Opinion

Neuroscience

Dose Toroidal Network Topology Exist in Our Brain Activities?

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Recent advances in computational neuroscience and topological data analysis have sparked a provocative question: does toroidal network topology exist in human brain activity? A torus—a donut-shaped manifold—is a recurring structure in complex dynamic systems, representing continuous yet cyclic patterns. Neural recordings increasingly reveal similar topological signatures, especially in grid-cell firing, sensory integration, and large-scale brain coordination. While the presence of a perfect geometric torus in the brain is unlikely, toroidal topology may reflect how neural populations encode periodicity, relational structure, and multidimensional information. This opinion article argues that toroidal topology should not be dismissed as abstract mathematics but recognized as a potentially fundamental organizational principle of cognition. It may be key to understanding memory, perception, consciousness, and the brain’s remarkable efficiency. Exploring toroidal patterns offers both conceptual insight and a methodological shift toward studying the brain as a dynamic, high-dimensional manifold rather than a static network.

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THE IDEA that the human brain may operate on toroidal topological principles sounds, at first, like an exotic marriage of mathematics and neuroscience. The torus—a donut-shaped structure—has long fascinated topologists for its balance of continuity and circularity, offering a compact way to encode cyclical processes without boundaries (Sarra et al., 2025). But what seems like a mathematical abstraction has recently begun to surface in the empirical study of neural activity. As recording techniques improve and analytical strategies shift toward geometric and topological representations of brain function, evidence is mounting that toroidal structures may underlie certain patterns of cognition (Yoon et al., 2024). The question is no longer whether toroidal network topology exists in the brain as a literal geometric object, but whether the functional organization of neural populations adopts toroidal-like manifolds to encode information. Increasingly, the answer appears to be yes.

One of the clearest examples comes from the study of grid cells in the entorhinal cortex. These cells fire in a hexagonal pattern as an animal navigates through space, producing a beautiful and mathematically precise lattice of activation. When researchers applied topological data analysis to these firing patterns, they found persistent homology signatures consistent with toroidal structures (Hermansen et al., 2024). The logic is intuitive: grid-cell activity encodes position as a set of periodic variables. Periodicity is naturally represented on a torus, where movement in one direction wraps around seamlessly without discontinuity. The toroidal manifold provides both efficiency and stability, enabling the brain to compute spatial states with minimal redundancy. If one wishes to identify a biologically grounded example of toroidal topology in neural activity, grid cells provide a compelling starting point.

But grid cells may be only the beginning. Cyclic patterns pervade brain function. Neural oscillations—from theta to gamma rhythms—create recurrent cycles of excitability and inhibition (Moser et al., 2014). Perceptual processes such as color, pitch, and orientation possess circular dimensions: hue maps onto a color wheel; tone maps onto repeating octaves. Motor control involves periodic coordination of muscle activations; memory often unfolds in rhythmic temporal chunks (VanRullen & Dubois, 2011). These cyclical features of brain computation are difficult to represent using simple linear geometry but map naturally onto tori and other higher-order manifolds.

The toroidal hypothesis gains additional support from the broader shift in neuroscience toward viewing neural populations as evolving on low-dimensional manifolds embedded in high-dimensional firing spaces. Rather than treating neurons as discrete units processing information independently, researchers now observe that populations move along smooth trajectories shaped by the task at hand (Yoon et al., 2024). Many of these geometries are curved, recurrent, and multidimensional—properties characteristic of toroidal or torus-like structures. Importantly, these manifolds arise not from anatomical wiring alone but from the emergent dynamics of interconnected neural systems.

One could argue that toroidal topology is simply a convenient mathematical model rather than a biologically meaningful structure. But this criticism misses the point. Biological systems often adopt topological solutions because they provide computational advantages. A toroidal network, for instance, allows the brain to encode periodicity without needing infinite representational space (Curto, 2016). It minimizes edge effects, reduces noise, and supports robust transitions between states. The fact that the brain appears to use toroidal-like manifolds repeatedly—in navigation, perception, motor planning, and perhaps even in attention and consciousness—suggests that this topology is not incidental but advantageous.

Another line of support comes from the study of recurrent neural networks (RNNs) trained to perform cognitive tasks. Even in artificial systems, toroidal manifolds spontaneously emerge when the network must represent cyclic or multidimensional variables (Sarra et al., 2025). For example, RNNs learning to track head direction, manage periodic signals, or combine multiple continuous variables often converge on toroidal or near-toroidal latent spaces (Gardner et al., 2022). If artificial networks, optimized purely through gradient descent, independently rediscover toroidal topology, it is reasonable to hypothesize that evolution might select similar solutions for the brain.

Yet the idea remains controversial. Skeptics argue that topological signatures may be artifacts of analytical methods. A toroidal shape extracted through dimensionality reduction does not guarantee that the underlying biology is genuinely toroidal. Neural activity is notoriously noisy and context-dependent; small variations across trials or individuals can masquerade as structural geometry (di Sarra et al., 2025). Moreover, the brain's complexity far exceeds that of a simple manifold. Any given neural circuit may contain multiple overlapping geometries depending on the task, the context, and the interaction of rhythms. Thus, claiming that toroidal topology "exists" in the brain can oversimplify a much richer reality.

Nevertheless, dismissing toroidal topology outright would be equally misguided. What matters is not whether the brain contains a literal donut-shaped cluster of neurons but whether its computational patterns are shaped by topological constraints similar to those described by a torus (Ivshina et al., 2025). The torus serves as a powerful conceptual and mathematical tool for describing how the brain handles periodicity, relationships, and seamless transitions in multidimensional space. If the brain's functional organization resembles a torus, even abstractly, this insight can reshape our understanding of cognition.

One of the most intriguing implications is that toroidal topology may help explain how the brain integrates multiple cyclic variables simultaneously. Consider activities like navigation, where direction, speed, environmental cues, and internal states all combine to shape behavior. If each of these dimensions contains periodic or recurrent elements, the brain may integrate them using multidimensional toroidal structures—essentially, tori within tori (Gardner et al., 2022). Such nested geometries can support complex computations while maintaining stability and efficiency. They may also form the backbone of cognitive maps that extend beyond physical space into abstract domains, such as conceptual knowledge or social dynamics.

Another potential implication involves consciousness. Some theories propose that conscious experience arises from the integration of recurrent and rhythmic neural activities across large-scale networks (Es et al., 2025). If so, consciousness may depend on topological structures that allow integration without collapse—structures that preserve cycles while enabling global coordination. Toroidal networks could, hypothetically, offer such properties, creating a stable yet flexible substrate for ongoing awareness.

Furthermore, toroidal topology may shed light on neurological and psychiatric disorders. Conditions such as epilepsy, schizophrenia, or depression involve disruptions in rhythmic coordination and network dynamics (Saggar et al., 2018). If these disruptions alter the underlying topology of neural activity—perhaps flattening a torus, fragmenting it, or forcing it into unstable geometries—this could contribute to symptoms. Understanding the “shape” of healthy versus disordered brain activity could open new pathways for diagnosis and intervention.

Despite these possibilities, the field is still in its infancy. We do not yet have the tools to fully map high-dimensional neural manifolds in real time across broad cortical networks. Most toroidal findings come from small circuits, specific behavioral tasks, or limited recording depths. Nevertheless, the rapid evolution of high-density electrode arrays, optical imaging, nonlinear dynamics analysis, and computational modeling promises to accelerate progress. As these technologies converge, the hidden geometries of thought may become visible.

In reflecting on whether toroidal network topology “exists” in the brain, we must adopt a nuanced view. The brain is not a static object but a dynamic system; asking whether a torus exists materially misses the more important question of whether neural dynamics operate on toroidal-like manifolds (McIntosh & Jirsa, 2019). The evidence increasingly suggests they do—at least in certain domains and under certain conditions. The torus appears again and again, not because the brain is shaped like one, but because the mathematics of periodicity, continuity, and multidimensional representation find a natural home in toroidal topology.

Ultimately, exploring toroidal structures in brain activity expands our scientific imagination. It forces us to move beyond simplistic models of neurons as switches or networks as wires. It invites us to consider the brain as a living geometry—shifting, folding, cycling, wrapping around itself in ways that encode meaning, memory, and experience. Whether or not toroidal topology becomes a central principle of future neuroscience, its presence in current research signals a paradigm shift: the understanding that cognition is not merely computation but computation shaped by topology.

The real question may not be whether toroidal topology exists in the brain, but how many forms of curved, cyclic, and multidimensional geometry the brain employs—and what these shapes reveal about the nature of mind itself. ■

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