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# EEG Phase/Coupling Metrics for Audiovisual Mapping

## Introduction and Context

Real-time EEG visualization for neurofeedback in a WebGL/Three.js environment demands both scientific accuracy and engaging aesthetics. This memo explores key EEG phase and coupling metrics—**Phase-Locking Value (PLV)**, **coherence**, and **Phase-Amplitude Coupling (PAC)**—and proposes how to map these metrics to visual parameters (geometry, “twist,” glow, pulse) in an audiovisual display. We assume consumer-grade EEG devices (e.g. Neurosity Crown, Muse, OpenBCI) with limited channels (often 4–8 sensors) and higher noise levels than clinical systems [1]. These constraints mean metrics must be computed robustly (e.g. using band-specific filtering and sliding windows) and mapped in a way that remains stable despite signal noise. A **hybrid mapping** strategy is advisable: use literal, direct mappings for basic signal features to ensure stable feedback (for example, mapping EEG power to an object’s size or brightness), and use metaphorical or abstract mappings for higher-level metrics (for example, mapping inter-channel synchrony to how multiple visual elements twist or flow together) to represent complex brain dynamics in intuitive ways. Below, we define each metric and outline neurofeedback usage, then detail proposed mapping rules for geometry, twist, glow, and pulse.

## Phase-Locking Value (PLV) – Phase Synchronization

**Definition:** *Phase-Locking Value (PLV)* is a metric of functional connectivity that quantifies how consistently the phases of two EEG signals align. Formally, PLV is defined as the absolute value of the mean phase difference between two signals, treated as unit-length complex vectors [2]. It ranges from 0 to 1, where 0 indicates a random, non-synchronized phase relationship and 1 indicates perfect phase-locking (the phase difference is constant across time or trials) [3] [4]. In essence, if two brain regions oscillate with a stable phase relationship, their PLV will be high, whereas a fluctuating or independent phase relationship yields a low PLV. Because PLV focuses purely on phase timing and discards amplitude information, it is not confounded by differences in signal power. This metric was popularized by Lachaux et al. (1999) for measuring long-range neural synchronization [5], and it has since become a common way to assess EEG/MEG connectivity.

**Neurofeedback/Relevance:** PLV is widely used in cognitive neuroscience research to detect functional connections (e.g. synchrony between frontal and parietal regions during tasks) and has potential for neurofeedback, although traditional neurofeedback has mostly used simpler measures (like band power ratios [6]). Connectivity training protocols in neurofeedback often target coherence (discussed next), but one could similarly use PLV as the feedback feature to train a person to increase or decrease phase synchrony between two locations. High PLV between two EEG channels might be desirable in protocols aiming to enhance communication between regions (for example, interhemispheric coordination), whereas reducing abnormal hyper-synchrony (lowering PLV) might be a goal in conditions where excessive coupling is observed. Because PLV can capture rapid changes in connectivity on a fine time scale [7], it is conceivable to compute a PLV time-course in real time and feed it back. However, one must smooth or average it over a short sliding window to avoid erratic feedback, and guard against spurious synchrony from volume conduction or noise. In summary, PLV provides a phase-based connectivity metric that, if made stable, can drive visual elements representing “connection” or synchronization in a neurofeedback display.

## Coherence – Frequency-Specific Connectivity (Amplitude + Phase)

**Definition:** *Coherence* in EEG is another functional connectivity metric, defined in signal-processing terms as the normalized cross-power spectrum between two signals [8]. In simpler terms, coherence measures how well two EEG channel signals correspond to each other at a particular frequency. It is computed from the cross-spectral density of the two signals and their individual power spectral densities, yielding a value between 0 and 1 for each frequency (or within a band) [8]. A coherence of 1 at a given frequency means the two signals have perfectly correlated activity (both amplitude and phase) at that frequency, whereas 0 means no consistent relationship. Unlike PLV, coherence depends on both phase *and* amplitude consistency [9]. This means high coherence could arise either because the signals’ phases are locked (in phase or with a constant phase lag) *or* simply because one signal’s amplitude fluctuations predict the other’s (or both). Coherence is essentially a frequency-domain correlation measure; it has been a classic metric for EEG connectivity analyses [10] [11]. However, because amplitude effects can inflate coherence, researchers sometimes prefer phase-only metrics like PLV or the phase-lag index to isolate true synchrony [9].

**Neurofeedback/Relevance:** Coherence has a direct history in neurofeedback training. *Coherence-based neurofeedback* protocols explicitly attempt to alter the connectivity between brain regions by rewarding changes in coherence values between specific electrode pairs or networks. This approach is based on findings that atypical EEG coherence (either too low or too high) is associated with certain neurological or cognitive issues. For example, abnormal coherence patterns have been noted in conditions such as epilepsy, autism spectrum disorder, and traumatic brain injury, prompting neurofeedback interventions targeting those patterns [12]. In practice, a coherence neurofeedback session might involve the user attempting to raise coherence between two regions (if connectivity is deficient) or suppress excessive coherence (if hyperconnectivity or runaway synchrony is a problem). Indeed, coherence training has shown promise in areas like reading ability improvement and epilepsy management [13]. One key challenge is ensuring that the coherence metric is computed over a stable enough window to provide meaningful feedback – too short a window and the estimate is noisy; too long and the feedback lags. Using coherence in a real-time visualization, we can represent it as a “link strength” between objects or as an emergent property like synchronized movement. Because coherence reflects simultaneous similarity in brain rhythms, it conceptually maps well to visuals that *flow together* or structures that become more *ordered* when coherence is high (and conversely become disordered when coherence drops).

## Phase-Amplitude Coupling (PAC) – Cross-Frequency Coupling

**Definition:** *Phase-Amplitude Coupling (PAC)* is a cross-frequency connectivity metric that describes an interaction between a low-frequency oscillation and a high-frequency oscillation in the brain. Specifically, PAC measures whether the phase of a slower brain wave modulates the amplitude (power) of a faster brain wave [14]. In practical terms, one might ask: *do bursts of high-frequency activity (e.g. gamma oscillations) tend to occur at a particular phase of a slower theta or alpha rhythm?* If so, there is phase-amplitude coupling. PAC is often quantified for particular frequency pairs, and results can be visualized in a *comodulogram* showing coupling strength between many frequency pairs [15]. It has attracted significant research interest as a mechanism of hierarchical organization in the brain: for example, theta–gamma PAC in the hippocampus and cortex is linked to working memory (theta phase orchestrating gamma bursts for item encoding) [16], alpha–gamma coupling appears in visual attention processes [16], and theta–alpha coupling has been observed in meditative states [17]. In general, cross-frequency coupling like PAC provides insight into how slower brain rhythms might regulate or gate faster information-processing oscillations [18]. A high PAC value indicates a strong coupling (the high-frequency amplitude reliably "locks into" a certain phase of the slow wave), whereas low PAC indicates that the two frequencies are operating more independently.

**Neurofeedback/Relevance:** PAC is a relatively advanced metric that has not been as commonly used in neurofeedback as simpler measures, but it represents a frontier for neurofeedback research. Traditional neurofeedback protocols focus on single-band amplitudes (e.g. increasing alpha power or reducing theta/beta ratio) [6], and only more recently have researchers considered targeting *coupling* metrics directly. To date, *few neurofeedback studies have explicitly trained PAC*, but initial evidence suggests it's feasible. For instance, a recent study demonstrated that participants could learn to intentionally **down-regulate** beta–gamma PAC in motor cortex through feedback, successfully reducing the coupling strength with practice [19]. This indicates that with appropriate feedback, the brain can adjust cross-frequency interactions. PAC is thought to be important for cognitive control and memory, so a future neurofeedback application might aim to enhance certain PAC (e.g. strengthen theta–gamma coupling for memory training) or suppress maladaptive PAC patterns (some abnormalities in PAC have been noted in Parkinson's disease and epilepsy research). In real-time visualization, PAC feedback would likely involve computing the coupling within one channel (or between a region's slow wave and fast activity) over short epochs (e.g. 1–2 seconds) and updating the display. Because PAC inherently links a slow oscillatory phase to a fast oscillatory amplitude, it invites a literal visual metaphor: for example, an object could have a fast pulsation whose intensity rises and falls in time with a slower global oscillation when PAC is present. Overall, PAC adds a *cross-scale* dimension to neurofeedback, indicating how well different brain rhythms are interacting.

## Mapping Metrics to Visual Parameters

With the metrics defined, we turn to mapping them onto audiovisual features. The goal is to create a visualization where changes in these EEG metrics manifest as intuitive visual changes, enhancing user engagement and aiding self-regulation. We propose the following mapping rules for **geometry**, **twist**, **glow**, and **pulse**, combining literal and metaphorical design:

- **Geometry (Shape & Structure):** Use **EEG power** or overall rhythmic activity to drive geometric size and form. A literal mapping would be to increase an object's scale or complexity as power in a particular band increases (for instance, a higher alpha power could inflate a sphere or make a fractal shape more detailed, reflecting "more activity"). Conversely, low power shrinks or simplifies the geometry. Additionally, cross-frequency **PAC** could influence structural layering: under strong PAC, the geometry might acquire an embedded sub-structure or pattern that oscillates at the higher frequency, nested within the base shape of the lower frequency. This way, the object's form itself visualizes coupling (e.g. a base geometric shape whose surface ripples or tessellates in sync with a faster rhythm when PAC is detected). The geometry parameter provides a stable, always-visible indicator of the brain's activity level (through size or complexity), ensuring the user has a continuous point of reference.

- **Twist (Spatial Rotation & Alignment):** Map **phase synchrony metrics** like PLV and coherence to the "twist" or coordinated motion of multiple visual elements. This is a metaphorical mapping: when two or more brain signals become more synchronized (higher PLV/coherence), their corresponding visual elements could start to twist or rotate around a common axis, or interlink in an orderly fashion. For example, imagine two shapes each representing one EEG channel – if their phase relationship locks in (high PLV), a visual link between them could appear and twist them into a braided or intertwined form. High coherence might similarly be represented by multiple parts of a shape aligning and rotating together smoothly (indicating they are "in step"). If coherence drops, the elements could drift out of phase visually – twisting in random or opposite directions, illustrating loss of coordination. In essence, **high connectivity = structured, unified twisting motion**, while **low connectivity = incoherent, independent movement**. This "flow order" effect (as in the user's suggestion of coherence → flow order) means a more synchronous brain produces more harmoniously flowing visuals, reinforcing the concept of mental harmony.

- **Glow (Brightness & Color Intensity):** Map **EEG amplitude (power)** to the glow or emissive intensity of objects as a straightforward literal mapping. As the power in a relevant band rises, the object's glow or brightness increases, making it more luminescent or haloed. For instance, if the user is training up their alpha waves for relaxation, a higher alpha power could make the scene or an avatar glow softly, whereas low alpha would appear dim. This immediate visual feedback leverages a natural association (bright = active/strong, dim = weak/low activity). Glow could also be modulated by **coupling metrics** in a supporting role: for example, a strong inter-hemispheric coherence could cause not just twisting alignment but also a subtle shared glow between two corresponding objects, indicating a "bridge" of connectivity. However, care should be taken not to overload too many meanings onto one visual variable. Primarily, brightness/glow should provide a stable indicator of how much of a desired brainwave is present. This is akin to traditional neurofeedback displays (like bar graphs) where more power fills the bar – here the bar is replaced by a glowing aura on a 3D object.

- **Pulse (Temporal Flicker or Rhythm):** Leverage the brain's intrinsic rhythms by mapping **oscillatory phase and PAC** to pulsing visual effects. A *pulse* in the visual domain could be an object throbbing in size, a light flashing, or a color oscillating. Ideally, this pulse should occur at the same frequency as a target brain rhythm to strengthen the user's awareness of that rhythm. For example, if the user is trying to increase theta-band coherence between regions, the visualization could include a theta-speed (≈5 Hz) pulsation when coherence is high – essentially the scene "breathes" at 5 Hz in unison with the user's theta. More interestingly, **phase–amplitude coupling** can be represented by nested pulses: the intensity of a fast flicker is modulated by a slower beat. For instance, suppose PAC is detected between 6 Hz (phase) and 40 Hz (amplitude); one could make an element emit a 40 Hz flickering light whose strength rises and falls at a 6 Hz rate. If PAC increases (meaning the coupling of 40 Hz activity to the 6 Hz phase is stronger), the 40 Hz flicker becomes markedly amplitude-modulated (very evident "bundles" of flashes tied to the slow cycle). If PAC is absent, the fast flicker might be steady or random with no low-frequency envelope. This mapping directly mirrors the definition of PAC and makes an otherwise invisible cross-frequency interaction tangible. The pulse parameter, therefore, translates the timing of the brain's oscillations into the timing of visual (or even auditory) effects. It's crucial to get the phase alignment right (e.g. starting the visual pulse at the detected phase angle of interest) so that the neurofeedback truly reflects the brain's timing – when successful, the user essentially sees a visualization of their brain's rhythmic pulses, which can be highly engaging and intuitively meaningful [6].

## Conclusion

Implementing these mappings in a real-time EEG visualization will create a rich feedback experience. The **literal mappings** (like power to glow/size) ensure that users always have a clear, direct understanding of how basic aspects of their brain activity change – brighter or bigger means "more" of the trained activity. The **metaphorical mappings** (like synchrony metrics to twisting or coupling to pulsating patterns) convey more complex neurophysiological relationships in an artistic yet interpretable manner – for example, seeing two shapes twist together informs the user that separate parts of their brain are interacting more cohesively. This dual approach addresses stability and depth: literal feedback provides immediate, easy-to-follow cues, while abstract feedback rewards the user with intriguing visuals as higher-order brain dynamics emerge.

Finally, given the limitations of consumer EEG (few channels, some noise), the system should calibrate and normalize these metrics for each user, perhaps establishing a baseline range for coherence or PLV so that the visual changes are neither too jittery nor too subtle. Techniques like smoothing the PLV/coherence over a 1–2 second window or thresholding PAC detection (to only visualize coupling when it's statistically significant [20]) will improve the experience. When done thoughtfully, **EEG phase and coupling metrics can be mapped to geometry, twist, glow, and pulse in ways that not only represent the data accurately but also resonate with the user's intuitions** – making neurofeedback training both scientifically grounded and visually captivating.

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