igMin Research STEM ISSN: 2995-8067 A Multidisciplinary Open Access Journal

SCIENCE SUBJECT
Cognitive Science | Neuro Science | Behavioral Science | TOPIC(S)

Article Information

Submitted: January 18, 2024
Approved: May 01, 2024
Published: May 02, 2024

How to cite this article: Grindrod P. Wishful Thinking about Consciousness. IgMin Res. May 02, 2024; 2(5): 302-308. IgMin ID: igmin180; DOI: 10.61927/igmin180; Available at: igmin.link/p180

Keywords: Quantum consciousness; Integrated information theory; Dynamical systems simulation; Evolutionary advantage; Performance surrogates

Review Article

Wishful Thinking about Consciousness

Peter Grindrod*

Mathematical Institute, University of Oxford, England

***Correspondence:** Peter Grindrod, Mathematical Institute, University of Oxford, England, Email: grindrod@maths.ox.ac.uk

Abstract

We contrast three very distinct mathematical approaches to the hard problem of consciousness: quantum consciousness, integrated information theory, and the very large-scale dynamical systems simulation of a network of networks. We highlight their features and their associated hypotheses, and we discuss how they are aligned or in conflict. We suggest some challenges to these theories, in considering how they might apply to the human brain as it develops both cognitive and conscious sophistication, from infancy to adulthood. We indicate how an evolutionary perspective challenges the distinct approaches to aver performance advantages and physiological surrogates for consciousness.

Introduction

The *hard problem of consciousness* [1,2] asks why there is something internal to our subjective experience, some set of phenomenological sensations, something that it is *like* to be a human brain experiencing the world. Such repeatable and consistent sensations range from large-scale emotions and feelings (anxiety, happiness, love, embarrassment) down to smaller-scale, more specific, *qualia* (headache pain, the sight of the blueness of blue, the brassy sound of a trumpet, the feel of stroking cat's fur, the crunch from biting into an apple,...). These are internal mental states with very distinctive subjective characters. How do such sensations come about within the physical brain and what is their possible role?

In this paper, we consider three alternative mathematical approaches to the hard problem and related matters. We do so to crystallize and contrast the pros and cons of each paradigm. We wish to avoid a *dialogue of the deaf*. We hope that a direct inter-comparison will stimulate interest and research within all three theories. Comparison, cross-fertilization, and competition are huge drivers within science and the present stage of the *mathematics of consciousness* demands a sharpening of its aims and objectives.

We should stress that other approaches are available (for example, those based on the free energy principle, conscious Turing machines, global workspace theory, integrated information-induced quantum collapse, and so on), so we have focused here on the three that are arguably most dominant at present.

Quantum Consciousness (QC)

Some scientists and writers hold that conscious phenomena, such as the existence, causes, and role, of internal phenomenological sensations (emotions, feelings, and qualia) relate to some type of quantum effects taking place somewhere within the physical brain, usually associated with the cognitive processing of information to produce consequent inferences and actions. Penrose proposed a type of wave function collapse, called *objective reduction*, from which consciousness phenomena are born [3].

Quantum Consciousness (QC) usually starts from a negative: that classical mathematics (dynamical systems, and other concepts) alone cannot explain consciousness, positing instead that quantum-mechanical phenomena, such as entanglement and superposition, might play an important part in the brain's function and could explain critical aspects of consciousness. Up until a few years ago perhaps the best evidence for this assertion was indeed the failure of those classical mathematical methods to define and substantiate a model that might expose the ``how, what, why" of conscious phenomena. This is no longer the case. In sections 1.2 and 1.3, below, we will discuss two now obvious, and available, alternative candidates: Integrated Information Theory (IIT), and the reverse engineering of Very Large Scale (VLS) Dynamical System Simulations (DSS). The former required a novel concept to be applied to information processing systems; whilst the latter could not be prosecuted until large simulations on (multi-core) super-computing platforms became available, or else until a suitable simplification of the VLS systems could be defined.

So the time is ripe to reconsider the logic and evidence behind the promulgation of QC.

The quantum mind remains a hypothetical speculation, as Penrose and others admit. Until it can support a prediction that is testable by experimentation, the hypothesis is not based on any empirical evidence. Indeed, quite recently Jedlicka [4] says of quantum biology (a superset of the quantum mind-brain), ``The recent rise of quantum biology as an emerging field at the border between quantum physics and the life sciences suggests that quantum events could play a non-trivial role also in neuronal cells. Direct experimental evidence for this is still missing....". In [5] there is a useful summary of the contemporary evidence both for and against there being a functional role for quantum effects in a range of biological (and physiological) systems. The authors find no clear evidence one way or the other and they couch their conclusions in weak conditional terms, suggesting further experimentation is required. More recently in [6] the authors consider quantum biology from the perspective of quantum physicists and they argue that photosynthesis and enzymatic effects may rely on quantum effects, such as tunneling, in governing the role of subatomic particles. Yet the cited experimental evidence is considered earlier in [5], and such quantum effects remain but one possible mechanism to explain observations. What is missing is any testable and necessary consequence of the quantum biology hypothesis. The same is true of the QC hypothesis, a sub-field of quantum biology.

However, just as any evidence to support the presence of quantum effects within the brain remains elusive, it is also hard to obtain positive evidence that rules them out. The major theoretical argument against the QC hypothesis is the assertion that any quantum states in the brain would lose coherency before they reached a scale where they could be useful [7,8]. Typical brain reactions are on the order of milliseconds, trillions of times longer than sub-picosecond quantum timescales. Over many years though, there have been successive attempts to be more explicit about where and how quantum effects might be present within the brain [9].

In [10], the authors consider the future of quantum biology as a whole and address QC explicitly. Given the objections above, based on time-scale and space-scale discrepancy between quantum effects and neuronal dynamics, they conclude that any `` *potential theory of quantum effects in biological neural networks would thus have to show how the macroscopic dynamics of biological neural nets can emerge from coherent dynamics on a much smaller scale.*"

With the present lack of any positive evidence for QC, despite many years of searching, and the existence of some coherent theoretical arguments to its contrary, why then does the quantum consciousness hypothesis persist? Perhaps the largest force driving its adoption is subjective: it comes from the desires and aspirations of quantum scientists themselves, to have their physics become relevant to one of the most elusive frontiers in science. This goes far beyond Chalmers' ``minimization of mysteries" jibe: it would act as a magnet and an employment-creation opportunity for quantum physicists.

Of course, the recent rise in quantum technologies (including quantum computing, quantum sensing, and quantum communication) within novel synthetic applications, lavishly funded via many national programs, performs a similar, though much more rational, purpose. Moreover, within those non-brain fields, there is a focus on fabricating novel effects in the lab and beyond, rather than on unpicking and understanding a particular existing natural complex system, such as the human brain.

More recent ideas about consciousness introduce modifications of the quantum-mechanical Schrödinger equation and discuss wave function collapse. For example, Chalmers and McQueen [11] and others [12] consider the evolution of quantum states within the universe when consciousness is also taken into account. They investigate whether conscious phenomena (within some paradigms) might collapse wave functions, inducing hard certainties. Such a role is normally reserved for acts of *observation* in quantum mechanics [13], though that is an ambiguous term. Hence they postulate that conscious phenomena (whether physical or dualist) could impact upon the real external world. Of course, this is the exact reverse of investigating whether or how quantum collapse might beget QC.

Integrated information theory (IIT)

Integrated Information Theory (IIT) [14] provides a framework capable of explaining why some physical systems (such as human brains) are conscious, why they feel the particular way they do in particular states, and whether other physical systems might be conscious. IIT does not build conscious-like phenomena out of physical systems and processes (as does dynamical systems modeling and simulation, discussed in Section 1.3 below), instead, it moves from the abstract phenomenology towards mechanism by attempting to identify the properties of conscious experience within general information processing systems.

Here a *system* refers to a set of elements each of which might be in two or more discrete internal states. The state of the system is thus summarised by the states of all of its elements. Subsets of the elements define ``mechanisms", and when the corresponding elements change state they do so in a way that may be conditional on one another's state since they are interdependent and can interact. There is thus a transition matrix that can stipulate the probability that the state of the system might switch to another state. IIT applies to whole systems that are capable of carrying out such internal dynamical state changes: it is an integrated view. In a real sense systems should be irreducible, since if they could be reduced (partitioned) into independent subsets then there would be no point in assembling those subsets into the whole and we might deal with each separately. This is akin to the notion of irreducibility (strong connectedness) for non-negative directed adjacency or dependency matrices (stipulating all pairwise influences between elements). Thus any properties of such an irreducible system are integrated and will depend upon all of its elements.

The details of IIT focus mainly on how a performance quantity called the ``integrated information", denoted by Φ, is defined and calculated for different systems. Φ is a real-valued measure of the subsets of elements within a system that have (physical) cause-effect power upon one another. Only an irreducible (strongly connected) system full of feedback cycles can have a non-trivial Φ, as it produces output causes (consequences) from the incoming sensory effects. The conscious part of the human brain thus has a very high Φ and is therefore highly conscious. Systems with a low Φ have a very small amount of consciousness.

It is rather surprising how much effort is focused on the calculation of Φ, as a surrogate for the system's internal *agility* and *sophistication*. This is apparent in the successively increasing formalism presented after a decade or so within IIT 3.0 in 2014 [15]. The much more recent, the latest version, is similar [16].

The mathematical essentials of IIT are well set out in [17], including its possible application within a quantum setting, introduced earlier in [18].

Of course, given any specific system, it would be *nice* to be able to calculate Φ, yet knowing its exact value is of no use to the system's owner (except possibly for bragging). The owner continues to operate the system just as it is configured. Analogously we might all accept that there is a performance measure of human intelligence, called IQ, but knowing its actual value does not affect an individual's decision-making or ability to operate as now. Of course, a high value of Φ (like a high value of IQ) might confer some advantages to the system owner, such as having a comfortable life or increased fecundity. It is easy to imagine how such advantages would cause some evolutionary selection to shift a population of owners to relatively higher and higher distributions of such measures. Thus the importance of higher Φ lies in its associated evolutionary advantages, not in its objective transparency or accessible calculation.

It is very interesting to ask how much improvement might be achieved if evolution re-architected the human brain; or even if individual (plastic) brains develop an abundance of connections when subject to specific training (specific experiences). Conversely, within a single operational lifetime, the brain's consciousness development is not necessarily a one-way street.

Equally, it is important to understand how Φ might increase as an infant's brain develops through puberty, when both the cognitive sophistication and the conscious inner life develop along with the evolving neural connectivity and neurological structures, due to neurotransmitters and life experience.

Thus, the most important and appealing part of IIT is that it supplies a performance measure, Φ, as a system-level attribute, that aims to be correlated with the level of internal conscious phenomena, and which might be increased. The ability to calculate Φ for any given class of systems is thus rather irrelevant to their owners – it is the internal consequences, that are measured by Φ, that will count. Any calculation Φ is only relevant to demonstrating its well-definedness and constructive nature, and possibly useful in future testing of the IIT.

Like the quantum mind, IIT has its critics. The claims of IIT as a theory of consciousness are not yet scientifically established or testable [19], and IIT cannot be applied at the scale of a whole brain system. There is also no demonstration that systems that exhibit integration, in the sense of IIT, are conscious at all. A relatively high Φ-level might be a necessary condition for consciousness phenomena yet it may not be sufficient [20]. An explanatory gap remains.

Very large scale (VLS) dynamical system simulations (DSS)

Recent years have seen the possibility of VLS DSS containing 10B individual neurons, as a dynamic model for the human cortex. This approach is based on empirical observations of the cortex structure; it is an open system, subject to ongoing sensory inputs; it is experimental; and it is predictive. It makes predictions about why the cortex architecture should be so uniform (so to maximize the total dynamical degrees of freedom while constraining energy and volume) [21]; it explains how the whole system response is governed by (competing) internal dynamical modes [22] which result in preconditioning of the immediate cognitive processing, providing a *fast thinking* advantage [23,24]; and it suggests that consciousness and cognition are entwined, with each catalyzing and constraining the other, and the brain has evolved to exploit that advantage. Yet, as we shall see, there remains an explanatory gap [23].

In such VLS DSS neurons are arranged within a directed network architecture based on that of the human cortex. It is a *network of networks*. The inner networks, called *modules* (or communities) in network theory, each represent a single neural column containing 10,000 or so individual neurons which are internally very densely connected. The outer network connects up the neural columns with occasional connections between pairs of neurons from near-neighboring columns. The columns are arranged in a grid across the (flattened-out) cerebral cortex. The individual neurons, just as in vivo, are both excitable (they spike when they are stimulated by receiving an incoming spike) and refractory (following a spike they require a recovery time for the intra- and extra-cellular ions to re-equilibrate and they will not fire immediately if re-stimulated). Each directed neuron-to-neuron transmission takes some time, based on the tortuous nature of the individual axonal-synaptic-dendritic connection.

Recent work in such VLS DSS shows that under many distinct externally stimulated conditions the internal response defaults to react within one of several (hierarchically related) dynamical modes [22]. The modes that exist across the cortex and across time cannot be represented by snapshots, and are also mutually exclusive at any particular level in the hierarchy. Such VLS simulations require a supercomputer [25], and the reverse engineering of the internal responses to stimulation, and the the identification of the hierarchically defined modes, is highly non-trivial [22].

The DSS approach recognizes that the cognitive processing system is open, as it is constantly subject to sensory stimulation: it is not about dynamical *emergence* (symmetry breaking within disordered complex systems). The observed dynamical modes arise in response to various stimulations, and they are extremely good candidates for hierarchical emotions, feelings, and qualia. The hypothesis that internal phenomenological sensations correspond to the brain's own experiences of dynamical modes kicking indirectly addresses the *hard problem*: how humans have such internal sensations and expose their role in enabling fast thinking [24] evolutionary advantage by preconditioning immediate cognition and reducing the immediate decisions set. Usefully, a set of internal modes is arranged hierarchically, and at any particular level, they are mutually exclusive. Is it ever possible to experience competing sensations at the same time?

Yet there remains an explanatory gap. While has been shown that any nonlinear system of this type, including the human cortex, must have such internal competing dynamical modes, it has not been proven that these are in correspondence with internal phenomenological sensations. Any complete model of consciousness would need to explain how the system is settles of the content of phenomenal experience, and the stimuli that generate it: this is alluded to in [26], where it is pointed out that sensations cannot be instigated through instability mechanisms or stochastic (noise) processes. This goes beyond showing a correspondence between modes and phenomenological sensations.

VLS DSS represents some of the largest numbers of simulations using massive cortex-like complex systems that have ever been made [27,28]. This endeavor requires significant resources. IBM has been particularly active and has carried out TrueNorth simulations in 2019 [29], realizing the vision of the 2008 DARPA Systems of Neuromorphic Adaptive Plastic Scalable Electronics (SyNAPSE) program. The simulations and analytics in [22] were carried out on the SpiNNaker 1 million-core platform [25,30,31].

The tribulations of two large science projects aiming to fully simulate human brains, within the US and EU, have been well documented [32]; and were caused by a variety of issues. These programs have become focused on the goals of brain mapping and building data processing facilities and new tools with which to study the brain. Many efforts have benefited from the computing facilities developed. The progress in [22], discussed above, exploited the massively parallel SpiNNaker supercomputer [25,30,31] that took over 10 years in construction, from 2006, and required £ 15M, funded by the UKRI/EPSRC and the EU Human Brain Project [33].

In [32] these big science projects were summarised, `` *...instead of answering the question of consciousness, developing these methods has, if anything, only opened up more questions about the brain—and shown just how complex it is.*"

In more recent work the modules (the neural columns) have been replaced by multi-dimensional clocks [34] (with multiple phases winding forwards, which are isolated), coupled via individual edge-based phase-resetting mechanisms, with appropriate time-delays. The results are the same as those for the full VLS DSS – internal, hierarchically arranged, dynamical modes responding to external stimulation. Yet these *Kuramoto*-type simulations only require 1M or so multi-dimensional clocks, with say 10M degrees of freedom in total. Whereas the full VLS DSS simulations require 10B degrees of freedom. As a result, the reduced system may run on a laptop (dual core), as opposed to a supercomputer [23,34].

Over many years various *toy* circuits built with neurons have been investigated. But this is a red herring. The full-scale simulations with realistic architectures and dynamics had to wait for suitable computing platforms. As a result, the possibility of VLS simulations producing dynamic systems and network science-enabled responses to the hard problem was discounted prematurely. Once investigators could peer inside such systems and reverse engineer them (in a way that is impossible for human brains, given the resolution of even the most powerful scanners), the internal dynamics became apparent. The *Entwinement Hypothesis* [23] is thus a logical outgrowth of VLS DSS.

Much of the earlier philosophical work often argued that cognition [35] and consciousness are separate, or that cognition begets consciousness as a consequence or by-product of processing (see the multiple drafts hypothesis [36], for example). However, it is now suggested that one should accept the corollary (from the insights) gained via DSS, that internal conscious phenomena are crucial to certain efficiencies within cognition. Cognition and consciousness would be thus mutually dependent and entwined [23].

Comparisons

DSS considers an open dynamical system containing up to 10B neurons embedded within a directed network of networks that is irreducible (strongly connected) and is subject to a continuous stream of sensory inputs, yet it responds in consistent ways. It moves from causes to effects - from stimuli to decisions, inferences, and instantiating appropriate internal modes. The structures employed rest on what is observed in terms of neuronal dynamics, cortex architecture, and transmission time lags. DSS enables the analysis and reverse engineering of the integrated system behavior, including the discovery of internal latent modes, which are hypothesized to be physical causes of sensations and qualia. DSS shows how these in turn can influence and constrain immediate cognition. These conclusions are thus based on the observed brain structure and behavior and a multitude of DSS experiments.

On the other hand, IIT moves in the opposite direction, It starts from a generalized irreducible (strongly connected) and agile system and measures the integrated (whole-system) performance via Φ. Seeks to measure a whole range of possible dynamical phenomena, including all possible internal response modes to incoming stimuli. Thus, within its generality, IIT subsumes the internal responsive structures that are exhibited by particular systems, yet it does not explicitly demonstrate the existence of dynamical modes within the integrated response. IIT does not rely on the specific network-of-networks architecture, only properties of; and consequently, IIT is not able to make testable predictions (such as having a fairly uniform size of neural columns [21,22] in maximizing the total number of dynamical degrees of freedom). The power of having a measure lies not in its derivation (and well-definedness) but in introducing a systems-level concept beyond energy, entropy, and complexity measures (such as modularity).

Both IIT and DSS are described by similar vocabulary and they exhibit the same obvious role in evolutionary cognitive and consciousness development. Assuming that high- Φ induces some advantages to an organism, such as the preconditioning and hence fast-thinking advantage [24] implied by DSS, then the brain can have evolved in structural form and dynamics to increase this.

IIT and VLS DSS are the same thing but coming from different directions. DSS constructs a bottom-up narrative of *what occurs within* [22] for a very specific class of cortex-like systems, making specific and testable predictions based on observed structure and experimentation. IIT provides a much more general setting, a top-down view, and it asserts that a high level of a suitably defined performance measure can imply the existence of conscious internal phenomena.

QC is a rather special case of a theoretical approach offering a (presently) theoretical solution. It comes with no practical justification nor evidence for its establishment and relevance, and yet it supplies some sophisticated benefits - elements that deal with uncertainty and also seek to explain why conscious phenomena are elusive and beyond physical measurement (observation).

The evolutionary question is important for QC, and quantum biology in general. Has biology evolved to exploit quantum effects within *warm and wet* environments, on the increasing spatial scales of molecules, cells, organs, and organisms? If not why not? Does cellular and systems biology take place at the wrong scales for quantum effects to be relevant? The advantages of quantum effects within cognitive and conscious performance might be very great, if ever achievable. Objections have encouraged proponents to become more specific about where and how quantum effects might ever arise within the human brain [9], and yet persist.

QC says nothing about relative levels of consciousness (compared to IIT) and nothing at all about the brain's evolved architecture or the plethora and role of inner sensations (compared with VLS DSS); beyond seeking subcellular structures that might support any quantum effects. Instead, it provides a theoretical *raison d'etre* for conscious experiences.

Of course, DSS is classical, and far more straightforward than QC. It is also testable and produces observable consequences, including support for the *Entwinement hypothesis* [23]. Moreover, any DSS progress at all required the development of supercomputing facilities that could simulate such VLS dynamics [25,30,31]. Hence such a classical approach (as set out in [22]) was held up until about five years ago. Perhaps its efficacy was simply discounted too early by commentators; since (human) ``nature abhors a vacuum".

VLS DSS implies that QC is unnecessary. QC implies that whatever DSS demonstrates is irrelevant.

Very usefully, in theory, IIT applies to both classical and quantum approaches [17,18]. Yet any implementation requires some detailed descriptions of the system architecture and dependencies of the systems' elements and mechanisms.

It would be fascinating if IIT could ever calculate Φ for the same systems set out and deployed within DSS, for both the VLS DSS and the simpler Kuramoto-style, network of multidimensional clocks systems. This would be a very good next step.

Furthermore, any physiological surrogate Φ, possibly tied to some evolutionary advantages, would be extremely useful. We can argue that DSS shows us some facets of the dynamics and architecture (the total dynamical degrees of freedom, for example) that would confer fast-thinking advantages. We can also observe many physiological surrogates for individual inner feelings (blushing, trembling, non-poker faces, heart rate, cortisol, and so on). Could we identify some more generalized observables that might be a surrogate for the full measure, Φ?

Conclusion

In summary, we suggest that the best next steps for IIT should be (i) to ground it further to the specific system observed within the cortex, from where DSS starts; and (ii) and identify appropriate physiological markers that are aligned with it Φ. For VLS DSS the immediate experimental challenge is to identify evidence for the existence of specific internal dynamical modes corresponding to certain internal sensations. Such a step requires high-resolution neuroimaging, over time as well as across the cortex (not highly localized), relating cognitive and consciousness entwinement more closely to the recent progress on *neural correlates of consciousness* [37]. The reverse engineering of massive ensembles of VLS simulations creates its own ``big data" problem. The methodology deployed in [22,34] should be improved and made more transparent.

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How to cite this article: Grindrod P. Wishful Thinking about Consciousness. IgMin Res. May 02, 2024; 2(5): 302-308. IgMin ID: igmin180; DOI: 10.61927/igmin180; Available at: igmin.link/p180