Review

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Dynamic Network Communication as a Unifying Neural Basis for Cognition, Development, Aging, and Disease

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ABSTRACT

Perception, cognition, and social interaction depend upon coordinated neural activity. This coordination operates within noisy, overlapping, and distributed neural networks operating at multiple timescales. These networks are built upon a structural scaffolding with intrinsic neuroplasticity that changes with development, aging, disease, and personal experience. In this article, we begin from the perspective that successful interregional communication relies upon the transient synchronization between distinct low-frequency (<80 Hz) oscillations, allowing for brief windows of communication via phase-coordinated local neuronal spiking. From this, we construct a theoretical framework for dynamic network communication, arguing that these networks reflect a balance between oscillatory coupling and local population spiking activity and that these two levels of activity interact. We theorize that when oscillatory coupling is too strong, spike timing within the local neuronal population becomes too synchronous; when oscillatory coupling is too weak, spike timing is too disorganized. Each results in specific disruptions to neural communication. These alterations in communication dynamics may underlie cognitive changes associated with healthy development and aging, in addition to neurological and psychiatric disorders. A number of neurological and psychiatric disorders —including Parkinson's disease, autism, depression, schizophrenia, and anxiety—are associated with abnormalities in oscillatory activity. Although aging, psychiatric and neurological disease, and experience differ in the biological changes to structural gray or white matter, neurotransmission, and gene expression, our framework suggests that any resultant cognitive and behavioral changes in normal or disordered states or their treatment are a product of how these physical processes affect dynamic network communication.

Keywords: Anxiety, Autism, Coherence, Coupling, Depression, Gamma, Network dynamics, Neural oscillations, Parkinson's disease, Schizophrenia, Theta

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A complete model of cognitive function and dysfunction must account for a diversity of factors including, but not limited to, brain structure and genetics, rapid neuronal temporal dynamics and neuroplasticity, and developmental and sociological considerations (1,2). Cognition is critically reliant upon the dynamic, parallel coordination of large groups of neurons separated by substantial neural distances. This coordination is surprisingly flexible but remarkably precise (3), especially considering behavior emerges in an inherently noisy electrochemical neuronal environment (4).

We propose a theory for how disruptions to dynamic network communication can lead to the neurocognitive changes observed during development and aging, as well as in neurological and psychiatric disorders. Our theory is predicated on evidence that neuronal oscillations bias the probability of spiking such that action potentials are more likely to occur during periods of interregional oscillatory coherence. We extend this by arguing that such oscillatory-mediated spike synchrony would feed back onto the local field potential (LFP), increasing LFP coherence. In the pathologic case, we theorize that this mechanism results in an exaggerated state of overcoupling. To break cycles of LFP-induced spike synchrony causing reinforced LFP coherence causing even stronger spike synchrony, some controlling or interfering mechanism needs to be introduced. We posit that one mechanism may be neural noise, defined as temporally decorrelated spikes occurring during nonpreferred LFP oscillatory phases.

This dynamic network communication framework differs from purely structural or neurochemical accounts in that, although neural architecture and neurochemistry play a critical role in cognitive functioning by providing the scaffolding upon which the dynamic communication system is built, structure and chemistry alone are insufficient for understanding neuronal dynamics (2,5); ultimately, cognition reduces to the dynamics of neural communication.

In this article, we begin by reviewing the evidence for the causal role of oscillatory interregional communication in support of healthy cognition and present an accounting for the possible neurophysiological basis for such a communication mechanism. We then explore the consequences of alterations to network communication dynamics, including both failures

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to establish and failures to break an oscillatory communication network. We then argue that these changes might be observable in mesoscale or even macroscale electrophysiological recordings, reflected in specific components of the power spectral density (PSD). We conclude by presenting a theoretical framework for how these disruptions to network communication dynamics provide a unifying framework for understanding a variety of neurological and psychiatric disorders in terms of neuronal activity, using Parkinson's disease, depression, anxiety, schizophrenia, and autism as exemplar cases. Thus, we argue that the resultant behavioral syndrome of any structural or neurochemical changes associated with development, aging, experience, and disease are manifested by their effect on dynamic network communication.

OSCILLATORY COMMUNICATION

Oscillations Bias Spiking Activity

Neural oscillations are (usually) lower frequency (< 80–100 Hz) and play a causal role in neural communication, cognition, and behavior (6,7) (though there exists rhythmic activity at higher frequencies, such as hippocampal ripples). Research into the functional role of scalp electroencephalography (EEG) and magnetoencephalography oscillations shows that ongoing visual cortical oscillatory phase (8–10) and power (11,12) predict performance on a variety of tasks (13–16). For example, people are more likely to correctly respond to target visual stimuli when those stimuli appear during the preferred phase or power of ongoing oscillatory activity, perhaps due to ongoing oscillatory phase biasing neuronal excitability (9).

In more causal direct tests on spiking activity, experiments have shown that applying relatively weak, low-amplitude oscillatory electric fields bias neuronal firing. This finding, known as ephaptic coupling (6,17), shows that subthreshold changes in extracellular electric fields affect the transmembrane voltage of nearby neurons. Experimental manipulations using exogenous oscillatory electric fields have found that low-frequency oscillatory stimulation (< 2 Hz) can entrain cortical—or even hippocampal—neurons in proportion to the stimulation intensity and behavioral state of the animal (18). Similarly, oscillatory gamma (~30 Hz) hippocampal stimulation affects cornu ammonis 1 pyramidal spike timing, locking spikes to the phase of the stimulation oscillation (19). The authors of that report argue that a decoherent extracellular field could lead to less temporally correlated spiking, which could act as a "safety mechanism to prevent hypersynchronization." This interaction between the coherence of the oscillatory field and spiking activity is a critical element in our framework, and we will refer to it throughout this article.

Synchronization and Neural Communication

There are a variety of methods for assessing interregional neural communication depending on the measurement scale and signal source. The LFP, which is the extracellular electrical potential recorded invasively using penetrating electrodes, is influenced by a number of factors including neuronal geometry and laminar depth. Electrical activity recorded either on the cortical surface, such as with electrocorticography (ECoG), or from noninvasive scalp EEG is dominated by postsynaptic potentials. Increases in local population firing rate are reflected by elevated broadband activity in the LFP and ECoG (20–23). This broadband shift is particularly evident in the high-gamma (70–200 Hz) range and less in the low-frequency range, possibly because the lower frequency portion of the PSD is masked by a simultaneous reduction in the oscillatory components of the LFP, which are less directly linked to neural firing rates and may reflect local excitatory-inhibitory circuit motifs (24) (Figure 1).

Interregional communication can be inferred, at the level of the LFP, from the interregional oscillatory phase coherence between two regions (25,26). In functional magnetic resonance imaging (fMRI), the temporal profile of activity in a seed region may be correlated with the activity in other regions (27). Such methods can be generalized as a statistical assessment of how much information the activity in one region provides about the activity in a second region. These methods are used to index neural communication; interestingly, fMRI blood oxygen level-dependent (BOLD) signal correlations may be driven

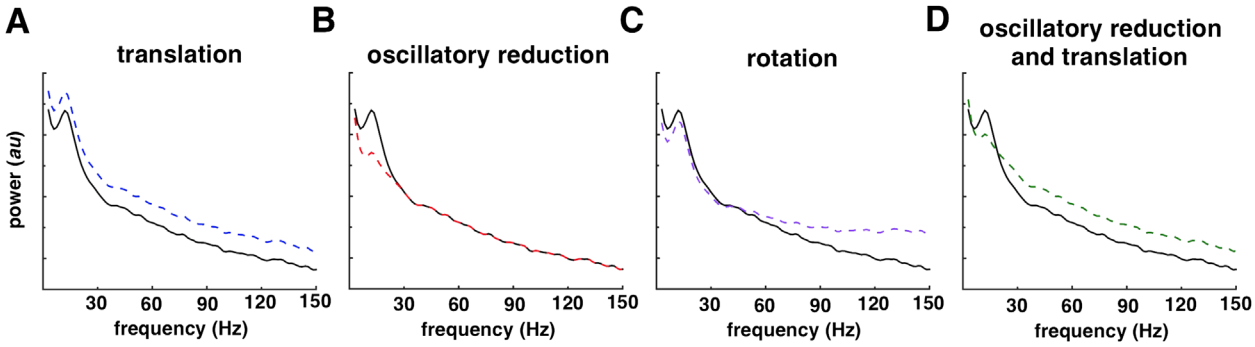

Figure 1. Example power spectral changes. All four plots contain an exemplar power spectral density (PSD) consisting of a 1/*f* process plus an oscillation centered around 12 Hz (solid black lines). This PSD is then modified in four different ways (dashed colored lines). **(A)** In this example, the PSD in black has been modified by simple translation, adding power at all frequencies (blue line). **(B)** Here, the background 1/*f* process remains unaffected; all that has changed is that the 12-Hz oscillation has been reduced in power (red line). **(C)** A single manipulation—rotation of the PSD about a pivot frequency (40 Hz)—results in a simultaneous decrease in low-frequency power and an increase in high-frequency power (purple line). **(D)** Here two separate effects—translation of the PSD and reduction of 12-Hz oscillatory power—have a similar effect as the single rotation process described in **(C)** in that low-frequency power is reduced and high-frequency power is increased [c.f. Miller *et al*. (21)].