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Quantum computing for neuroscience: opportunities beyond classical limits

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Some of the least understood phenomena in the brain emerge from interactions between local and global brain states, yet representing their joint activity is a considerable computational challenge. As neuroscience datasets grow and classical methods reach their limits, alternative approaches are needed. Quantum computing, through its novel approach to information processing, may offer a solution.

Fundamentally, the brain operates through bidirectional causation across various spatiotemporal scales. Local activity shapes global networks, global states and all levels that lie between them. In turn, these networks and states constrain local dynamics. For example, slow oscillatory phases actively constrain local activity, such as fast gamma oscillations and neuronal spiking[1]. Understanding this interaction requires moving beyond assessing individual units, such as neurons or regions of interest, to examining how the system (that is, the brain) works as a whole. In this Comment, we argue that capturing such system-level dynamics is fundamentally limited by the representational capacity of classical computing. We propose that through its leveraging of quantum mechanical properties, quantum computing offers a principled, complementary approach to this representational problem. We outline where it could be useful to neuroscience in the near term.

The challenge of the joint state space

Modern neuroscience generates large-scale datasets that capture neural activity across multiple brain regions, modalities and timescales. Among the phenomena in these data, the least understood are the emergent properties of the brain: upward causation, in which local interactions between neurons affect higher levels and give rise to large-scale network activity that is not predictable from microscopic information alone, and downward causation, in which those emergent global states feed back to lower levels and constrain local dynamics at the next time step[1] (Supplementary Fig. 1).

This bidirectional interaction between global and local scales, termed the brain's 'loose vertical coupling'[1], means no one scale can be fully derived from any other. These scales should instead be represented jointly. For a system of n interacting elements (for example, individual neurons or regions of interest), the space of possible joint configurations scales exponentially as 2^n (ref. 1). Classical computers represent information using bits, each in one of two definite states (0 or 1), so to track such a system they must store a separate value for every one of these 2^n configurations. A classical computer's representational capacity, however, scales only linearly with the allocated storage, whereas the joint state space it must capture scales exponentially with n (Supplementary Fig. 1d). Once n grows beyond a moderate size, the full joint state can neither be represented classically nor accurately measured, regardless of advances in raw computing power. Representing the joint activity is therefore the central computational challenge.

Faced with this challenge, standard computational methods rely on approximations, such as dimensionality reduction, or analyse neural activity at each level separately using generalized linear models. These techniques are important, but they come at a cost. They discard information about upward and downward causation between scales, the very phenomena that are least understood (Supplementary Fig. 1a,b). As a result, classical analyses can capture only a limited view of multiscale brain dynamics. Given the challenges outlined above, the primary bottleneck for multiscale analysis is not a lack of data but, rather, a representational one.

A structural solution

Quantum computing offers a structural solution to this representational challenge. An n-qubit quantum processor is a physical system whose natural state space is a 2^n-dimensional Hilbert space. This is the same exponentially large joint state space that a classical computer cannot store, but is here held implicitly in the physics of the device. Representing such a system using quantum states, therefore, takes only polynomial physical resources (Supplementary Fig. 1d). The trade-off is that one may never simultaneously access this entire joint state space. Instead, we must sample from the distribution of measurement outcomes defined by the quantum state, which requires repeating the computation to build up statistical confidence.

This quantum representational advantage is not only one of capacity. It also reflects a fundamental structural difference between classical and quantum architectures. In a classical computer, the logical state is simply the collection of its individual bits. Each bit is engineered to behave independently of the others; the logical (higher) level is decoupled from the physical (lower) level by design (Supplementary Fig. 1b). The levels of a quantum computer cannot be decomposed this way. Through quantum mechanical properties such as entanglement, the joint state of n qubits is, in general, not separable into independent single-qubit states; the whole is not the product of its parts. Interactions between qubits build a global state that is not reducible to its components (upward causation), and that global state, in turn, fixes the statistics of any local quantum states (downward causation). This non-separable coupling between the local (single-qubit) and global (n qubits) scales is precisely the property identified as organizationally distinctive about the brain (Supplementary Fig. 1a,c).

This representational capacity is latent and realizing it depends on algorithms that operate within the quantum processor's

high-dimensional space. Using quantum interference and entanglement, such algorithms could extract high-dimensional multiscale features of the brain at lower relative computational cost[2]. For this reason, the standard challenge of representation shifts instead to algorithm design, which includes efficiently encoding neural data into quantum states, modelling realistic brain dynamics, and reading the relevant features back out. Careful attention must be paid at each step of the quantum algorithm design such that the quantum advantage persists. For example, an algorithm might use a property of quantum mechanics such as interference to raise the probability of sampling joint activity in which a slow oscillation constrains local spiking, while suppressing all other activity.

Non-separable coupling between the local and global scales in a quantum device also connects to a deep distinction between what an ideal machine could compute in principle, given unlimited time and memory, and what a particular physical system can compute in practice[3]. Regarding the latter, the physical properties themselves shape what can be represented or measured[4]. The brain, in which local activity and global states are causally coupled across scales (Supplementary Fig. 1a), is a biological example of a system whose computation cannot be separated from its physical substrate.

This structural alignment must be correctly understood. We make no claim that the brain is itself a quantum system or that its function depends on quantum effects. Rather, we propose quantum computing as a computational tool whose physical hardware differs fundamentally from classical computers. This is valuable for representing high-dimensional problems (of which multiscale interactions in brain activity are one), not for modelling neural tissue. The resemblance to the brain is a guide showing why a high-dimensional, non-separable state space is a natural medium for multiscale problems. Any advantage comes from that representational capacity and the algorithms designed to use it, not from the resemblance from non-separable coupling between the local and global scales. The open question is whether that capacity for high-dimensional representation can enable new ways to analyse the multiscale interactions that define brain function.

Promising areas for application in neuroscience

Evidence for the representational advantage of quantum computing is beginning to emerge. Such examples come from various scientific areas, including areas of biology, although not from neuroscience; quantum advantage is yet to be shown for a neuroscience problem. Quantum algorithms for topological data analysis offer potential exponential speedups, in certain regimes, for computing high-dimensional topological features directly from quantum states that encode the entire data structure[5]. Also, quantum processors, combined with classical supercomputing, have simulated the structure of systems with many interacting particles at scales at the limits of leading classical methods[6]. This hardware is still pre-fault-tolerant, but active development of error mitigation and correction is gradually expanding the systems that can be reliably simulated.

This capacity for high-dimensional representation is directly relevant to modelling downward causation. Testing how large-scale oscillatory dynamics govern shifts in local spiking activity[7], for example, requires tracking the exponential state space of their joint activity. This is a task that remains classically prohibitive in large-scale electrophysiology and whole-brain imaging. The same limit constrains theoretical frameworks such as predictive coding and ephaptic coupling, which presuppose these cross-scale relationships but have, so far, been tested in reduced form. Quantum methods offer a potential path to make downward causation measurable and not just conceptual, and, as hardware improves, to realize the complete predictions of such frameworks. Until then, this applies only to small, well-defined systems rather than the whole-brain scale. A computationally tractable population of simultaneously recorded neurons, in which the joint distribution of their action potentials can scale linearly rather than exponentially relative to the target oscillation, is one such bounded problem.

Across these neural examples, the common thread is that many critical brain signals are subtle relational patterns distributed across many elements, precisely the information averaged away as noise or lost in dimensionality reduction. Representing the entire high-dimensional joint state space directly, rather than reducing it, is what the quantum approach is structurally suited to do.

Future directions

The immediate path forward requires solving practical challenges. The top priority is codeveloping quantum algorithms related to neuroscience questions, such as how to understand the brain's multiscale organization. Neuroscientists in particular need to identify problems where state-space representation is the bottleneck and where established frameworks are reaching their limits. Continued progress in quantum hardware towards fault-tolerant operation will then determine which of these questions become tractable, and on what timeline. In the near term, as quantum computing integrates supercomputing architectures, applications are expected to be hybrid with classical hardware doing most of the work, and only the representationally difficult step running on quantum resources[8]. Hurdles in software and interdisciplinary training remain, but this focused codevelopment is a critical starting point.

Ultimately, success must be judged by new neuroscientific insight, not computational benchmarks alone. For example, quantitatively modelling phenomena at multiple scales could provide evidence to inform longstanding theoretical debates about hierarchical organization in the brain. These include debates between frameworks that propose largely independent levels of analysis[9] and frameworks that propose interdependent, compositional levels of mechanism[10].

Conclusion

The fundamental challenge in modelling the brain's multiscale dynamics is the exponential growth of the joint state space. Classical computing is poorly suited to this representational task. Quantum computing, by its inherent structure, operates naturally in such high-dimensional spaces. Although considerable practical obstacles currently exist, this structural alignment offers a principled and testable avenue for neuroscience research, a way to experimentally probe how the physical substrate of computation shapes representational capacity, multiscale interactions and the emergent properties that define brain function.

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Competing interests

A.C. is a physicist employed by IBM. The other authors declare no competing interests.

Additional information

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