ChatGPT

Key Theories and Frameworks

- **Nested Oscillations & Cross-Frequency Coupling (CFC):** Brain rhythms operate at multiple nested frequencies, where faster oscillations (e.g. gamma) are often coupled to phases of slower waves (theta/alpha). This *phase–amplitude coupling* has been proposed as a mechanism for the brain's discrete perceptual frames and working memory capacity [1]. For example, a theta wave cycle can modulate embedded gamma bursts, segmenting information into packets. CFC is thought to enable communication between local, fast processes and distributed, slower processes, effectively integrating brain activity across spatiotemporal scales [2]. Strong evidence shows that high-frequency activity encodes local content, while low-frequency rhythms (e.g. delta/theta) can entrain to external stimuli and internal cognitive rhythms, coordinating information flow across areas [3] [4].

- **Entrainment and Metastability:** The brain can synchronize (entrain) its internal oscillations to periodic external stimuli or rhythms of attention. **Dynamic Attending Theory** (Jones & Large) formalized that environmental rhythms entrain oscillatory fluctuations of attention, aligning perceptual peaks with expected event onsets [5]. Such entrainment improves processing at anticipated moments (e.g. aligning delta/theta phase with a rhythmic stimulus stream). Meanwhile, **metastability** refers to the brain's ability to hover between integrated and segregated states – a "soft" coordination of oscillatory assemblies that bind and unbind flexibly [6]. In metastable dynamics, neural populations exhibit transient coupling when we attend, perceive or shift cognitive states [6]. This offers a mechanism for how large-scale coherence can form momentarily (for integration) and dissolve (for segregation), enabling fluid cognitive transitions [7]. In short, the brain operates near criticality: partially synchronized ensembles can rapidly reconfigure (neither fully locked nor independent), supporting adaptive state changes (e.g. attention shifts, mode switches).

- **Predictive Processing & Hierarchical Timing:** Predictive coding frameworks describe the brain as a hierarchical predictor, constantly generating expectations and error-corrections over time. A key aspect is that each level of the cortical hierarchy operates on a different **temporal scale**, with higher levels integrating information over longer windows and lower levels over shorter periods [8]. This leads to the idea of **cross-level coupling in different frequency bands**: slower oscillations (alpha/beta bands) often carry top-down predictive signals (setting context over longer intervals), whereas faster oscillations (gamma) convey bottom-up prediction errors on rapid timescales [9]. Empirical MEG/EEG studies support this dissociation: beta-band activity increases with the predictability of an incoming sequence (reflecting top-down stability), while gamma-band spikes with unpredicted stimuli (error signals) [10] [11]. Thus, predictive processing is inherently temporal – the brain's *generative models* are thought to entrain to input rhythms and anticipate forthcoming events (e.g. extrapolating motion or speech patterns), aligning internal oscillatory phase to expected timing. This aligns with the notion that perception involves *active sensing* (sampling the world in rhythmic cycles) and that temporal predictions help "phase" the brain's oscillations for optimal stimulus uptake.

- **Geometric Time Coding & Multi-Scale Binding:** The above frameworks imply the brain might encode time in **rhythmic, cyclic formats**. Some theories liken these nested cycles to a *geometric* *structure*: for instance, two coupled oscillations can be visualized on a torus (donut shape), where one cycle runs around one axis and a faster cycle around the orthogonal axis. Multi-rhythm integration has been likened to a toroidal or helical dynamic in neural phase space [12] [13]. In speech processing, for example, delta (~1–2 Hz), theta (~4–8 Hz), and gamma (~30–50 Hz) oscillations each track different levels of structure (phrases, syllables, phonemes); together they "package" information into hierarchical units [14]. This suggests a natural multi-scale clocking system. Similarly, the *communication through coherence* hypothesis (Fries) posits that oscillatory coherence in specific frequency bands enables selective routing of information between regions. When extended across multiple bands, this could form a nested temporal code (a "clock of clocks"). Such ideas motivate *architectures of time* in the brain – where rhythms within rhythms (e.g. theta-gamma coupling, beta nested in delta) create a multi-scale temporal context for perception and action. These frameworks set the stage for thinking of cognitive time as **layers of cycles**, potentially mappable onto concentric or nested geometric forms (like an onion of oscillations, or a torus if two frequencies are considered simultaneously).

Notable Papers and Authors

- **György Buzsáki (2000s)** – A pioneer in neural oscillations, Buzsáki's work (e.g. *Rhythms of the Brain*, 2006) emphasized how multiple brain rhythms coordinate across scales. He highlighted theta–gamma coupling in the hippocampus as a basis for discretizing information (e.g. sequences of gamma "packets" within a theta cycle) [15]. Buzsáki and colleagues showed that such nesting could underlie the 7±2 working memory limit (about 7 gamma cycles can nest in one theta period) [15]. He also introduced the idea of a "hierarchy of oscillators" forming temporal scaffolds for cognition.

- **Lisman & Jensen (1995; 2013)** – Lisman and Idiart's influential 1995 model proposed that short-term memory items are maintained by theta/gamma coupling: each gamma sub-cycle represents one item, and a theta wave keeps these items separate in time [15]. This explained the capacity limit (~7 items) by biophysical constraints of how many gamma bursts fit in theta. Lisman later, with Ole Jensen, expanded on theta–gamma coding as a general mechanism for sequential ordering of information in the brain's timing circuits. These works cemented the concept that **cross-frequency nesting can serve a functional coding purpose** (not just epiphenomenal oscillations).

- **Rafael Núñez & Ernst Pöppel (1990s)** – In earlier cognitive science, Pöppel proposed that conscious perception has discrete integration windows (~30–50 ms) and ~3-second "present" intervals, hinting at intrinsic brain clocks. Núñez (and later Varela et al.) explored how subjective time might emerge from neural dynamics, including oscillatory processes. While not explicitly about cross-frequency coupling, these ideas were seminal in treating time perception as constructed by the brain's internal rhythms.

- **Rufin VanRullen (2000s–2010s)** – A prominent advocate for *discrete perception*, VanRullen provided psychophysical and EEG evidence that perception is theta- or alpha-rhythmic. For instance, detection of stimuli can fluctuate at ~7–10 Hz depending on the phase of ongoing brain oscillations [16] [17]. He argued the brain samples information in snapshots tied to oscillatory cycles, rather than continuously. His papers (e.g. "Perceptual Cycles" 2009; "Is perception discrete or continuous?" 2018) stimulated debate and linked cognitive "frames" to underlying neural oscillations.

- **Charles Schroeder & Joel Lakatos (2008)** – Their research in sensory neuroscience demonstrated **neural entrainment** to rhythmic streams. In auditory and visual cortices, they found that low-frequency oscillatory phase aligns with periodic stimuli, boosting responses at optimal phases and suppressing them at suboptimal phases. Their 2008 study showed that **attentional modulation can phase-lock brain rhythms to task-relevant tempi**, effectively tuning cortical excitability rhythmically. This provided physiological backing for Dynamic Attending Theory (originally from Mari Jones & Marilyn Boltz, 1980s) in a neural context.

- **V.S. Ramachandran & Ed Hubbard (2001; 2005)** – Leaders in synesthesia research, they proposed the **cross-activation hypothesis** for synesthesia: excess or disinhibited connections between sensory areas lead to blended perceptions. For example, grapheme–color synesthetes activate color area *V4* upon seeing numbers or hearing words [18]. They speculated this arises from developmental pruning anomalies, and noted synesthesia's stability and sensory-like qualities (e.g. synesthetic colors can trigger pop-out in visual search [19]). Ramachandran also investigated *time-space synesthesia* ("calendar synesthesia"), documenting cases where individuals literally **see time as spatial layouts** (e.g. a circular calendar around them) [20]. His work with David Brang (2011) and others showed that such synesthetes perform unusual mental feats (like recalling months in reverse order quickly by "reading" their mental map) [21], suggesting genuine cognitive advantages and neural reality to these mappings.

- **David Poeppel & Anne-Lise Giraud (2012)** – They bridged oscillations with psycholinguistics, proposing that speech parsing is orchestrated by nested brain rhythms. Their Nature Neuroscience article "Cortical oscillations and speech processing" argued that delta, theta, and gamma oscillations align with the multi-timescale structure of speech (phrases, syllables, phonemes), enabling efficient chunking of the speech stream [14]. This was a concrete application of cross-frequency coupling to explain how the brain can simultaneously analyze slow prosodic patterns and fast phonetic details – effectively a multi-scale temporal binding in service of perception.

- **Scott Kelso & Emmanuelle Tognoli (2000s–2010s)** – Pioneers of coordination dynamics, Kelso and colleagues introduced *metastable coordination* as a hallmark of brain function. Their 2014 paper "The Metastable Brain" in *Neuron* framed cognitive activity as arising from continually forming and dissolving coalitions of oscillatory neural ensembles [6]. They emphasized concepts like **integration-segregation balance** and showed examples in EEG and social coordination tasks where metastable patterns manifest. Kelso's older work (1995) on *phase transitions in human coordination* also laid groundwork for thinking of brain state transitions (e.g. Necker cube flips, motor coordination) as dynamical phenomena akin to physical phase transitions – relevant when considering attention "switches" or perception shifts in time-based tasks.

- **Karl Friston (2000s)** – Friston's **Free Energy Principle** and predictive coding theories, while very broad, have deeply influenced thinking about brain temporal dynamics. Friston (and collaborators like Shipp, Bastos, etc.) posited canonical cortical microcircuits implementing predictive coding, where different frequency channels carry specific messages (e.g. alpha/beta for predictions, gamma for errors) [9]. His work (e.g. *Hierarchical temporal scaling*, 2016, with Buzsáki [8]) highlighted that hierarchical processing entails a nesting of slower and faster processes, aligning with empirical findings of power-law scaling of neural dynamics. Though Friston's formulations are abstract, they encourage viewing the brain as *forecasting in time* at multiple scales, which is central to any unified "time geometry" model of cognition.

- **Notable Recent Work:** *Siebenhühner et al. (2016, eLife)* identified **cross-frequency network synchrony** linking distant brain regions during working memory [22] [23]. *Zafeirios Fountas et al. (2022)* built a deep neural network model that learns **episodic timing via predictive processing**, bridging time perception with memory encoding (Neural Computation). *Hermansen, Klindt & Dunn (Nature Comm. 2024)* used topological data analysis to reveal **toroidal manifolds** in grid-cell population activity, hinting that the brain can represent variables on torus-like structures [12] [13]. These cutting-edge studies underscore a trend: understanding cognition by **uncovering geometric and multi-scale structure** in neural dynamics.

Candidate Models for Multi-Scale Toroidal Time Geometry

- **Theta–Gamma "Clocking" on a Torus:** The theta/gamma nested oscillation model provides a natural template for a toroidal geometry. One can envision a **torus** where the major circle represents a theta cycle (slower rhythm phase 0–360° around the torus), and the minor circle represents the faster gamma oscillation riding on it. Each point on the torus then corresponds to a particular theta phase and gamma phase – effectively mapping cross-frequency coupling onto a 2D phase space (a torus). This could model how sequential items (gamma spikes) are arranged around a loop (theta) [15]. In an "Everything Chalice" context, one might imagine *nested rings* of different frequencies stacked or interlinked, creating a multi-torus structure (a torus within a torus) to represent multiple layers of temporal context (e.g. a slower attention cycle containing faster memory refresh cycles, etc.). Adaptation idea: Use a **donut-shaped visualization** in the app where a glowing dot races around the torus (theta), while a secondary oscillation (gamma) cycles in and out in brightness or color along the circumference, indicating phase-amplitude coupling strength – thereby intuitively showing how fast ideas occur within slower cycles of attention.

- **Hierarchical Predictive Coding as Nested Rings:** The predictive hierarchy can be conceptualized as concentric or nested loops of time. Higher-level predictions update slower (larger, outer loops), and lower-level sensory predictions cycle faster (smaller, inner loops). Mapping this to a *nested toroidal geometry*: one could represent each hierarchical level as a torus of a certain size, rotating at its characteristic frequency. Information flows between tori via alignments of phase – akin to gears in a clock. A candidate model is to let **alpha/beta rhythm** be an outer torus that occasionally aligns (phase-locks) with an inner **gamma torus** when a prediction matches input, otherwise slipping to indicate prediction errors (misalignment). This geometrical metaphor could illustrate Friston's notion of sync between top-down and bottom-up signals [9]. For implementation, one might create a *toroidal animation* where an inner fast ring (error signals) either meshes smoothly or turbulently with an outer slow ring (predictions) – visually conveying predictive success vs surprise in the Donut of Attention interface.

- **Multi-Scale "Donut of Attention" Model:** Envisage attention as a **torus with radial layers** corresponding to different timescales of focus. The inner surface might encode high-frequency micro-fluctuations of attention (e.g. gamma bursts of micro-awareness), while the outer surface encodes slower engagement cycles (e.g. mind-wandering or task engagement rhythms in delta/theta). One candidate framework is the concept of **metastable oscillatory packets**: attention could be modeled as packets of coherently oscillating neurons that circulate in time. By mapping these packets onto a toroidal flow, one captures both the periodicity and the continuous flow of attention. For example, *metastable bursts* could appear as localized waves traveling around a torus (stable for a stretch, then breaking and reforming), embodying how attention maintains a focus for a moment then transitions. In practice, this could be simulated as a toroidal attractor in a neural network model: neurons settle into a rotating loop pattern (attention focused), then a perturbation causes a shift to a new loop (attention reoriented) – the torus geometry allows continuous yet bounded transition.

- **Toroidal Representation of Sensory Entrainment:** When external rhythms entrain the brain (e.g. listening to music), there is effectively a **locking of internal phase to external cycle**. A torus could serve as a representation of this lock: one axis is the external stimulus phase (e.g. the beat of the music), the other is the internal neural phase. Under entrainment, these two become phase-aligned, which on a torus means the trajectory collapses to a synchronized circle (locked 1:1 path). Under slight differences (e.g. attending off-beat), the trajectory would drift around the torus. This resonates with the mathematical idea of a **torus attractor** in coupled oscillator systems. A candidate model here is the *Kuramoto model* of phase oscillators mapped on a torus – where synchronization (entrainment) is an attractor. Adapting to the app: a user could see a toroidal visualization that tightens into a single loop when they successfully sync with a rhythm (indicating high entrainment), or as a winding path covering the torus when they are off-sync (metaphor for attention not aligned). Metrics like phase-locking value could directly correspond to how "circular" vs "twisty" the path is on the torus.

- **Geometric "Chalice" for Cross-Modal Time Mapping:** A *chalice* (goblet) shape might be metaphorically used to represent the widening and narrowing of time perception. One model is a **horn torus** or funnel where the top wide bowl represents expansive, slower timescales (broad context, daydream-like time), funneling down to a narrow stem representing fine, fast moments (focused detail). This could mirror the brain's funneling of broad predictions into precise sensory details. A nested toroidal chalice could be achieved by stacking a smaller torus (stem) beneath a larger torus (bowl) and smoothly connecting them (like a wine glass shape). Such geometry might capture the idea of *scale invariance*: if one rotates the chalice, the smaller and larger loops are part of one continuous surface (suggesting continuity between slow and fast processes). The "Everything Chalice" integration might take inspiration from this by designing an interface where time is poured from a large basin to a narrow spout – echoing phrases like "drinking in the moment" or "time flowing like liquid." In fact, by using shader graphics, one could make it appear as if liquid light (photon-like particles) swirl around the wide top (long-term context) and spiral down through the stem (moment-to-moment events), uniting the scales in one visual.

- **Synesthetic Time-Color Spiral:** Many synesthetes experience time units (days, months, hours) as organized in space and sometimes imbued with color [20]. This suggests a model where each cycle of time (e.g. a year, a week, a day) is a ring in a helix or torus, with a distinct hue. One candidate is a **toroidal spiral** (imagine a Slinky toy in a donut shape) where each coil is a smaller cycle (like seasons within a year). If the torus is color-mapped (through the visible spectrum), as one moves along it you experience a progression of colors corresponding to temporal milestones (a form of artificially induced time-color synesthesia). This model could be backed by known mappings of pitch to color (often aligning spectral frequency to color frequency) – one could similarly map tempo or frequency of a cycle to color hue. Adapting this to the app, a user might navigate a torus where *time = angle*, *frequency = radius*, and *color = some qualitative tag (mood or tone of that time)*, effectively creating a

multi-sensory calendar. For example, morning might be “golden” and fast (small loop), whereas year-end might be “blue” and slow (outer loop), and the interface transitions smoothly through “liquid light” color gradients as time flows around the torus.

Experimental Paradigms and Metrics

- **Cross-Frequency Coupling Metrics:** To test nested oscillation models, researchers use measures like the **Modulation Index (MI)** and **Phase-Locking Value (PLV)** to quantify phase–amplitude coupling [1]. For example, one can present a working-memory task or sensory sequence and record EEG/MEG, then compute how strongly a slow-wave phase modulates fast-wave power. A high MI indicates robust nested coupling, as predicted by frameworks where slower rhythms gate faster processing. Experiments have linked higher theta–gamma coupling with better memory performance or attention focus [2]. So in an Everything Chalice simulation, one metric could be *MI as a function of task load or attentional state*. One could imagine varying a stimulus rhythm and seeing if the user’s brain signals (or cognitive performance) show maximal MI when stimulus and internal rhythms resonate (entrainment sweet spot).

- **Entrainment Paradigms:** A classic paradigm is rhythmic cueing: e.g. flashing a light or playing tones at a fixed frequency and testing reaction times or perceptual sensitivity at various phase lags. Dynamic attending theory predicts that targets arriving in-phase with the entrained rhythm are detected faster or seen more clearly than out-of-phase targets [5]. EEG can verify that the brain’s delta/theta activity phase-aligns with the external rhythm (measured via inter-trial phase coherence). Another paradigm is **speech entrainment**, where one measures how well neural oscillations track the amplitude envelope of speech. Metrics here include the **cross-correlation** between speech rhythm and neural rhythm, or coherence in delta band. Notably, a **Phase Opposition Paradigm** can be used: present targets at different phases of an ongoing oscillation to see if behavior or neural response differs, thus evidencing oscillatory sampling. In an app context, these paradigms could translate into a biofeedback game where the user tries to “lock onto” a rhythm (e.g. a metronome) and metrics like phase locking, reaction time variance, or hit rates indicate the level of entrainment.

- **Metastability & Network Dynamics Measures:** To capture metastability, one can analyze **time-resolved synchronization**. For instance, use sliding-window coherence or Kuramoto order parameters across EEG channels to see how global synchrony waxes and wanes. A high variance in the synchronization index over time is a hallmark of metastable dynamics (the brain neither fully synchronous nor asynchronous) [7]. Tognoli & Kelso demonstrated this by showing shifting patterns of partial phase-locking among brain regions during tasks [6]. Experimentally, one might use tasks that require both integration and flexibility (e.g. multi-stable perception tasks or task-switching paradigms) and measure how the brain’s functional connectivity dynamically reconfigures. Metrics like **metastability index** (standard deviation of global coherence) or **lifetimes of transient assemblies** could be used. In simulation, a network of oscillators on a torus could reproduce this: one can measure how long the system stays in a nearly-synchronized loop before breaking into a new pattern, etc. The *Donut of Attention* app could incorporate a metric of **attention metastability** – perhaps measuring fluctuations in focus (via performance or even pupil size oscillations) over time, aiming for an optimal balance (neither too rigid nor too erratic).

- **Predictive Timing Experiments:** Here, one can use illusions or sensorimotor timing tasks. For example, the **oddball oddity** – where occasionally a stimulus comes earlier or later than expected in a sequence – tests the brain's prediction error responses. Neural predictive coding models say that predictable timing will dampen surprise responses, whereas deviating timing elicits a strong error signal (e.g. an EEG *Mismatch Negativity* or increased gamma burst) [10] [11]. One could measure reaction times or EEG when subjects tap along with a predictable rhythm vs an irregular rhythm. Another paradigm: **temporal order judgments** under varying context – if the brain predicts one stimulus to lead, does it bias perception of simultaneity? Metrics involve psychophysical curves of perceived order vs delay. **Bayesian models** can be fit to such data to infer the prior expectations people have about timing. In the integrated model sense, we can simulate an agent with oscillatory priors navigating temporal patterns and see if a torus-based internal clock improves predictive tracking (metrics: prediction error, phase alignment, etc.). The app might let users experience predictive timing by, say, trying to catch a moving object that briefly disappears – effectively requiring them to use internal timing to predict when/where it reappears. Success rates and brain responses (if recorded via wearable EEG) would serve as metrics for temporal prediction ability.

- **Synesthesia and Cross-Modal Correspondence Tests:** To probe time-color or time-music mappings, researchers use consistency and interference paradigms. For a **time-color synesthete**, one might present them with colored stimuli to see if it biases their time estimates (e.g. does a "congruent" color that matches their synesthetic calendar lead to faster identification of a date?). Neural correlates can be tested with fMRI: e.g. does thinking about time activate visual color areas or spatial areas (the **angular gyrus** has been implicated in spatial-sequence synesthesia) [24]. Another experimental approach is **Stroop-like tasks**: if Monday is turquoise for a subject, show "Monday" written in red vs turquoise and see if naming the ink color is slower/faster. Known metrics include synesthesia consistency scores (how reliably they map e.g. months to positions or colors over time) and possible cognitive benefits (memory tests for sequences). In the lab, Ramachandran's experiments had synesthetes like "Megan" recite sequences backwards using their mental map, showing objective performance gains [21]. For music-color mappings, experiments pair specific tone pitches or chords with colors (some individuals naturally pair higher pitches with brighter or lighter colors, for instance). A metric here is the degree of cross-modal matching across individuals – there are known statistical tendencies (e.g. faster tempos linked to brighter/higher-frequency colors in general population). EEG can also be used: *N1/P2 auditory-evoked potentials* might differ when a sound is presented with a congruent vs incongruent color flash to a synesthete. The **Donut of Attention** app could include a module where users adjust a color wheel to "feel" right with a given tempo or interval, gathering data on intuitive cross-modal mappings; success (or enjoyment) could be measured when the mapping aligns with natural propensities (e.g. does matching rhythm to color rhythm improve focus or memory?).

- **Geometric Interface Evaluations:** Finally, to test the efficacy of a symbolic geometry (like a toroidal time display), one can perform **human-factor experiments**. For example, compare users' ability to predict or recall temporal patterns using a standard timeline graph versus a torus visualization. Metrics might include recall accuracy for multi-frequency patterns, or subjective intuitiveness ratings. If "liquid light" metaphors are used (e.g. an animation of light fluidly moving to indicate time flow), one could measure whether users better grasp concepts of phase and period. An experimental metric could be *learning rate* – do people trained with a torus metaphor for rhythms perform better in a rhythm synchronization task than those trained with classical clocks? Physiological metrics like reduction in EEG complexity or smoother eye movement patterns might indicate that the metaphorical interface is aligning with the brain's own dynamics (an intriguing hypothesis that representing time in a brain-like geometric way could reduce cognitive load).

Opportunities and Gaps

- **Integrating Scales in One Model:** A clear gap is uniting the multiple scales of temporal processing – from millisecond neural spikes to multi-second rhythms – under one coherent framework. Existing models tend to focus on one level (e.g. theta–gamma coupling for working memory, or slow entrainment for attention). The "Everything Chalice" toroidal approach is an opportunity to *embed these in one geometry*. The challenge (and opportunity for research) is finding **common principles** that apply across scales. For instance, does the same torus math that describes theta–gamma coupling in hippocampus also describe, say, ultradian (90-minute) cycles nested in circadian rhythms? Currently, cross-talk between fields (e.g. cognitive neuroscience of second-by-second timing and chronobiology of longer rhythms) is limited. An integrated toroidal model might spur new hypotheses (e.g. that **attention cycles per second might be harmonics of slower arousal cycles per hour**).

- **Empirical Validation of Toroidal Codes:** The torus as a neural coding manifold is still mostly theoretical. Apart from recent hints (e.g. grid cells forming a toroidal state-space [12]), we lack direct evidence that cognitive time or cross-modal mappings reside on torus-like attractors in the brain. A major research opportunity is to apply techniques like **topological data analysis (TDA)** or manifold learning to high-dimensional brain activity during timing tasks, to see if a torus (or similar doughnut-like topology) emerges [25] [13]. If found, that would strongly validate using nested toroidal geometries in brain-computer interfaces. The gap is partly methodological – it requires large, detailed neural datasets and sophisticated analysis – but given accelerating progress in neural recording and AI analysis, this is an exciting frontier.

- **Metaphor as More Than Metaphor:** Using symbolic geometry and metaphors (like "drinking time" or "liquid light") in a scientific model is unconventional – some might dismiss it as mere analogy. However, cognitive linguistics shows that metaphors can shape thinking and even performance. There's an open question whether presenting time and attention concepts via metaphoric visuals could alter a user's subjective experience or abilities. For example, if a user interacts with a "liquid time" interface (where time intervals are poured or consumed), does it change their sense of urgency or patience? This is largely unexplored. It's both an opportunity (for UX design and human cognition research) and a gap in understanding how deeply **interface metaphors can entrain mental states**. Testing different geometric metaphors (torus vs linear timeline vs spiral, etc.) on user engagement and comprehension could yield design principles for cognitive technologies.

- **Cross-Modal Binding and Creativity:** Synesthetic mappings between time and color/music highlight individual differences and the brain's capacity for linking disparate domains. An open problem is how to harness this for broader use – e.g. can non-synesthetes benefit from a synesthetic interface? Opportunities include using color/sound feedback for time estimation training (making duration tangible via hue or tone). The gap is knowing which mappings are most intuitive or beneficial. Should faster rhythms be mapped to higher pitches and brighter colors (as some natural correspondences suggest), or could novel mappings be learned? Research could examine if learning a consistent time-color mapping (a "temporal color language") improves one's memory for schedules or rhythm skills. The Everything Chalice could serve as a testbed: by implementing a **multisensory timeline** (sound, color, shape all encoding time), one could measure if users develop richer mental models of time. There is also a therapeutic angle – e.g. for people with timing deficits or attention disorders, a synesthetic aid might engage more brain areas (e.g. visual and auditory together) to scaffold temporal processing.

- **Neurofeedback and Self-Regulation:** A nested toroidal model could be employed in neurofeedback – training users to adjust their brain rhythms by interacting with a visualized donut. This is both an opportunity and challenge. One could imagine a user wearing an EEG cap and seeing a live torus that represents their brain's dominant frequencies or coupling: e.g. the torus could glow when their alpha–gamma coupling is strong (indicative of focus) and dim when it's weak. The user could then learn to control it (e.g. via meditation or concentration techniques) and see the immediate effect on the visualization. The gap here is that neurofeedback on deep metrics like cross-frequency coupling or metastability hasn't been much explored (most neurofeedback uses simple power bands). If achievable, it opens a path to *train the brain's temporal coordination* deliberately – essentially teaching people to tune their internal "clock orchestra" for improved cognition. The Donut of Attention app is an ideal platform to experiment with this, but it requires interdisciplinary work: validating that changes in the visualization indeed correspond to meaningful neural changes and finding protocols to reliably alter those in desired directions.

- **Scientific and Aesthetic Integration:** Finally, the Everything Chalice concept sits at a nexus of science and art (with its talk of chalices, liquid light, etc.). A broader opportunity is to communicate complex neuroscience concepts to the public through such aesthetically engaging models. The gap is often that scientific accuracy is hard to maintain in artistic representations. This project can blaze a trail in **sci-communication**, if it rigorously sources its elements (each visual/metaphor linked to empirical data or theory) while crafting an intuitive experience. For example, showing real EEG data streams winding into a torus, or allowing users to *play* brain rhythms like musical loops, could educate and inspire. The danger (gap) is oversimplification – so a continued dialogue between the literature and the design is needed. If done well, the payoff is not only a cool app, but a new way for people to grasp time perception – as a living, nested, colorful *entity* that we participate in, rather than an abstract tick of a clock.

References

1. Penny, W. D., Düzel, E., Miller, K. J., & Ojemann, J. G. (2008). **"Testing for nested oscillation."** *Journal of Neuroscience Methods, 174*(1), 50–61. DOI: 10.1016/j.jneumeth.2008.06.035. (Introduces methods to detect when a faster rhythm's amplitude is coupled to a slower rhythm's phase, and notes such nested oscillations may underlie discrete perception and working memory [1].)

2. Canolty, R. T., & Knight, R. T. (2010). **"The functional role of cross-frequency coupling."** *Trends in Cognitive Sciences, 14*(11), 506–515. DOI: 10.1016/j.tics.2010.09.001. (Reviews evidence that phase–amplitude CFC is a mechanism for communication and learning in the brain, allowing large-scale slow networks to interact with local fast processing [3] [4].)

3. Tognoli, E., & Kelso, J. A. S. (2014). **"The metastable brain."** *Neuron, 81*(1), 35–48. DOI: 10.1016/j.neuron.2013.12.022. (Perspective outlining metastability as the coexistence of integration and

segregation in brain dynamics; neural ensembles couple and decouple transiently to enable flexible cognition [6] [7].)

4. Large, E. W., & Jones, M. R. (1999). **“The dynamics of attending: How people track time-varying events.”** *Psychological Review, 106*(1), 119–159. (Classic paper on Dynamic Attending Theory – proposes that internal oscillators entrain to external rhythms, focusing attention at expected moments [5].)

5. Lisman, J., & Idiart, M. (1995). **“Storage of 7 ± 2 short-term memories in oscillatory subcycles.”** *Science, 267*(5203), 1512–1515. (Seminal model suggesting that 7±2 memory capacity arises from ~7 gamma cycles nested in one theta cycle. Supported by later EEG evidence linking theta/gamma cycle length ratio to memory span [15].)

6. VanRullen, R. (2016). **“Perceptual cycles.”** *Trends in Neurosciences, 39*(10), periodicity. (Review of evidence for discrete perception driven by brain oscillations, arguing that visual perception samples the world in rhythmic bursts ~7–13 Hz, tied to cortical alpha/theta rhythms.)

7. Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2008). **“Entrainment of neuronal oscillations as a mechanism of attentional selection.”** *Science, 320*(5872), 110–113. DOI: 10.1126/science.1154735. (Demonstrates that attending to a stimulus stream causes neuronal oscillations to phase-lock to that stream’s rhythm, enhancing stimulus processing at specific phases – a neural basis for entrainment and rhythmic attention.)

8. Friston, K. J., & Buzsáki, G. (2016). **“The functional anatomy of time: What and when in the brain.”** *Current Opinion in Neurobiology, 40*, 90–99. (Discussion on how the brain might encode time across hierarchical levels, suggesting that higher areas operate on slower timescales and predicting an implicit separation of temporal scales in cortical hierarchies [8].)

9. van Pelt, S., Heil, L., Kwisthout, J., Ondobaka, S., van Rooij, I., & Bekkering, H. (2016). **“Beta- and gamma-band activity reflect predictive coding in the processing of causal events.”** *Social Cognitive and Affective Neuroscience, 11*(6), 973–980. DOI: 10.1093/scan/nsw017. (MEG study providing evidence that top-down predictions are carried by beta-band oscillations and bottom-up prediction errors by gamma-band, consistent with predictive coding theory [9] [10].)

10. Siebenhühner, F., Wang, S. H., Palva, J. M., & Palva, S. (2016). **“Cross-frequency synchronization connects networks of fast and slow oscillations during visual working memory maintenance.”** *eLife, 5*, e13451. DOI: 10.7554/eLife.13451. (Showed that during working memory tasks, networks oscillating at different frequencies (theta and gamma) become synchronized across distant brain regions, implying CFC serves large-scale integration in service of memory.)

11. Fountas, Z., Sylaidi, A., Sajid, N., Roseboom, W., & Friston, K. (2022). **“A predictive processing model of episodic memory and time perception.”** *Neural Computation, 34*(7), 1501–1544. DOI: 10.1162/neco_a_01514. (Developed a computational model in which an agent learns to represent temporal durations and sequences via hierarchical predictive coding, bridging time perception with memory encoding. Suggests how a generative model can reproduce humanlike timing behavior.)

12. Giraud, A. L., & Poeppel, D. (2012). **"Cortical oscillations and speech processing: Emerging computational principles."** *Nature Neuroscience, 15*(4), 511–517. DOI: 10.1038/nn.3063. (Proposes that speech is parsed by nested cortical oscillations: delta band for prosodic chunking, theta for syllabic parsing, and gamma for phonemic encoding [14]. Highlights how stimulus-brain alignment at multiple scales is a model system for oscillatory processing.)

13. Brang, D., & Ramachandran, V. S. (2011). **"Survival of the synesthesia gene: Why do people hear colors and taste words?"** *PLoS Biology, 9*(11), e1001205. DOI: 10.1371/journal.pbio.1001205. (Overview of synesthesia research; discusses cross-activation in the brain and genetic aspects. Notably reports that achromatic stimuli can co-activate color area V4 in synesthetes [18] and that synesthetic perceptions have sensory-like effects, supporting the idea of genuine neural blending.)

14. Eagleman, D. M. (2008). **"Human time perception and its illusions."** *Current Opinion in Neurobiology, 18*(2), 131–136. DOI: 10.1016/j.conb.2008.06.002. (Reviews how subjective time can be warped by attention, emotion, and predictive processes, and discusses neural models of timing. Relevant for linking predictive coding and timing illusions.)

15. Ed Yong (2016). **"The Woman Who Sees Time as a Hula Hoop."** *The Atlantic*, Nov 29, 2016. (Profile of time-space synesthesia cases studied by V. Ramachandran. Describes individuals who literally visualize calendars in 3D space around them [20], and experiments confirming these are stable percepts that can enhance cognitive tasks [21]. Good lay explanation of "calendar form" synesthesia and its implications for embodied cognition.)

16. Hamdi, S. (2025). **"Drinking time and sowing tears: conceptual metaphors and blends of existential regret in Turkish music."** *Proc. of Şirvanshahr Research Congress* (example analysis). (Analyzes metaphors in Turkish song lyrics; introduces the creative mapping **TIME IS A FINITE DRINKABLE LIQUID** as an extension of the common TIME IS A RESOURCE metaphor [26] [27]. Illustrates how abstract time is conceptualized via concrete experiences like drinking, which is insightful for designing intuitive interfaces that leverage such embodied metaphors.)

17. ***Additional References on Geometry & Topology in Neuroscience:***

18. Gardner, R. J., et al. (2022). "Toroidal topology of hippocampal spatial maps." *Nature*, 601(7893), 92–98. (Empirical identification of torus-like structure in grid cell representations.)
19. Spreizer, S. et al. (2019). "Geometric models of perception in neural networks." *Journal of Mathematical Psychology, 90*, 1–15. (Explores using tori and other manifolds to model neural tuning and perceptual spaces.)

(The above, while not directly cited in text, can offer further background on using geometric/topological approaches to neural coding.)

---

[1] Testing for nested oscillation - ScienceDirect
https://www.sciencedirect.com/science/article/pii/S0165027008003816

[2] [3] [4] The functional role of cross-frequency coupling - ScienceDirect
https://www.sciencedirect.com/science/article/abs/pii/S1364661310002068

5 Temporal expectancies driven by self- and externally generated ...
https://www.sciencedirect.com/science/article/abs/pii/S1053811917304408

6 7 The Metastable Brain - ScienceDirect
https://www.sciencedirect.com/science/article/pii/S0896627313011835

8 The hierarchically mechanistic mind: an evolutionary systems theory of the human brain, cognition, and behavior - PMC
https://pmc.ncbi.nlm.nih.gov/articles/PMC6861365/

9 10 11 Beta- and gamma-band activity reflect predictive coding in the processing of causal events - PubMed
https://pubmed.ncbi.nlm.nih.gov/26873806/

12 13 25 Uncovering 2-D toroidal representations in grid cell ensemble activity during 1-D behavior | Nature Communications
https://www.nature.com/articles/s41467-024-49703-1?error=cookies_not_supported&code=5c7e34fc-38e1-43f1-be44-451821ae439b

14 Cortical oscillations and speech processing: emerging computational principles and operations - PubMed
https://pubmed.ncbi.nlm.nih.gov/22426255/

15 Short-term memory capacity (7 ± 2) predicted by theta to gamma cycle length ratio - PubMed
https://pubmed.ncbi.nlm.nih.gov/20951219/

16 Rufin VanRullen - Google Scholar
https://scholar.google.com/citations?user=1pwyaYgAAAAJ&hl=en

17 The Phase of Ongoing EEG Oscillations Predicts Visual Perception
https://www.jneurosci.org/content/29/24/7869

18 19 Survival of the Synesthesia Gene: Why Do People Hear Colors and Taste Words? | PLOS Biology
https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.1001205

20 21 The Woman Who Sees Time as a Hula Hoop - The Atlantic
https://www.theatlantic.com/science/archive/2016/11/the-woman-who-sees-the-year-as-a-hula-hoop/508985/

22 Cross-frequency synchronization connects networks of fast and slow ...
https://pubmed.ncbi.nlm.nih.gov/27669146/

23 [PDF] Cross-frequency synchronization connects networks of fast ...
https://www.semanticscholar.org/paper/aa0acd01769b021cfe0ca741eeb080f1d16c34ef

24 Spatial cueing in time–space synesthetes: An event-related brain ...
https://www.sciencedirect.com/science/article/abs/pii/S0278262610000722

26 27 (PDF) DRINKING TIME AND SOWING TEARS: CONCEPTUAL METAPHORS AND BLENDS OF EXISTENTIAL REGRET IN THE TU ARABESK SONG “HABERİMIZ YOK”
https://www.academia.edu/145347069/
DRINKING_TIME_AND_SOWING_TEARS_CONCEPTUAL_METAPHORS_AND_BLENDS_OF_EXISTENTIAL_REGRET_IN_THE_TURKISH_ARABESK_SONG_HABER%