement with this general model, attention in the absence of visual stimulation increases the spike-field locking of putative fast-spiking interneurons, but not putative excitatory neurons, to γ rhythms in primate V4 cortex (Vinck et al., 2013). Similarly, the allocation of attention is linked to enhanced PV$^+$ interneuron entrainment to γ oscillations in prefrontal cortex in mice (Kim et al., 2016). Enhanced synchronization at γ frequencies in primate visual cortex is correlated with faster task reaction times, suggesting a potential role for this patterned activity in optimizing encoding and transmission of behaviorally relevant information (Womelsdorf et al., 2006; Fries et al., 2007; Fries, 2015). γ power in visual cortex is likewise modulated by attention in humans (Gruber et al., 1999; Siegel et al., 2008; Self et al., 2016).

Functional consequences

Current evidence suggests a functional role for the rhythmic synaptic interactions underlying γ oscillations in directly modulating sensory processing by individual neurons. The rhythmic engagement of inhibitory, or inhibitory and excitatory, synaptic activity can enhance the precision and efficacy of sensory encoding. Indeed, encoding of visual stimulus orientation varies over the γ cycle (Womelsdorf et al., 2012). Hyperpolarizing IPSPs can increase subsequent spike probability, potentially raising response amplitude (Mainen and Sejnowski, 1995; Tamás et al., 2004). Inhibition may further regulate the signal-to-noise ratio and gain of sensory responses by several mechanisms (Fellous et al., 2003; Börgers et al., 2008; Atallah et al., 2012; Lee et al., 2012; Wilson et al., 2012; Khubieh et al., 2016). Phasic inhibition from PV$^+$ interneurons at γ frequencies restricts the spiking of excitatory neurons to specific phases of the γ cycle and increases the temporal precision of sensory-evoked spiking (Cardin et al., 2009; Siegle et al., 2014). Increased precision of spike timing across a local population of neurons may contribute to synchrony, potentially enhancing the synaptic efficacy of these spikes at downstream targets. The inhibition-dependent regulation of evoked responses at specific γ phases is associated with improved behavioral detection of low-amplitude sensory stimuli (Siegle et al., 2014). γ oscillations may also play more complex roles in the encoding and transmission of information (Fries et al., 2007; Fries, 2015), but the circuit-level underpinnings and functional consequences of these roles remain to be fully explored.

Open questions

Despite decades of exploration, several aspects of the mechanisms underlying γ oscillations remain unknown. γ is often observed as a nonstationary activity pattern, typically occurring in short bouts, whose peak frequency may vary systematically with a number of developmental, behavioral, and stimulus-dependent variables. Rather than confounds arising from specific experimental paradigms, these variations are hints of underlying network and synaptic dynamics. The current model for γ generation is based on recurrent E-I interactions in local circuits, with rhythmic engagement of PV$^+$ interneurons and pyramidal neurons. It is still unclear exactly how short epochs of rhythmic synaptic activity and spike synchrony with varying frequency components are repeatedly recruited and quenched in continuously active cortical or hippocampal circuits *in vivo*.

Extensive *in vitro*, *in vivo*, and computational work has provided a nuanced view of the sources of γ activity in the hippocampal-entorhinal circuit. However, the local mechanisms of γ generation in cortical circuits are less well understood. In particular, the participation of inhibitory and excitatory neurons across different cortical layers and the relative contributions of E-I and I-I interactions to cortical γ rhythms *in vivo* remain to be explored in more detail.

Finally, although rhythmic interactions between pyramidal cells and PV [+] interneurons have been deeply examined, the roles of non-PV [+] interneurons in γ oscillations remain largely unknown. The diverse populations of GABAergic interneurons have distinct intrinsic properties and synaptic targets. They may thus contribute in varying ways to generating and regulating the expression, amplitude, and spread of γ oscillations. Non-PV [+] interneurons may either directly generate rhythmic activity via novel mechanisms or indirectly influence the pyramidal-PV [+] circuit by inhibiting excitatory neurons or other inhibitory interneurons. Understanding their role in the broad suite of neural circuit behaviors that contribute to γ activity will provide further insight into the complex circuit architecture underlying network computations.

Response from Dual Perspective Companion Author–Vikaas Sohal

Jess' review highlights the extraordinary diversity of γ oscillations which may be generated by excitatory-inhibitory or interneuron-interneuron networks, occur within pyramidal cell somata or their dendritic tufts, oscillate at slow (30 – 80 Hz) or fast (90 –140 Hz) frequencies, arise from sources in the superficial versus deep layers of cortex, reflect thalamic input versus local cortical circuit interactions, and appear spontaneously or in response to a stimulus. Furthermore, Jess notes that "γ oscillations occur in transient bouts and with varying frequencies." These important observations are fully compatible with our proposal that γ oscillations "flexibly reroute the flow of information between groups of neurons" and/or "modulate patterns of activity within local circuits." The specific mechanisms we describe, through which γ oscillations may contribute to information processing, do not require that γ oscillations have a constant frequency or amplitude, or that they occur in a stereotyped way. What they do require are that γ oscillations "enforce a narrow window for postsynaptic spiking" and entrain the firing of at least some excitatory neurons. As Jess notes, many forms of γ oscillations appear to satisfy these conditions. When γ-frequency fluctuations in inhibition inhibit the firing of excitatory neurons at certain times, then there are invariably consequences for how information is processed at a local level and/or transmitted between structures. The mechanisms we outlined simply describe these consequences. In this context, the heterogeneous and nonstationary nature of γ oscillations noted by Jess does not complicate potential function(s) of γ oscillations but rather enhances them. Specifically, even within a single microcircuit, one type of γ oscillation may appear at one moment in time, transiently enhancing a particular circuit operation or the flow of information along a particular pathway, only to be supplanted a short time later by another type of γ oscillation performing an alternate function. This highlights the potential utility of γ oscillations for endowing neuronal circuits with profound flexibility. As Jess notes,

fast-spiking basket cells have intrinsic resonance in the γ range, as well as synaptic and firing properties that promote γ oscillations, suggesting (to us) that they are optimized to exploit these potential functions, rather than to produce γ oscillations simply by happenstance.

In conclusion, there is now a compelling body of theoretical work showing how γ oscillations ought to impact information processing, *in vivo* observations that are consistent with these mechanisms, and studies that have observed behavioral consequences after optogenetically manipulating γ oscillations. All that being said, the field is still missing the "smoking gun" that brings together all of these elements: by describing the behavioral effects of optogenetic manipulations, which create or disrupt the detailed properties of γ oscillations that are required by specific mechanisms through which γ oscillations are hypothesized to impact information processing. As Jess notes, the dynamic and heterogeneous nature of γ oscillations makes establishing this sort of link extremely challenging. Nevertheless, this represents the crucial next step that the field needs to take to definitely establish how γ oscillations impact neural circuit function.

References

Adesnik H, Scanziani M (2010) Lateral competition for cortical space by layer-specific horizontal circuits. Nature 464:1155–1160. CrossRef Medline

Ahmed OJ, Mehta MR (2012) Running speed alters the frequency of hippocampal γ oscillations. J Neurosci 32:7373–7383. CrossRef Medline

Atallah BV, Scanziani M (2009) Instantaneous modulation of γ oscillation frequency by balancing excitation with inhibition. Neuron 62:566–577. CrossRef Medline

Atallah BV, Bruns W, Carandini M, Scanziani M (2012) Parvalbumin-expressing interneurons linearly transform cortical responses to visual stimuli. Neuron 73:159–170. CrossRef Medline

Barth DS, Di S, Baumgartner C (1989) Laminar cortical interactions during epileptic spikes studied with principal component analysis and physiological modeling. Brain Res 484:13–35. CrossRef Medline

Bartos M, Vida I, Frotscher M, Geiger JR, Jonas P (2001) Rapid signaling at inhibitory synapses in a dentate gyrus interneuron network. J Neurosci 21:2687–2698. Medline

Bartos M, Vida I, Frotscher M, Meyer A, Monyer H, Geiger JR, Jonas P (2002) Fast synaptic inhibition promotes synchronized γ oscillations in hippocampal interneuron networks. Proc Natl Acad Sci U S A 99:13222–13227. CrossRef Medline

Bartos M, Vida I, Jonas P (2007) Synaptic mechanisms of synchronized γ oscillations in inhibitory interneuron networks. Nat Rev Neurosci 8:45–56. CrossRef Medline

Bastos AM, Briggs F, Alitto HJ, Mangun GR, Usrey WM (2014) Simultaneous recordings from the primary visual cortex and lateral geniculate nucleus reveal rhythmic interactions and a cortical source for γ-band oscillations. J Neurosci 34:7639–7644. CrossRef Medline

Berger H (1929) On the electroencephalogram of man. Electroencephalogr Clin Neurophysiol 28:37–74.

Bieri KW, Bobbitt KN, Colgin LL (2014) Slow and fast γ rhythms coordinate different spatial coding modes in hippocampal place cells. Neuron 82:670–681. CrossRef Medline

Börgers C, Epstein S, Kopell NJ (2008) γ oscillations mediate stimulus competition and attentional selection in a cortical network model. Proc Natl Acad Sci U S A 105:18023–18028. CrossRef Medline

Bragin A, Jandó G, Nádasdy Z, Hetke J, Wise K, Buzsáki G (1995) γ (40–100 Hz) oscillation in the hippocampus of the behaving rat. J Neurosci 15:47–60. Medline

Bressler SL, Freeman WJ (1980) Frequency analysis of olfactory system EEG in cat, rabbit, and rat. Electroencephalogr Clin Neurophysiol 50:19–24. CrossRef Medline

Briggs F, Usrey WM (2009) Modulation of γ-band activity across local cortical circuits. Front Integr Neurosci 3:15. CrossRef Medline

Brunel N, Wang XJ (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. CrossRef Medline

Brunet NM, Bosman CA, Vinck M, Roberts M, Oostenveld R, Desimone R, De Weerd P, Fries P (2014) Stimulus repetition modulates γ-band synchronization in primate visual cortex. Proc Natl Acad Sci U S A 111: 3626–3631. CrossRef Medline

Buffalo EA, Fries P, Landman R, Buschman TJ, Desimone R (2011) Laminar differences in γ and alpha coherence in the ventral stream. Proc Natl Acad Sci U S A 108:11262–11267. CrossRef Medline

Buzsáki G, Leung LW, Vanderwolf CH (1983) Cellular bases of hippocampal EEG in the behaving rat. Brain Res 287:139–171. Medline

Cabral HO, Vinck M, Fouquet C, Pennartz CM, Rondi-Reig L, Battaglia FP (2014) Oscillatory dynamics and place field maps reflect hippocampal ensemble processing of sequence and place memory under NMDA receptor control. Neuron 81:402–415. CrossRef Medline

Cardin JA, Carlén M, Meletis K, Knoblich U, Zhang F, Deisseroth K, Tsai LH, Moore CI (2009) Driving fast-spiking cells induces γ rhythm and controls sensory responses. Nature 459:663–667. CrossRef Medline

Cardin JA, Kumbhani RD, Contreras D, Palmer LA (2010) Cellular mechanisms of temporal sensitivity in visual cortex neurons. J Neurosci 30: 3652–3662. CrossRef Medline

Carr MF, Karlsson MP, Frank LM (2012) Transient slow γ synchrony underlies hippocampal memory replay. Neuron 75:700–713. CrossRef Medline

Castelo-Branco M, Neuenschwander S, Singer W (1998) Synchronization of visual responses between the cortex, lateral geniculate nucleus, and retina in the anesthetized cat. J Neurosci 18:6395–6410. Medline

Chattopadhyaya B, Di Cristo G, Higashiyama H, Knott GW, Kuhlman SJ, Welker E, Huang ZJ (2004) Experience and activity-dependent maturation of perisomatic GABAergic innervation in primary visual cortex during a postnatal critical period. J Neurosci 24:9598–9611. CrossRef Medline

Chen G, Rasch MJ, Wang R, Zhang XH (2015) Experience-dependent emergence of beta and γ band oscillations in the primary visual cortex during the critical period. Sci Rep 5:17847. CrossRef Medline

Chrobak JJ, Buzsáki G (1998) γ oscillations in the entorhinal cortex of the freely behaving rat. J Neurosci 18:388–398. Medline

Chrobak JJ, Lörincz A, Buzsáki G (2000) Physiological patterns in the hippocampo-entorhinal cortex system. Hippocampus 10:457–465. CrossRef Medline

Cobb SR, Halasy K, Vida I, Nyiri G, Tamás G, Buhl EH, Somogyi P (1997) Synaptic effects of identified interneurons innervating both interneurons and pyramidal cells in the rat hippocampus. Neuroscience 79:629–648. CrossRef Medline

Colgin LL, Denninger T, Fyhn M, Hafting T, Bonnevie T, Jensen O, Moser MB, Moser EI (2009) Frequency of γ oscillations routes flow of information in the hippocampus. Nature 462:353–357. CrossRef Medline

Contreras D, Steriade M (1995) Cellular basis of EEG slow rhythms: a study of dynamic corticothalamic relationships. J Neurosci 15:604–622. Medline

Cottam JC, Smith SL, Häusser M (2013) Target-specific effects of somatostatin-expressing interneurons on neocortical visual processing. J Neurosci 33:19567–19578. CrossRef Medline

Csicsvari J, Hirase H, Czurkó A, Mamiya A, Buzsáki G (1999) Fast network oscillations in the hippocampal CA1 region of the behaving rat. J Neurosci 19:RC20. Medline

Csicsvari J, Jamieson B, Wise KD, Buzsáki G (2003) Mechanisms of γ oscillations in the hippocampus of the behaving rat. Neuron 37:311–322. CrossRef Medline

Cunningham MO, Davies CH, Buhl EH, Kopell N, Whittington MA (2003) γ oscillations induced by kainate receptor activation in the entorhinal cortex in vitro. J Neurosci 23:9761–9769. Medline

Das NN, Gastaut H (1955) Variations de l'activite electrique du cerveau, du coeur et des muscles squellettiques au cours de la meditation et de l'extase yogique. Electroencephalogr Clin Neurophysiol 6:211–219.

Doischer D, Hosp JA, Yanagawa Y, Obata K, Jonas P, Vida I, Bartos M (2008) Postnatal differentiation of basket cells from slow to fast signaling devices. J Neurosci 28:12956–12968. CrossRef Medline

Eckhorn R, Frien A, Bauer R, Woelbern T, Kehr H (1993) High frequency (60–90 Hz) oscillations in primary visual cortex of awake monkey. Neuroreport 4:243–246. CrossRef Medline

Einevoll GT, Kayser C, Logothetis NK, Panzeri S (2013) Modelling and analysis of local field potentials for studying the function of cortical circuits. Nat Rev Neurosci 14:770–785. CrossRef Medline

Engel AK, König P, Kreiter AK, Singer W (1991) Interhemispheric synchronization of oscillatory neuronal responses in cat visual cortex. Science 252:1177–1179. CrossRef Medline

Engel AK, Fries P, Singer W (2001) Dynamic predictions: oscillations and synchrony in top-down processing. Nat Rev Neurosci 2:704–716. CrossRef Medline

Ermentrout B (1996) Type I membranes, phase resetting curves, and synchrony. Neural Comput 8:979–1001. CrossRef Medline

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. CrossRef Medline

Fagiolini M, Hensch TK (2000) Inhibitory threshold for critical-period activation in primary visual cortex. Nature 404:183–186. CrossRef Medline

Fellous JM, Sejnowski TJ (2000) Cholinergic induction of oscillations in the hippocampal slice in the slow (0.5–2 Hz), theta (5–12 Hz), and γ (35–70 Hz) bands. Hippocampus 10:187–197. CrossRef Medline

Fellous JM, Rudolph M, Destexhe A, Sejnowski TJ (2003) Synaptic background noise controls the input/output characteristics of single cells in an in vitro model of in vivo activity. Neuroscience 122:811–829. CrossRef Medline

Fisahn A, Pike FG, Buhl EH, Paulsen O (1998) Cholinergic induction of network oscillations at 40 Hz in the hippocampus in vitro. Nature 394: 186–189. CrossRef Medline

Fisahn A, Contractor A, Traub RD, Buhl EH, Heinemann SF, McBain CJ (2004) Distinct roles for the kainate receptor subunits GluR5 and GluR6 in kainate-induced hippocampal γ oscillations. J Neurosci 24:9658–9668. CrossRef Medline

Fries P (2005) A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. Trends Cogn Sci 9:474–480. CrossRef Medline

Fries P (2015) Rhythms for cognition: communication through coherence. Neuron 88:220–235. CrossRef Medline

Fries P, Reynolds JH, Rorie AE, Desimone R (2001) Modulation of oscillatory neuronal synchronization by selective visual attention. Science 291: 1560–1563. CrossRef Medline

Fries P, Nikolić D, Singer W (2007) The γ cycle. Trends Neurosci 30:309–316. CrossRef Medline

Fries P, Womelsdorf T, Oostenveld R, Desimone R (2008) The effects of visual stimulation and selective visual attention on rhythmic neuronal synchronization in macaque area V4. J Neurosci 28:4823–4835. CrossRef Medline

Galarreta M, Hestrin S (1999) A network of fast-spiking cells in the neocortex connected by electrical synapses. Nature 402:72–75. CrossRef Medline

Gallinat J, Winterer G, Herrmann CS, Senkowski D (2004) Reduced oscillatory γ-band responses in unmedicated schizophrenic patients indicate impaired frontal network processing. Clin Neurophysiol 115:1863–1874. CrossRef Medline

Ghose GM, Freeman RD (1992) Oscillatory discharge in the visual system: does it have a functional role? J Neurophysiol 68:1558–1574. Medline

Gibson JR, Beierlein M, Connors BW (1999) Two networks of electrically coupled inhibitory neurons in neocortex. Nature 402:75–79. CrossRef Medline

Goldberg EM, Jeong HY, Kruglikov I, Tremblay R, Lazarenko RM, Rudy B (2011) Rapid developmental maturation of neocortical FS cell intrinsic excitability. Cereb Cortex 21:666–682. CrossRef Medline

Gray CM, Singer W (1989) Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. Proc Natl Acad Sci U S A 86:1698–1702. CrossRef Medline

Gray CM, Engel AK, König P, Singer W (1990) Stimulus-dependent neuronal oscillations in cat visual cortex: receptive field properties and feature dependence. Eur J Neurosci 2:607–619. CrossRef Medline

Gregoriou GG, Gotts SJ, Zhou H, Desimone R (2009) High-frequency, long-range coupling between prefrontal and visual cortex during attention. Science 324:1207–1210. CrossRef Medline

Gruber T, Müller MM, Keil A, Elbert T (1999) Selective visual-spatial attention alters induced γ band responses in the human EEG. Clin Neurophysiol 110:2074–2085. CrossRef Medline

Gulyás AI, Szabó GG, Ulbert I, Holderith N, Monyer H, Erdélyi F, Szabó G, Freund TF, Hájos N (2010) Parvalbumin-containing fast-spiking basket cells generate the field potential oscillations induced by cholinergic receptor activation in the hippocampus. J Neurosci 30:15134–15145. CrossRef Medline

Haider B, Duque A, Hasenstaub AR, McCormick DA (2006) Neocortical network activity in vivo is generated through a dynamic balance of excitation and inhibition. J Neurosci 26:4535–4545. CrossRef Medline

Harris KD, Csicsvari J, Hirase H, Dragoi G, Buzsáki G (2003) Organization of cell assemblies in the hippocampus. Nature 424:552–556. CrossRef Medline

Hasenstaub A, Shu Y, Haider B, Kraushaar U, Duque A, McCormick DA (2005) Inhibitory postsynaptic potentials carry synchronized frequency information in active cortical networks. Neuron 47:423–435. CrossRef Medline

Hasenstaub A, Otte S, Callaway E (2016) Cell type-specific control of spike timing by γ-band oscillatory inhibition. Cereb Cortex 26:797–806. CrossRef Medline

Hauck M, Lorenz J, Engel AK (2007) Attention to painful stimulation enhances γ-band activity and synchronization in human sensorimotor cortex. J Neurosci 27:9270–9277. CrossRef Medline

Higley MJ, Contreras D (2006) Balanced excitation and inhibition determine spike timing during frequency adaptation. J Neurosci 26:448–457. CrossRef Medline

Hofer SB, Ko H, Pichler B, Vogelstein J, Ros H, Zeng H, Lein E, Lesica NA, Mrsic-Flogel TD (2011) Differential connectivity and response dynamics of excitatory and inhibitory neurons in visual cortex. Nat Neurosci 14:1045–1052. CrossRef Medline

Hoy JL, Niell CM (2015) Layer-specific refinement of visual cortex function after eye opening in the awake mouse. J Neurosci 35:3370–3383. CrossRef Medline

Ito H, Maldonado PE, Gray CM (2010) Dynamics of stimulus-evoked spike timing correlations in the cat lateral geniculate nucleus. J Neurophysiol 104:3276–3292. CrossRef Medline

Jasper H (1938) Brain potentials and voluntary muscle activity in man. J Neurophysiol 1:87–100.

Kay LM (2015) Olfactory system oscillations across phyla. Curr Opin Neurobiol 31:141–147. CrossRef Medline

Kemere C, Carr MF, Karlsson MP, Frank LM (2013) Rapid and continuous modulation of hippocampal network state during exploration of new places. PLoS One 8:e73114. CrossRef Medline

Khubieh A, Ratté S, Lankarany M, Prescott SA (2016) Regulation of cortical dynamic range by background synaptic noise and feedforward inhibition. Cereb Cortex 26:3357–3369. CrossRef Medline

Kim H, Ährlund-Richter S, Wang X, Deisseroth K, Carlén M (2016) Prefrontal parvalbumin neurons in control of attention. Cell 164:208–218. CrossRef Medline

Klausberger T, Somogyi P (2008) Neuronal diversity and temporal dynamics: the unity of hippocampal circuit operations. Science 321:53–57. CrossRef Medline

Koepsell K, Wang X, Vaingankar V, Wei Y, Wang Q, Rathbun DL, Usrey WM, Hirsch JA, Sommer FT (2009) Retinal oscillations carry visual information to cortex. Front Syst Neurosci 3:4. CrossRef Medline

Lasztóczi B, Klausberger T (2014) Layer-specific GABAergic control of distinct γ oscillations in the CA1 hippocampus. Neuron 81:1126–1139. CrossRef Medline

Laurent G, Wehr M, Davidowitz H (1996) Temporal representations of odors in an olfactory network. J Neurosci 16:3837–3847. Medline

Lazarus MS, Huang ZJ (2011) Distinct maturation profiles of perisomatic and dendritic targeting GABAergic interneurons in the mouse primary visual cortex during the critical period of ocular dominance plasticity. J Neurophysiol 106:775–787. CrossRef Medline

LeBeau FE, Towers SK, Traub RD, Whittington MA, Buhl EH (2002) Fast network oscillations induced by potassium transients in the rat hippocampus in vitro. J Physiol 542:167–179. CrossRef Medline

Lee SH, Kwan AC, Zhang S, Phoumthippavong V, Flannery JG, Masmanidis

SC, Taniguchi H, Huang ZJ, Zhang F, Boyden ES, Deisseroth K, Dan Y (2012) Activation of specific interneurons improves V1 feature selectivity and visual perception. Nature 488:379–383. CrossRef Medline

Light GA, Hsu JL, Hsieh MH, Meyer-Gomes K, Sprock J, Swerdlow NR, Braff DL (2006) γ band oscillations reveal neural network cortical coherence dysfunction in schizophrenia patients. Biol Psychiatry 60:1231–1240. CrossRef Medline

Lund JS (1988) Anatomical organization of macaque monkey striate visual cortex. Annu Rev Neurosci 11:253–288. CrossRef Medline

Mainen ZF, Sejnowski TJ (1995) Reliability of spike timing in neocortical neurons. Science 268:1503–1506. CrossRef Medline

Malach R, Amir Y, Harel M, Grinvald A (1993) Relationship between intrinsic connections and functional architecture revealed by optical imaging and in vivo targeted biocytin injections in primate striate cortex. Proc Natl Acad Sci U S A 90:10469–10473. CrossRef Medline

Milne E, Scope A, Pascalis O, Buckley D, Makeig S (2009) Independent component analysis reveals atypical electroencephalographic activity during visual perception in individuals with autism. Biol Psychiatry 65: 22–30. CrossRef Medline

Mitzdorf U (1985) Current source-density method and application in cat cerebral cortex: investigation of evoked potentials and EEG phenomena. Physiol Rev 65:37–100. Medline

Montgomery SM, Buzsáki G (2007) γ oscillations dynamically couple hippocampal CA3 and CA1 regions during memory task performance. Proc Natl Acad Sci U S A 104:14495–14500. CrossRef Medline

Nase G, Singer W, Monyer H, Engel AK (2003) Features of neuronal synchrony in mouse visual cortex. J Neurophysiol 90:1115–1123. CrossRef Medline

Niell CM, Stryker MP (2010) Modulation of visual responses by behavioral state in mouse visual cortex. Neuron 65:472–479. CrossRef Medline

Okaty BW, Miller MN, Sugino K, Hempel CM, Nelson SB (2009) Transcriptional and electrophysiological maturation of neocortical fast-spiking GABAergic interneurons. J Neurosci 29:7040–7052. CrossRef Medline

Orekhova EV, Butorina AV, Sysoeva OV, Prokofyev AO, Nikolaeva AY, Stroganova TA (2015) Frequency of γ oscillations in humans is modulated by velocity of visual motion. J Neurophysiol 114:244–255. CrossRef Medline

Oren I, Mann EO, Paulsen O, Hájos N (2006) Synaptic currents in anatomically identified CA3 neurons during hippocampal γ oscillations in vitro. J Neurosci 26:9923–9934. CrossRef Medline

Otte S, Hasenstaub A, Callaway EM (2010) Cell type-specific control of neuronal responsiveness by γ-band oscillatory inhibition. J Neurosci 30: 2150–2159. CrossRef Medline

Packer AM, Yuste R (2011) Dense, unspecific connectivity of neocortical parvalbumin-positive interneurons: a canonical microcircuit for inhibition? J Neurosci 31:13260–13271. CrossRef Medline

Peiker I, David N, Schneider TR, Nolte G, Schöttle D, Engel AK (2015) Perceptual integration deficits in autism spectrum disorders are associated with reduced interhemispheric γ-band coherence. J Neurosci 35: 16352–16361. CrossRef Medline

Perrenoud Q, Pennartz CM, Gentet LJ (2016) Membrane potential dynamics of spontaneous and visually evoked γ activity in V1 of awake mice. PLoS Biol 14:e1002383. CrossRef Medline

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. CrossRef Medline

Pi HJ, Hangya B, Kvitsiani D, Sanders JI, Huang ZJ, Kepecs A (2013) Cortical interneurons that specialize in disinhibitory control. Nature 503: 521–524. CrossRef Medline

Pinault D, Deschênes M (1992) Voltage-dependent 40-Hz oscillations in rat reticular thalamic neurons in vivo. Neuroscience 51:245–258. CrossRef Medline

Pouille F, Scanziani M (2001) Enforcement of temporal fidelity in pyramidal cells by somatic feed-forward inhibition. Science 293:1159–1163. CrossRef Medline

Quilichini P, Sirota A, Buzsáki G (2010) Intrinsic circuit organization and theta-γ oscillation dynamics in the entorhinal cortex of the rat. J Neurosci 30:11128–11142. CrossRef Medline

Ray S, Maunsell JH (2010) Differences in γ frequencies across visual cortex restrict their possible use in computation. Neuron 67:885–896. CrossRef Medline

Ray S, Maunsell JH (2015) Do γ oscillations play a role in cerebral cortex? Trends Cogn Sci 19:78–85. CrossRef Medline

Ribary U, Ioannides AA, Singh KD, Hasson R, Bolton JP, Lado F, Mogilner A, Llinás R (1991) Magnetic field tomography of coherent thalamocortical 40-Hz oscillations in humans. Proc Natl Acad Sci U S A 88:11037–11041. CrossRef Medline

Rinzel J, Terman D, Wang X, Ermentrout B (1998) Propagating activity patterns in large-scale inhibitory neuronal networks. Science 279:1351–1355. CrossRef Medline

Roelfsema PR, Engel AK, König P, Singer W (1997) Visuomotor integration is associated with zero time-lag synchronization among cortical areas. Nature 385:157–161. CrossRef Medline

Saleem AB, Lien AD, Krumin M, Haider B, Roson MR, Ayaz A, Rieinhold K, Busse L, Caranini M, Harris KD (2016) Origin and modulation of the narrowband γ oscillation in the mouse visual system. bioRxiv 050245. Advance online publication. Retrieved September 20, 2016. doi: 10.1101/050245.

Salkoff DB, Zagha E, Yüzgeç Ö, McCormick DA (2015) Synaptic mechanisms of tight spike synchrony at γ frequency in cerebral cortex. J Neurosci 35:10236–10251. CrossRef Medline

Schomburg EW, Fernández-Ruiz A, Mizuseki K, Berényi A, Anastassiou CA, Koch C, Buzsáki G (2014) Theta phase segregation of input-specific γ patterns in entorhinal-hippocampal networks. Neuron 84:470–485. CrossRef Medline

Self MW, Peters JC, Possel JK, Reithler J, Goebel R, Ris P, Jeurissen D, Reddy L, Claus S, Baayen JC, Roelfsema PR (2016) The effects of context and attention on spiking activity in human early visual cortex. PLoS Biol 14:e1002420. CrossRef Medline

Siegel M, Donner TH, Oostenveld R, Fries P, Engel AK (2008) Neuronal synchronization along the dorsal visual pathway reflects the focus of spatial attention. Neuron 60:709–719. CrossRef Medline

Siegle JH, Pritchett DL, Moore CI (2014) γ-range synchronization of fast-spiking interneurons can enhance detection of tactile stimuli. Nat Neurosci 17:1371–1379. CrossRef Medline

Smith MA, Jia X, Zandvakili A, Kohn A (2013) Laminar dependence of neuronal correlations in visual cortex. J Neurophysiol 109:940–947. CrossRef Medline

Sohal VS, Huguenard JR (2005) Inhibitory coupling specifically generates emergent γ oscillations in diverse cell types. Proc Natl Acad Sci U S A 102:18638–18643. CrossRef Medline

Sohal VS, Zhang F, Yizhar O, Deisseroth K (2009) Parvalbumin neurons and γ rhythms enhance cortical circuit performance. Nature 459:698–702. CrossRef Medline

Spencer KM, Nestor PG, Niznikiewicz MA, Salisbury DF, Shenton ME, Mc-Carley RW (2003) Abnormal neural synchrony in schizophrenia. J Neurosci 23:7407–7411. Medline

Spencer KM, Niznikiewicz MA, Shenton ME, McCarley RW (2008a) Sensory-evoked γ oscillations in chronic schizophrenia. Biol Psychiatry 63:744–747. CrossRef Medline

Spencer KM, Salisbury DF, Shenton ME, McCarley RW (2008b) γ-band auditory steady-state responses are impaired in first episode psychosis. Biol Psychiatry 64:369–375. CrossRef Medline

Steriade M (2006) Grouping of brain rhythms in corticothalamic systems. Neuroscience 137:1087–1106. CrossRef Medline

Steriade M, Amzica F (1996) Intracortical and corticothalamic coherency of fast spontaneous oscillations. Proc Natl Acad Sci U S A 93:2533–2538. CrossRef Medline

Steriade M, Curró Dossi R, Contreras D (1993) Electrophysiological properties of intralaminar thalamocortical cells discharging rhythmic (~40 HZ) spike-bursts at ~1000 HZ during waking and rapid eye movement sleep. Neuroscience 56:1–9. CrossRef Medline

Steriade M, Contreras D, Amzica F, Timofeev I (1996) Synchronization of fast (30–40 Hz) spontaneous oscillations in intrathalamic and thalamo-cortical networks. J Neurosci 16:2788–2808. Medline

Sukov W, Barth DS (1998) Three-dimensional analysis of spontaneous and thalamically evoked γ oscillations in auditory cortex. J Neurophysiol 79:2875–2884. Medline

Sullivan D, Csicsvari J, Mizuseki K, Montgomery S, Diba K, Buzsáki G (2011) Relationships between hippocampal sharp waves, ripples, and fast γ oscillation: influence of dentate and entorhinal cortical activity. J Neurosci 31:8605–8616. CrossRef Medline

Swettenham JB, Muthukumaraswamy SD, Singh KD (2009) Spectral prop-

erties of induced and evoked γ oscillations in human early visual cortex to moving and stationary stimuli. J Neurophysiol 102:1241–1253. CrossRef Medline

Takahashi M, Nishida H, Redish AD, Lauwereyns J (2014) θ phase shift in spike timing and modulation of γ oscillation: a dynamic code for spatial alternation during fixation in rat hippocampal area CA1. J Neurophysiol 111:1601–1614. CrossRef Medline

Tallon-Baudry C, Bertrand O, Fischer C (2001) Oscillatory synchrony between human extrastriate areas during visual short-term memory maintenance. J Neurosci 21:RC177. Medline

Tamás G, Somogyi P, Buhl EH (1998) Differentially interconnected networks of GABAergic interneurons in the visual cortex of the cat. J Neurosci 18:4255–4270. Medline

Tamás G, Buhl EH, Lörincz A, Somogyi P (2000) Proximally targeted GABAergic synapses and gap junctions synchronize cortical interneurons. Nat Neurosci 3:366–371. CrossRef Medline

Tamás G, Szabadics J, Lörincz A, Somogyi P (2004) Input and frequency-specific entrainment of postsynaptic firing by IPSPs of perisomatic or dendritic origin. Eur J Neurosci 20:2681–2690. CrossRef Medline

Tiesinga P, Sejnowski TJ (2009) Cortical enlightenment: are attentional γ oscillations driven by ING or PING? Neuron 63:727–732. CrossRef Medline

Tiitinen H, Sinkkonen J, Reinikainen K, Alho K, Lavikainen J, Näätänen R (1993) Selective attention enhances the auditory 40-Hz transient response in humans. Nature 364:59–60. CrossRef Medline

Traub RD, Contreras D, Cunningham MO, Murray H, LeBeau FE, Roopun A, Bibbig A, Wilent WB, Higley MJ, Whittington MA (2005) Single-column thalamocortical network model exhibiting γ oscillations, sleep spindles, and epileptogenic bursts. J Neurophysiol 93:2194–2232. CrossRef Medline

Tukker JJ, Fuentealba P, Hartwich K, Somogyi P, Klausberger T (2007) Cell type-specific tuning of hippocampal interneuron firing during γ oscillations in vivo. J Neurosci 27:8184–8189. CrossRef Medline

Ushimaru M, Kawaguchi Y (2015) Temporal structure of neuronal activity among cortical neuron subtypes during slow oscillations in anesthetized rats. J Neurosci 35:11988–12001. CrossRef Medline

van Pelt S, Fries P (2013) Visual stimulus eccentricity affects human γ peak frequency. Neuroimage 78:439–447. CrossRef Medline

Van Vreeswijk C, Abbott LF, Ermentrout GB (1994) When inhibition not excitation synchronizes neural firing. J Comp Neurosci 1:313–321. CrossRef Medline

Vidal JR, Chaumon M, O'Regan JK, Tallon-Baudry C (2006) Visual grouping and the focusing of attention induce γ-band oscillations at different frequencies in human magnetoencephalogram signals. J Cogn Neurosci 18:1850–1862. CrossRef Medline

Vinck M, Womelsdorf T, Buffalo EA, Desimone R, Fries P (2013) Attentional modulation of cell-class-specific γ-band synchronization in awake monkey area v4. Neuron 80:1077–1089. CrossRef Medline

Vinck M, Batista-Brito R, Knoblich U, Cardin JA (2015a) Arousal and loco-motion make distinct contributions to cortical activity patterns and visual encoding. Neuron 86:740–754. CrossRef Medline

Vinck M, Bos JJ, Van Mourik-Donga LA, Oplaat KT, Klein GA, Jackson JC, Gentet LJ, Pennartz CM (2015b) Cell-type and state-dependent synchronization among rodent somatosensory, visual perirhinal cortex, and hippocampus CA1. Front Syst Neurosci 9:187. CrossRef Medline

Wang XJ, Buzsáki G (1996) γ oscillation by synaptic inhibition in a hippocampal interneuronal network model. J Neurosci 16:6402–6413. Medline

Wehr M, Zador AM (2003) Balanced inhibition underlies tuning and sharpens spike timing in auditory cortex. Nature 426:442–446. CrossRef Medline

Welle CG, Contreras D (2016) Sensory-driven and spontaneous γ oscillations engage distinct cortical circuitry. J Neurophysiol 115:1821–1835. CrossRef Medline

Whittington MA, Traub RD, Jefferys JG (1995) Synchronized oscillations in interneuron networks driven by metabotropic glutamate receptor activation. Nature 373:612–615. CrossRef Medline

Whittington MA, Traub RD, Kopell N, Ermentrout B, Buhl EH (2000) Inhibition-based rhythms: experimental and mathematical observations on network dynamics. Int J Psychophysiol 38:315–336. CrossRef Medline

Whittington MA, Cunningham MO, LeBeau FE, Racca C, Traub RD (2011) Multiple origins of the cortical γ rhythm. Dev Neurobiol 71:92–106. CrossRef Medline

Wilent WB, Contreras D (2004) Synaptic responses to whisker deflections

in rat barrel cortex as a function of cortical layer and stimulus intensity. J Neurosci 24:3985–3998. CrossRef Medline

Wilson HR, Cowan JD (1972) Excitatory and inhibitory interactions in localized populations of model neurons. Biophys J 12:1–24. CrossRef Medline

Wilson NR, Runyan CA, Wang FL, Sur M (2012) Division and subtraction by distinct cortical inhibitory networks in vivo. Nature 488:343–348. CrossRef Medline

Womelsdorf T, Fries P, Mitra PP, Desimone R (2006) γ-band synchronization in visual cortex predicts speed of change detection. Nature 439:733–736. CrossRef Medline

Womelsdorf T, Schoffelen JM, Oostenveld R, Singer W, Desimone R, Engel AK, Fries P (2007) Modulation of neuronal interactions through neuronal synchronization. Science 316:1609–1612. CrossRef Medline

Womelsdorf T, Lima B, Vinck M, Oostenveld R, Singer W, Neuenschwander S, Fries P (2012) Orientation selectivity and noise correlation in awake monkey area V1 are modulated by the γ cycle. Proc Natl Acad Sci U S A 109:4302–4307. CrossRef Medline

Xing D, Yeh CI, Burns S, Shapley RM (2012) Laminar analysis of visually evoked activity in the primary visual cortex. Proc Natl Acad Sci U S A 109:13871–13876. CrossRef Medline

Yamamoto J, Suh J, Takeuchi D, Tonegawa S (2014) Successful execution of working memory linked to synchronized high-frequency γ oscillations. Cell 157:845–857. CrossRef Medline

Zheng C, Bieri KW, Hsiao YT, Colgin LL (2016) Spatial sequence coding differs during slow and fast γ rhythms in the hippocampus. Neuron 89: 398–408. CrossRef Medline