COGSCI132_Rhythms of the Brain
Final Project Spring 2025 **Jiyun Woo**

3. The Hierarchical Structure of Brainwaves and Its Evolutionary Implications

(Explain the hierarchy of oscillations and its relation to evolution. Describe the hierarchical organization of different frequency components in the brain. Use a drawing to explain this. What are the advantages of this organization in terms of autonomy and cooperativity? Use at least two drawings in total to answer this question. Creative and original drawings will receive extra credit.)

The brain's electrical rhythms resemble a hierarchical symphony composed over hundreds of millions of years. At the foundation of this complex orchestration lies the infra-slow oscillation, operating below 1Hz, where a single cycle can last several seconds or more. This slowest rhythm spreads widely across the entire cerebral cortex, encompassing the Default Mode Network (DMN), membrane potential fluctuations, and physiological rhythms like heartbeat and respiration. Evolutionarily ancient, infra-slow rhythms appeared long before advanced mammals, present even in primitive vertebrates. The primary evolutionary advantage of this rhythm is its global integrative capability—its slow and widespread synchronization provides an essential spatial and temporal scaffold. All faster rhythms depend on this foundational infra-slow oscillation to operate effectively, creating a three-dimensional virtual space in which sensory experiences, concepts, and memories can be spatially organized, thus integrating large brain regions without extensive axonal connections.

Above the infra-slow foundation lies the delta (δ) rhythm, operating at 1–4Hz, prominently found in early vertebrates such as fish and amphibians. In mammals, this rhythm persists as an electrical signature of fundamental survival instincts and homeostasis, including hunger, thirst, pain avoidance, and sexual drives. Delta waves ensure that higher cognitive functions remain closely aligned with survival and physiological needs, thereby strictly constraining cognitive activity.

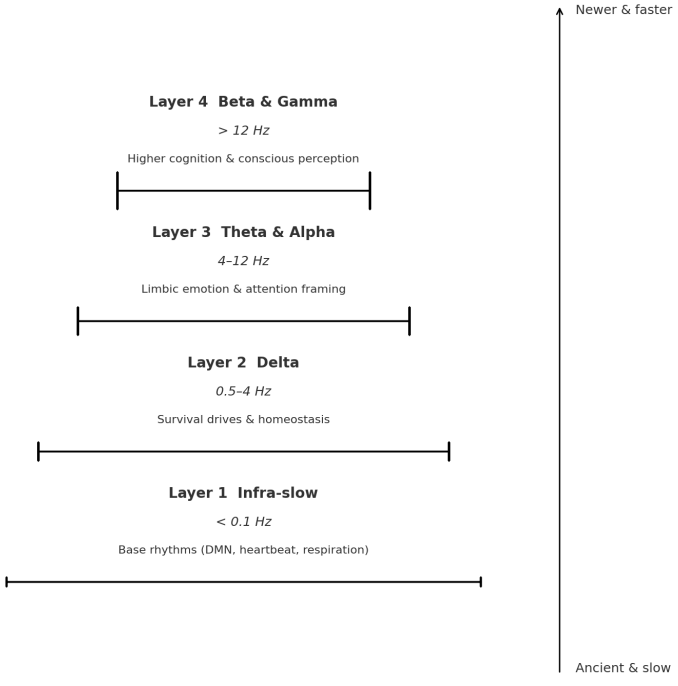
Stacked upon the delta rhythm are the mid-frequency theta (θ, 4–8Hz) and alpha (α, 8–12Hz) rhythms, predominantly associated with limbic structures and the hippocampal-septal loop. These rhythms mediate higher-order emotional processing, memory consolidation, and working memory. Theta rhythms, in particular, support emotional memory and learning, whereas alpha rhythms contribute to sensory integration and stable conscious experiences, setting the temporal frame for attention and cognitive processing.

At the apex of this hierarchical structure are the beta (β) and gamma (γ) rhythms, operating at frequencies above 13Hz. These high-frequency oscillations, primarily generated within localized neocortical networks, facilitate complex cognitive activities, sensory integration, conscious perception, and linguistic processing. Gamma and beta rhythms bind discrete sensory features into unified perceptions and experiences, depending crucially upon

synchronization with lower-frequency rhythms to integrate information temporally and spatially into coherent conscious experiences.

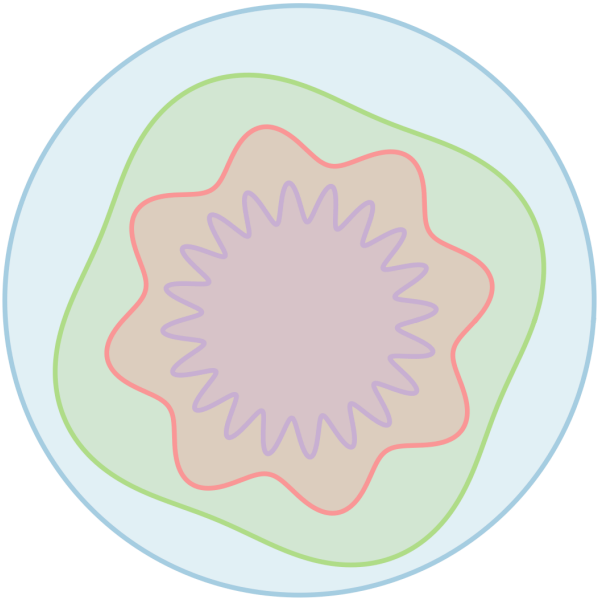
This hierarchical organization of oscillatory rhythms simultaneously achieves autonomy and cooperativity. Each rhythm layer maintains functional autonomy, independently producing its own oscillations within specialized neural circuits. Yet, crucially, these layers cooperate closely through a phenomenon known as phase-locking, whereby the phases of slower rhythms provide temporal windows during which faster rhythms organize their activity. This hierarchical phase-amplitude coupling allows the brain to perform parallel processing at multiple temporal and spatial scales, simultaneously preserving independent specialized functions and ensuring coherent, integrated cognitive and conscious experiences.

From an evolutionary perspective, this layered structure optimizes neural functioning across different scales. The infra-slow rhythms, being the oldest and slowest, ensure global coherence and stability, while the progressively newer and faster rhythms allow increasingly sophisticated and specialized information processing. Thus, the hierarchical brainwave structure promotes both stability through autonomy at lower levels and adaptability through cooperativity at higher levels, offering evolutionary advantages in complex cognitive and behavioral flexibility.



Hierarchical Brainwave "Cake": Layer 1 (Infra-slow, <0.1 Hz) forms the broad foundational rhythm for global integration (DMN, respiration, heartbeat). Layer 2 (Delta, 1–4 Hz) encapsulates fundamental survival drives and homeostatic mechanisms. Layer 3 (Theta/Alpha, 4–12 Hz) facilitates limbic emotion and cognitive framing. Layer 4 (Beta/Gamma, >12 Hz) governs higher-order cognition and conscious perception. Each

layer, while functionally distinct, overlaps and interacts continuously with adjacent layers, illustrating the seamless integration of different frequencies into a cohesive whole.



Phase Locking Donut: A concentric visualization where slower outer rhythms support and structure increasingly faster inner rhythms. The outermost infra-slow ring represents one extremely slow cycle, within which faster delta, theta, and gamma cycles occur multiple times. This depiction emphasizes how slower rhythms provide temporal scaffolding for faster oscillations, ensuring precise synchronization across diverse brain functions and promoting coherent cognitive and emotional experiences.

7. The Role of Theta Oscillations in Regulating the Limbic System

(What is the role of the theta band regulating the limbic system and what are the structures involved?)

The theta rhythm is a representative oscillation of the limbic system and serves as a core regulator of emotional processes**.** According to the paper, synchronization in the theta frequency range (approximately 4–8 Hz) plays a critical role in detecting, integrating, and evaluating emotionally significant stimuli. Theta activity is particularly prominent in limbic structures such as the hippocampus and amygdala, and electrical stimulation of these regions often leads to a marked increase in theta oscillations. In this sense, the theta rhythm can be considered an intrinsic oscillatory mode of the limbic system. When this rhythm is enhanced, it contributes to the modulation of emotional states like fear and anxiety by influencing the output dynamics of limbic circuits.

Beyond emotional regulation, theta waves are also associated with unconscious cognitive functions such as integrating new sensory inputs with internal representations and

contributing to memory formation. For instance, during repeated exposure to emotionally relevant stimuli, theta rhythms facilitate the encoding of contextual and affective information, promoting efficient memory consolidation.

The modulatory role of the theta rhythm in the limbic system is closely tied to inter-regional synchronization. Strong theta rhythms are observed across the entire limbic system, with hippocampal theta activity serving as a coordinating rhythm that binds multiple structures into a unified functional network. Notably, theta synchronization between the hippocampus and the prefrontal cortex or cingulate cortex provides a well-established neurobiological foundation for emotion-memory interactions. As theta rhythms propagate from the hippocampus to these cortical regions, emotional context is integrated into cognitive processes, effectively linking feeling and thought.

In higher mammals, the limbic system contains ancient cortical regions such as the paleocortex, which also oscillate in the theta range and are tightly entrained with hippocampal activity. This allows affective signals from the limbic system to modulate cognitive functions in the neocortex.

In summary, theta oscillations coordinate various limbic structures—including the hippocampus, amygdala, and cingulate cortex—into a rhythmic system that facilitates emotional generation and regulation, as well as the coupling of emotion and memory. The effective orchestration of limbic theta rhythms enables the brain to detect and learn from emotionally salient experiences while maintaining a degree of emotional stability over time.

8. The Effect of Gamma Oscillations on Cognition

(Explain the effect of Gamma oscillations in cognition according to the explanation given by the paper.)

Gamma waves, typically defined as high-frequency brain oscillations above 30 Hz, are strongly associated with cognitive processing and conscious awareness. According to the paper, gamma and beta oscillations represent the uppermost layer of the brain's hierarchical oscillatory structure and are hypothesized to play a fundamental role in high-order cognition. Gamma activity is particularly implicated in processes such as feature binding, attentional focus, and working memory. These functions involve the integration of discrete pieces of information into unified perceptual experiences.

Empirical studies have shown that when a particular sensory stimulus reaches conscious perception, there is a marked increase in gamma synchronization across spatially distributed brain regions. For example, during visual awareness, gamma phase synchronization can be observed between the visual cortex and the prefrontal cortex. This suggests that gamma oscillations facilitate large-scale neural integration, essentially binding information into coherent conscious experiences.

While the precise functional significance of gamma oscillations remains a topic of ongoing scientific debate, the authors of the paper present several compelling hypotheses. They propose that gamma activity may contribute to the richness of sensory experience, or qualia—for instance, the vividness of color or the texture of sound. Gamma waves are also

linked to higher-order executive functions, such as problem solving and insight generation. Experimental data suggest that gamma activity increases during moments of deep understanding or self-reflective thought, and even during meta-cognitive processes. This association implies that gamma oscillations support the fine-tuning of neuronal communication required for advanced cognitive tasks.

Furthermore, gamma rhythms appear to modulate the level of arousal and attention. By coordinating the precise timing of neural firing across networks, gamma activity helps distribute energy and synchronize processing within and between cortical regions. Some researchers argue that gamma waves might be mere epiphenomena—byproducts of brain activity—but others counter this by pointing to the presence of spontaneous gamma oscillations during states of deep muscle relaxation, and consistent correlations between gamma power and cognitive performance across numerous studies.

In summary, the paper views gamma oscillations as the pinnacle of the brain's oscillatory hierarchy. Their spatiotemporal synchronization, especially when aligned with slower oscillations through cross-frequency coupling, allows for the integration of sensory input, attention, and memory into conscious thought. This perspective highlights gamma rhythms as crucial mechanisms through which the brain constructs coherent, dynamic, and richly textured conscious experiences.

9. The Effect of Meditation on Brain Oscillations

(Explain the effect of meditation on electrical oscillations in the brain.)

Meditation is known to produce distinct and measurable changes in brainwave activity. Although different types of meditation may affect brain oscillations in slightly different ways, a general trend observed across many studies is an overall increase in brain oscillatory activity, especially through enhanced synchronization in slower frequency bands.

Experienced meditators often show significantly greater power and synchrony in the alpha (8–12 Hz) and theta (4–8 Hz) bands. These increases have been shown to correlate with the amount and depth of meditation training. Such neural signatures reflect a state of “relaxed awareness,” wherein the practitioner maintains heightened internal focus while reducing mind-wandering. For example, during focused-attention meditation, alpha and theta power tend to increase in frontal and parietal regions, whereas in open-monitoring practices that involve awareness of bodily sensations, increases in similar low-frequency bands are observed in occipital and sensory-related areas.

Interestingly, high-frequency gamma activity has also been reported in certain meditative states. In particular, advanced practitioners such as Tibetan monks have demonstrated increased gamma-band synchronization in the frontal and parietal cortices during compassion meditation and deep absorptive states. While some researchers have raised concerns that such gamma increases may result from muscle micro-movements (artifacts), studies that rigorously control for muscular activity have still detected endogenous gamma oscillations, suggesting that such patterns reflect genuine cognitive and conscious arousal associated with meditation.

Overall, meditation appears to induce both an enhancement of slow oscillations and a more structured activation of fast rhythms, resulting in a harmonious reorganization of the brain's entire spectral profile. For instance, meditators often display more symmetrical EEG activity between frontal and occipital regions—suggesting a rebalancing of interhemispheric asymmetries that are commonly exaggerated under stress (e.g., excessive beta activation in one frontal hemisphere). Furthermore, the presence of delta activity during meditation—typically associated with deep sleep—may indicate a restorative effect, akin to the brain's recovery processes during slow-wave sleep. After deep meditation sessions, individuals often report improved clarity and enhanced alertness, possibly reflecting the benefits of such waking-state delta activity.

Ultimately, meditation appears to recalibrate both the attentional control networks and the autonomic nervous system. Through regular practice, it enhances the power and synchrony of slow rhythms while reducing overreactivity to external stimuli. This shift supports better cognitive control, emotional regulation, and overall psychological well-being. In sum, meditation fosters a brain state characterized by internal stability and reduced reactivity—achieved through dynamic, rhythmically coherent neural activity across multiple frequency bands.

10. Disruption of Brain Oscillations in Chronic Diseases – Parkinson's Disease Example

(Find a paper that complements the description of oscillations in chronic diseases in the last section of the paper and describe the general findings in that paper that relate to possible involvement of electrical oscillations in a disease of your interest. Attach the paper that you chose to the submission.)

Parkinson's disease (PD) is a chronic neurodegenerative disorder characterized by motor dysfunction due to the degeneration of dopaminergic neurons. One hallmark feature of Parkinson's disease is the abnormal enhancement of beta (β) oscillations in the subthalamic nucleus (STN), typically in the frequency range of 13–35 Hz. According to recent research published by Neumann et al. (2024), persistent excessive beta oscillations are strongly correlated with the severity of motor symptoms in PD patients. These abnormal beta rhythms occur not only during wakefulness but also throughout sleep stages, contributing to sleep disturbances and rigidity of movement.

The abnormal elevation of beta activity in Parkinson's disease is thought to reflect pathological synchronization within motor circuits, effectively "locking" these networks and impeding the initiation and fluid transition of movements. Treatment approaches such as dopamine medication (L-DOPA) substantially reduce these pathological beta oscillations, leading to significant improvements in motor symptoms. Moreover, deep brain stimulation (DBS) targeting the STN has been employed to suppress abnormal beta activity. Recent advancements, including adaptive DBS, involve real-time monitoring of beta rhythms and delivering stimulation only when necessary, effectively minimizing side effects while optimizing therapeutic outcomes.

Innovative research has also explored real-time biofeedback training using beta oscillation data obtained from deep brain stimulation devices. This approach enables patients to consciously modulate their beta activity levels through visual feedback, resulting in improved motor function. Such methods demonstrate the potential of biofeedback-assisted modulation of pathological brainwave patterns as an adjunctive therapy for Parkinson's disease.

In summary, pathological beta oscillations serve as critical biomarkers and therapeutic targets in Parkinson's disease. Understanding these oscillatory disruptions provides valuable insights into the disease's mechanisms and paves the way for novel therapeutic interventions aimed at correcting aberrant brain rhythms, thereby improving patients' motor and overall quality of life.

Reference: Neumann et al. (2024). Modulation of subthalamic beta oscillations by movement, dopamine, and deep brain stimulation in Parkinson's disease. Nature Parkinson's Disease. Retrieved from: https://www.nature.com/articles/s41531-024-00693-3