

Thalamic Coordination of Cortical Communication

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Higher-order thalamic nuclei, like the pulvinar, have extensive connections with cortex, suggesting a role in the coordination of cortical communication. A recent study in *Science* by Saalman et al. (2012) implicates the pulvinar in promoting cortical alpha-band synchronization that subserves communication of attended information.

Modern views of thalamic functions emphasize an intimate relationship with cortical processes. Important insights arise from basic anatomical and electrophysiological findings (Sherman, 2007): layer 5 cortical neurons send powerful “driving” axons to the pulvinar nucleus in the visual and the posteromedial complex (PoM) in the somatosensory system. From there, thalamic neurons project back to superficial cortical layers, often branching into several areas, where they converge on targets of cortico-cortical projections—an ideal position to regulate communication among cortical areas. Although the functional analysis of cortico-thalamo-cortical communication is still in its early days, there is accumulating evidence in support of an essential involvement of “higher-order” thalamus in cortical processes. Responses of pulvinar and PoM neurons depend on input from cortex, have latencies in the same range as cortical neurons, and inherit properties resulting from cortical computations such as receptive field layout or the sensitivity for direction of motion in the case of pulvinar (Berman et al., 2011). Conversely, two recent studies demonstrated in both the visual as well as the somatosensory domain that cortical activity critically depends on the intactness of higher-order thalamic nuclei such as the pulvinar (Theyel et al., 2010; Purushothaman et al., 2012). Considering all these features together, it is not surprising that cortico-thalamo-cortical loops have been implicated as central ingredients of higher cognitive functions.

In the visual system, several theories on the mechanisms of spatial attention

discuss an involvement of pulvinar gating (Olshausen et al., 1993). Evidence from electrophysiological, imaging, and lesion studies together lend some support to this view, as, for example, monkeys with pulvinar lesions commonly display behavioral changes ranging from increased reaction times to neglect-like symptoms (Petersen et al., 1987; Wilke et al., 2010). However, how pulvinar activity contributes to attentional processes in the intact animal and controls selective routing of cortical activity remains unknown.

A new study published in *Science* by Saalman et al. (2012) aims to fill this gap by investigating the role of pulvinar neurons in coordinating synchronization of cortical signals in the alpha range (8–12 Hz) during visual spatial attention. Saalman et al. (2012) performed multi-site electrophysiological recordings and sampled neural activity from two adjacent midlevel cortical areas of the occipito-temporal stream, thought to be involved in the processing of visual shape and object information and a region in the ventro-lateral part of the pulvinar that they had identified using diffusion tensor imaging (DTI). To control attention, Saalman et al. (2012) trained two monkeys to report the shape of a visual target stimulus presented among an array of distracters. The position of the target was cued by a preceding stimulus flashed for 100 ms at the target location followed by a brief delay period before target onset. Saalman et al. (2012) demonstrate a cue-triggered enhancement of pulvinar responses, which is strongest during the cue presentation and sustained to a smaller extent during the delay period,

most likely reflecting attentional engagement. The study does not document the cue effects on the firing rates of the cortical neurons, making it difficult to decide whether attention modulates cortical and thalamic responses to the same extent.

Building upon the idea that the intimate connectivity of pulvinar neurons with cortical areas might contribute to the coordination of neuronal activity across areal boundaries, Saalman et al. (2012) focused their subsequent analyses on synchrony effects both within pulvinar as well as between the cortical areas and pulvinar, respectively. Here Saalman et al. (2012) report an attention-dependent increase in coherence between pulvinar spikes and local field potentials (LFPs) in an alpha-frequency band peaking around 12 Hz, suggesting that attention enhances thalamo-cortical reverberation in this particular frequency band. In agreement with this scenario, LFP coherence between pulvinar and cortex also increased with attention at this frequency. This finding extends earlier observations of alpha coherence between thalamus and cortex in the canine brain (Lopes da Silva et al., 1980). Going one step further in testing the role of pulvinar as pacemaker for cortical alpha oscillations, Saalman et al. (2012) use conditional Granger causality analysis to determine the direction of interactions. The findings suggest that the alpha coherence between cortical areas is entirely driven by the pulvinar and that this pulvinar-mediated alpha coherence is enhanced with attention. These results implicate the pulvinar in actively modulating cortico-cortical synchrony as

a function of attentional allocation, challenging the prevailing view that higher cognitive functions are exclusively driven by and within the cortex.

The most unexpected findings of Saalman et al. (2012) are that visual stimulation induces rather than reduces alpha-band activity and that attention enhances rather than diminishes it. Alpha was discovered by Berger as the rhythm that is strongest when the brain is not externally stimulated, coining the term “idling rhythm.” Since then, countless studies confirmed that alpha in a given cortical area is strongest when this area is not functionally activated (Jensen and Mazaheri, 2010). Likewise, alpha is enhanced when attention is disengaged from a given area, i.e., when attention is directed to a different modality, a different spatial location, or a different stimulus than the ones activating a given cortical region (Jensen and Mazaheri, 2010). Far fewer studies have reported stimulus or attention-related increases of alpha-band activity. It is difficult to integrate these studies into a coherent model. Yet, one hint for reconciling the different observations might come from those studies that have differentiated between cortical layers and suggest multiple alpha generators (Buffalo et al., 2011; Bollimunta et al., 2008). Buffalo et al. (2011) report that visual stimulation has opposite effects on two alpha generators in the supra- and infragranular cortical layers of early visual cortex: while visual stimulation reduced supragranular alpha, it enhanced infragranular alpha. The pulvinar alpha reported by Saalman et al. (2012) was also enhanced by stimulation and might therefore be related to the infragranular cortical alpha source. Consistent with this conjecture, the main driving input to pulvinar arises from cortical layer 5 (Sherman, 2007). Contrastingly, the alpha that has been reported in a large number of electroencephalographic/magnetoencephalographic (EEG/MEG) studies to be reduced by functional activation might be related to supragranular alpha sources. Supragranular alpha sources might be more readily detected by EEG/MEG methods, because the synaptic inputs generated by those alpha

sources probably impinge on the dendrites of large pyramidal cells, resulting in vertical currents for which EEG/MEG measures are sensitive. Alternatively or in addition, the increased alpha-band coherence during the delay period described by Saalman et al. (2012) could reflect effects related to short-term memory load, which have been related to increased alpha-band power in several studies (Jensen and Mazaheri, 2010).

Saalman et al. (2012) further extend their core findings related to pulvinar-driven alpha-band synchronization to establish a functional relationship between alpha- and gamma-band synchronization during attentional allocation. At the cortical level, previous studies have reported increases in gamma coherence primarily in the context of selective visual attention (Fries, 2009), with the idea that it promotes a more efficient communication between cortical areas (Fries, 2009). Important questions follow regarding the circuits needed to generate gamma oscillations and the attentional mechanisms modulating the phase synchrony across neurons. Regarding the former, current evidence indicates the importance of inhibitory mechanisms provided by local GABAergic input (Fries, 2009). Regarding the latter, several theories have suggested that nonspecific circuits that exhibit low-frequency oscillations could mediate gamma synchrony via cross-frequency coupling (VanRullen and Koch, 2003; Fries, 2009). The Saalman et al. (2012) paper provides important new information in this respect, as the authors show that, unlike cortical circuits, the pulvinar engages in local synchrony in the alpha and not in the gamma range. This is not surprising given the evidence for alpha generators in the thalamus and for an absence of gamma sources in deep cortical layers, where the corticothalamic projection neurons are located (Buffalo et al., 2011). Moreover, a supplementary figure provided by Saalman et al. (2012) shows increased cross-frequency coupling between cortical alpha- and gamma-band activity with attention. Clarifying the mechanistic details and functional implications of this alpha-gamma coupling deserves further

consideration in future research. An attractive speculation is that alpha rhythms generated during wakefulness by pulvinar neurons reflect periodic perceptual sampling (VanRullen and Koch, 2003; Fries, 2009; Landau and Fries, 2012). This sampling process could synchronize cortical oscillations, so that communication between neurons could be enhanced by appropriate phase coupling between spiking activity and membrane potential oscillations. In short, the new study by Saalman et al. (2012) assigns a new role to alpha rhythms and refocuses attention from a cortico-centric view back to a more integral consideration of thalamocortical interactions.

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