Quantum Interface Theory: From Conscious Agents to Quantum Dynamics

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Abstract

The interface theory of perception maintains that sensory systems evolved to present agents with an 'adaptive desktop' rather than a veridical picture of the world. Physical reality is an evolutionary construct. By contrast, consciousness and agency are fundamental, irreducible elements not emergent from physics.
Building on this framework, the quantum interface theory ('QIT') is introduced. Several core quantum-mechanical features, such as entanglement, superposition, and decoherence, are artefacts of the interface. Moreover, the formalism of 'quantum conscious agents' is sketched to provide a foundation for QIT. Thereby, perception is modelled as a quantum instrument, enabling the study of back-reactions on agent–environment dynamics.
Consciousness exhibits quantum-like properties when it 'measures itself,' leading to the following prediction: signatures of quantum coherence in biological systems correlate to consciousness only if they modulate an agent's interface dynamics. By integrating evolutionary theory, quantum information, and metaphysics, QIT offers a unifying framework for modern consciousness science.*

Keywords: Quantum consciousness, interface theory of perception, conscious agents, superposition, decoherence, entanglement, prototime, self-measurement, quantum instruments

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1 Why quantum consciousness?

A dismissive attitude toward research into quantum consciousness underestimates the significant scientific productivity in the arena (Atmanspacher, 2024). For example, the often-berated idea of quantum effects in the brain is still alive and well and has led to genuine empirical investigations into coherent excitations in cytoskeletal microtubules (Babcock et al., 2024) or anesthesia (Wiest, 2025). Moreover, well-known puzzles in fundamental physics like the nature of space and time could be approached through the lens of consciousness (Hoffman, Prakash, & Prentner, 2023; Schneider & Bailey, 2025) and might thus be viewed from a new perspective. Arguably then, consciousness should be included into fundamental ontologies (Quine, 1948).

Some salient properties of consciousness have long been speculated to be quantum-like in nature: For example, already in the 1970s, physicists have speculated that entanglement somehow underlies the apparent unity or coherence of consciousness (Kaiser, 2011). Even to this day, such ideas fuel ongoing speculations (D'Ariano & Faggin, 2022; Georgiev, 2017; Schneider & Bailey, 2025). Moreover, a generation of pioneers in quantum physics speculated that the infamous collapse of the quantum wavefunction is inherently related to consciousness (London & Bauer, 1939; von Neumann, 1955; Wigner, 1961). Again, an old speculation by physicists is still pursued by modern thinkers (Chalmers & McQueen, 2021; Penrose, 1994; Pylkkänen, 2014).

However, there exists a danger of recycling historical conjectures. An alternative literature explores "quantum-like" probabilistic models of cognition without positing a "quantum brain" (Busemeyer & Bruza, 2024; Haven & Khrennikov, 2013; Tsuchiya, Bruza, Yamada, Saigo, & Pothos, 2025; Wang, Busemeyer, Atmanspacher, & Pothos, 2013), thus connecting the mathematical structure of quantum mechanics to cognitive science and psychology. This direction of research is arguably a better fit for research into AI since those structures can in principle be implemented in (quantum) computing systems.

So while we agree with the general thrust of the article by Schneider and Bailey (2025), there are some points where we disagree. However, they should be taken as disagreements between kindred spirits. We discuss more about our disagreements in Section 2 and about how we think they should be dealt with in Section 3.

2 Quantum at the interface

2.1 The great beyond

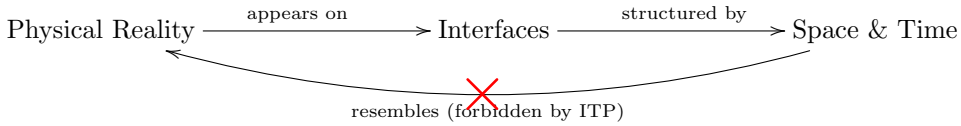
According to the Interface Theory of Perception (ITP; Hoffman (2019); Hoffman, Singh, and Prakash (2015); Prakash (2020); Prentner (2021)), evolution shaped perception to utilize structures that let us navigate our environment (assuming that perception is heavily tied to action via a range of cognitive processes). For example, our perception of space and time can be viewed as the "species-specific desktop" (Fields, Hoffman, Prakash, & Prentner, 2017; Hoffman, 2019) that lets us interact with the environment in a satisficing way as prescribed by evolution and various (e.g.,

physical-chemical) constraints.[1] In ITP, the process of evolution is modeled in terms of optimization of fitness. However, fitness functions depend on both subjective, agent-dependent factors and objective, agent-independent ("worldly") factors. As a consequence, the structures that define our perceptions do generically not align with any supposed structures that exist "out there," independent of the agent. This puts a firm limitation on anything that we can say. There exists at least a metaphorical[2] commonality between approaches in quantum consciousness and ITP: the problem of acquiring knowledge of what exists beyond our best representation of the world, be it scientific or perceptual/cognitive. This problem raises at least the following two questions:

Q1: What exists beyond our interface?
Q2: Can we recover the structures of our interface?

There are several options to address **Q1**:

- One option is to simply postulate a purely physical (spatio-temporal) domain behind the interface and regard perceptual structures as their representation (e.g., as "approximation to the truth"). But, then, if fundamental reality differs radically from the interface, why should it resemble interface-like structures such as spacetime?[3]



  One is, of course, free to call a mix of these ideas — (i) an acknowledgement that interfaces (appearances) are a part of the fundamental fabric of the universe that (ii) is not spatiotemporal in nature — to be the "real physics" (Strawson, 2006) that will be featured, perhaps, in future scientific theories. This, however, seems to be primarily a semantic fix.
- A different option is to regard consciousness as the "categorical ground" (Schneider & Bailey, 2025) of physical processes. After all, consciousness arguably lies beyond a purely structural/physical characterization (Goff, 2017; Seager, 2006). Moreover, such a characterization would stay metaphysically incomplete, so "plug the hole

[1] A common misunderstanding of ITP is that it is really just a souped-up version of "sense datum theory" (McLaughlin & Green, 2015). However, ITP does not posit the existence of three entities: an observer, the world, and a mediating sense datum. It simply says that the world is presented a certain way. This presentation ("the perception") is identical with the awareness itself; it is not a separate "object of awareness". We do not perceive the interface, but we perceive the world (quite literally) "through" the interface.

[2] How this "metaphorical" should best be understood is an important question. For example, one could argue that it is merely a (more or less) loose analogy, or that it indicates structural resemblance between formalized domains, or that it even points to one and the same (metaphysical) problem.

[3] A strategy similar to illusionism (Dennett, 1991; Frankish, 2016) dissolves the dualism between "physical reality" and its "appearance on the interface" by declaring appearances to be nothing over and above physical processes. Accordingly, there really is no (metaphysical) difference here, even though there *seems* to be such a difference. Some highly-evolved cognitive systems merely think or act as if there were this difference, but in fact it is simply a form of information-processing that is (metaphysically) like any other. Still, this line of thinking, while it could perhaps be made logically consistent, awaits empirical validation.

with consciousness" (Goff, 2019).

$$\text{Consciousness} \xrightarrow{\text{as categorical ground of}} \text{Physics}$$

Still, this proposal also faces difficulties, and how we meet those difficulties defines the direction for developing the idea of "*consciousness as fundamental*" in the future. Let us sketch one difficulty here: ITP, agreeing with a host of other theories, such as Thomas Metzinger's self-model theory (Metzinger, 2003) or variants of predictive processing (Clark, 2019), suggest that the "self" is not objectively real. Fundamentally, there are no selves. But if there are no selves, how should we think about the claim that consciousness is fundamental? This requires us to adopt a "self-less notion" of consciousness. True, such an account is not entirely unpopular these days (Harris, 2019), but the difficulty is exacerbated if one generalizes this to a form of consciousness that lacks *any prestated* structure at all (which has been inferred from perception).[4]

2.2 Quantum structures as interface artifacts

But perhaps there *are* structures, not inferred from perception (which ITP would thus not directly target). Invoking quantum mechanics at this point becomes suggestive. Arguably, quantum mechanics features plenty of structures that are very unlike our usual way of perceiving the world.

Still, the difficulty of "stepping out" of one's perceptual make-up is generally underestimated, which motivates the "*quantum interface theory*" (QIT). At first sight, the defining structures of fundamental physics seem to be different from the corresponding structures in perception. This is already the case when we think about space and time as they are perceived vs. spacetime as it features in, e.g., quantum field theory. The issue becomes even more salient when we compare, for example, the notion of superposition (the quantum structure) with the idea of particles taking "all paths at once," an often-heard (though slightly incorrect) way of conceptualizing the superposition (of paths) using our usual way of perceiving the world. On closer inspection, though, quantum structures seem to be *derived* from our perceptions (cf. the idea that spacetime is an extension of space and time as we perceive it; Koenderink, Richards, and van Doorn (2012)) or *result* from a "projection" onto our three-dimensional interface (Hoffman, 2019). One could thus reinterpret quantum(-like) structures within interface theory:

1. **Superposition**: While pictures of the double slit experiment regularly surface in the popular science literature, the fact is that no one ever saw a superposition. Instead, "superposition" is a name for a formal structure that we associate with the mathematics of quantum theory – not a phenomenon that can directly be perceived. What we observe are measurement outcomes, and measurement itself is a procedure defined within space and time. So, the apparent strangeness of superposition may be

[4] One way to understand this is to say that any such structure has to be *transcendental* in a Kantian sense: it expresses a conditions of possibility for having a (perceptual) experience. This does not commit us to assume the real (i.e., perception-independent) existence of those structures.

less a feature of the world itself and more a residue of how perceptual systems engage with their environment. It would thus be more accurate to say that superposition is inferred from counterintuitive patterns on the interface – on our "desktop" – not observed as such. This subtly underscores a core tenet of the interface theory: that what appears strange may simply reflect the constraints and distortions of the interface, not the underlying structure of reality.

2. **Entanglement**: The violation of Bell inequalities in numerous experiments (e.g., Aspect, Grangier, and Roger (1982); Hensen et al. (2015); Weihs, Jennewein, Simon, Weinfurter, and Zeilinger (1998)) demonstrates correlations that are inherently quantum and inexplicable classically. Often described as "non-local" (Bell, 1964; Gröblacher et al., 2007; Maudlin, 2011) (and sometimes popularly referred to as "spooky action", Einstein, Podolsky, and Rosen (1935); NobelPrize.org (2022)), this phenomenon entails that a measurement at one site instantaneously establishes correlated outcomes at a distant site. Experiments over separations of hundreds of meters have confirmed this instantaneous connection, definitively ruling out explanations based on subluminal signals. Yet, entanglement is conceptually puzzling only if one conflates the spatial layout depicted by our perceptual interface with an observer-independent spacetime. This conflation can lead to the mistaken intuition that entanglement enables faster-than-light signaling. However, the no-signaling theorem (Gisin, 1990) explicitly forbids such communication even in the presence of entanglement. This becomes especially acute in speculative proposals that identify specific properties of consciousness with entanglement. For instance, if entangled quantum states were assumed to instantiate unified conscious experiences across spatially separated systems, this could, in principle, enable superluminal signaling (Neven et al., 2024). Such scenarios highlight the conceptual tension that arises when perceptual appearance (space) is taken as literal depiction of reality. This again is consistent with the interface theory: Only by taking our perceptions to be literally true, do we run into the conceptual danger of viewing entanglement as a non-local correlation that really exists "out there" in space.
3. **(De)coherence**: Any sign of coherence in quantum systems (due to entanglement or superpositions) is lost in a process of decoherence, which naturally arises whenever a (small) quantum system evolves together with a (larger) environment. One mechanism that has been hypothesized to account for this is "Quantum Darwinism" (Zurek, 2003), which selects robust pointer states through environmental monitoring. Evolutionary selection within ITP serves an analogous role for perceptual states: both processes favor stable patterns that persist under selection pressure, albeit at different levels of analysis. This analogy does not imply that decoherence determines what perceptual systems must evolve to detect. Rather, both quantum Darwinism and evolutionary perceptual dynamics involve *structurally similar selection principles*. The hypothesis here is that perceptual representations (e.g., those involved in color vision) are evolutionarily tuned to exploit informationally stable channels in the environment (e.g., those consistent with surface reflectance properties). These may correspond, in form if not origin, to the environmental regularities amplified during the quantum-to-classical transition. What becomes evolutionarily useful from the interface perspective thus overlaps with the states that quantum

Darwinism identifies as robust through decoherence. Pushing this analogy further, according to the interface theory, decoherence might be less of an "intrinsic" feature of nature but arises as *effect on the interface*. We would thus maintain that "causality" is merely the name for a regularity that one can observe on the interface.[5] This is in contrast to the idea of Schneider and Bailey who take the "proto-temporal" realm (see discussion below) as a "causal arena" (Schneider & Bailey, 2025, sec. 4).

The interface theory regards *any* physical regularity as interface representation, derived from perception (Prakash, 2020). This entails an indirect answer to **Q1**: perception does not mirror any physical regularity "out there" (this is the basic finding of ITP); what appears as if it were a physical regularity "out there" irrespective of perception (including various quantum effects), can still be understood as derived from our perception (this is the extension to QIT). It is also the reason why the quantum world looks unfamiliar and counter intuitive to us. Yet, this feeling only arises when we try to make sense of our observations within the narrow bounds of our perceptual interface (e.g., interpreting entanglement as non-local correlation in space and time).

Even if the interface theory puts hard limits on the ontology beyond the interface, it is still possible to assume that interfaces emerge from some dynamical principle. This would suggest an affirmative answer to **Q2**: physical structures are instantiated (as interface representation) within the dynamics that ground interfaces. This is the dynamics of conscious agents.

3 From consciousness to physics?

3.1 A cautionary note

While the above is still compatible with the general thrust of quantum consciousness research, it warns us against taking quantum effects literally: the unity of consciousness need not be literally identical with entanglement; rather, entanglement may be the fundamental-physical signature of unity when consciousness is re-described in third-person terms. Such a description of consciousness would likely be an "ultra-thin" conception, quite distinct from our human-centric idea of it. The slogan is not "consciousness lives in the quantum" but "the quantum lives in consciousness."

Moreover, it also cautions against hypothesizing an ontic description "behind the phenomena" to explain these quantum effects. They can be more parsimoniously explained epistemically, namely as remnants of the way we apprehend the natural world. This is consistent with Bertrand Russell's dictum to substitute inferred entities by logical constructions whenever possible (Russell, 1914). An epistemic, Heisenberg-style reading of the formalism suffices; invoking hidden ontic entities adds little explanatory value.

[5] Assuming, that causality is here understood in terms of causes that happen in the past and effects that happen in the future. There are other notions of causation, such as causality as generalized form of "difference making," which might well be consistent with both approaches.

3.2 Toward a theory of quantum conscious agents

If QIT is true, it seems suggestive to say something like "the quantum is consciousness as seen through an interface." But this statement automatically raises the question of how one looks through an interface and what it is that is looked at. ("Who looks at what?"). According to a theory of consciousness in the vicinity of the interface theory, the answer is: consciousness looks at itself. We now outline the theory of conscious agents (Fields, Hoffman, Prakash, & Singh, 2018; Hoffman & Prakash, 2014; Hoffman et al., 2023; Prentner & Hoffman, 2024) to make this claim more precise. We proceed in three steps to sketch how this theory could be extended to a theory of *quantum conscious agents* that perceive, think, and act on their environment. First, we review some basic ideas and give a simplified definition of the original conscious agent formalism. Second, we identify the perceptual component of the quantum conscious agent with a quantum instrument. Third, we introduce the concept of "conscious realism" (Hoffman, 2008), namely the idea that, at least from the perspective of the agent, the agent's whole environment is to be modeled as a network of conscious agents:

1. Within ITP, evolutionary principles are invoked to explain the structure of our perceptual interface. Notably, concepts such as *computation* and *embodiment* can be reinterpreted as dynamic interactions within networks of experiences and actions that mutually update over time (Prentner & Hoffman, 2024). Figure 1 shows a minimal model of such a system (a "conscious agent") that consists of experiences X and actions G that are interlinked and interact recursively with the world W. Evolution shapes these feedback loops.

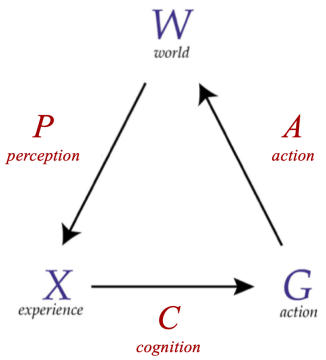


Fig. 1 A conscious agent as loop composed of perception, cognition, and action; slightly adapted from Hoffman & Prakash (2014).

This circular structure implies that an agent's current experience is conditionally dependent on its prior experience:

$$Q : X \times X \to [0, 1]. \tag{1}$$

Here, Q assigns a probability to each possible transition from one experience $x_k \in X$ to another $x_j \in X$. In the finite or countable and discrete case, Q can be represented as a stochastic matrix with entries $p(x_j|x_k)$.

Interpreted differently, this kernel encodes a minimal form of computation as information-processing dynamics over the space of experiences, governed by probabilistic transition rules. Crucially, the likelihood of future experiences is not static but depends on the agent's perceptions, cognitions, and actions. These can be modeled as compositional factors of the kernel:

$$Q = P \circ A \circ C, \tag{2}$$

where P represents perception, A action, and C cognition. On this view, computation is not disembodied but minimally embodied: the probability of undergoing a particular experience in the future is shaped by the agent's prior actions and internal dynamics.

One difficulty for this idea is that some notion of time is seemingly required here. Both the concepts of computation and evolution presuppose this notion: computation, because executing the rules encoded by Q is done step-by-step (even though multiple agents might do so in parallel), and evolution because variation and selection are processes that happen over time. One possible solution to this conundrum would be to say that kernel executions happen in a second dimension of "prototime" (Schneider & Bailey, 2025) and that the dynamics of agents, if suitably abstracted or approximated, only appear as systems evolving over our usual (e.g., entropic) time. Building on the suggestion by Schneider and Bailey (2025) that decoherence anchors classical time in a prototemporal realm, QIT proposes to map prototime onto an "orthogonal time dimension" for agent kernel operations. Environmental selection in quantum Darwinism and fitness optimization in the interface theory could then be regarded as dual expressions of this proto-temporal dynamics.

2. A measurement in quantum mechanics could be understood as some type of action on the world that (i) leads to a noticeable change in the system's experience, and (ii) affects both the world and the measuring system — an observation "acts back" on the observer. This view of measurements is made explicit in several interpretations of quantum mechanics, for example, in QBism (Fuchs, 2010). In psychological applications, the theory of quantum instruments naturally applies (Khrennikov, 2023; Ozawa & Khrennikov, 2019) whenever one wants to work with open systems and study their evolution after a measurement – arguably this is exactly what characterizes a (quantum) conscious agent.

   It has recently been proposed that experience ("qualia") should be understood as observables of a cognitive system, rather than as its "internal state" (Tsuchiya et al., 2025). The probability with which a specific experience obtains is given as a measurement outcome in the theory of quantum instruments. A quantum instrument is a set of completely positive and trace non-increasing maps $\{\mathcal{I}_j\}$ where each outcome j (corresponding to a perceptual experience) transforms the joint

agent-environment state ρ as:

$$\rho \mapsto \frac{\mathcal{I}_j(\rho)}{p_j},\ p_j = \mathrm{Tr}[\mathcal{I}_j(\rho)]$$

Here, p_j gives the probability of experience j, while the total map $\sum_j \mathcal{I}_j$ is trace-preserving, which ensures consistent state evolution. Crucially, this models perception as an interaction rather than collapse, thus preserving unitarity in the total system. In the theory of conscious agents, action is generally assumed to play the "inverse" role to perception, effectively modeling an agent's action as an environment's "perception" (Hoffman & Prakash, 2014).

We thus arrive at the idea to model the perceptual part of the kernel Q by a quantum instrument, which couples a quantum conscious agent to its environment. In contrast, the cognitive and purely environmental components correspond to the unitary (coherent) evolution of the joint agent-environment system. This dual structure allows for both probabilistic experience generation and deterministic system dynamics, offering a quantum-informational foundation for modeling conscious agency.

3. Unlike standard approaches, the formalism should not invoke the presence of a theory-external (and ill-defined) observer. After all, what could be a more fundamental theory "outside" of quantum theory? Quantum theory requires consistency within its framework. So at least, the formalism should be indifferent to things that happen outside the whole system: the environment is as good a quantum system as the agent itself. This is different from the classical story, where "agency" is often understood as acting against the backdrop of a purely non-agentic world outside the agent, a strange-but-pervasive intuition that could be described as a two-world conception: the "conjecture" outside vs. the "dream" inside (Whitehead, 1920).

   Instead, within the framework of "conscious realism" (Hoffman, 2008), the system might be intrinsically self-referential: conscious agents observe and interact with themselves and one another, forming a closed network of experiential dynamics. From this perspective, the entire environment of an agent is modeled as a network of conscious agents. These interactions, recursive and probabilistic, constitute the fabric of what we call reality. "Measurement," then, is not an extrinsic imposition but an intrinsic dynamic: a conscious agent perceiving and acting upon itself. This might resolve energy-conservation concerns: unlike projective measurements, quantum instruments embed perception within unitary agent-environment dynamics. For a self-measuring agent coupled to an environment, governed by a total system Hamiltonian H, the overall evolution satisfies $\frac{d}{dt}\langle H\rangle = 0$ when $\mathcal{I}_j$ commutes with H (e.g., for energy-symmetrized instruments). This avoids unwanted (e.g. quantum Zeno, Itano, Heinzen, Bollinger, and Wineland (1990)) effects by eliminating external measurement devices. Energy conservation follows from modeling perception as quantum interaction (not as measurement-via-external-observation).

4 Discussion and outlook

To summarize, the theory of quantum conscious agents presents an extension of a previous model of (idealist but also embodied) perception-cognition-action loops, which features the theory of quantum instruments to for perceptual experiences (qualia) and regards them as outcomes of the "self-measurements" of a network of conscious agents. This loop-like structure is shaped by an evolutionary principle, which is consistent with ideas from quantum Darwinism and the prototime-interpretation of Schneider and Bailey (2025), thus grounding a seemingly classical evolution that effectively happens over (entropic) time. Concretely, QIT can be empirically grounded through three modeling priorities:

- **Bridge prototime and selection dynamics:** Derive evolution-like dynamics (e.g., fitness optimization) from proto-temporal agent interactions, formalizing Schneider's claim that spacetime emerges from entanglement (Schneider & Bailey, 2025).
- **Reconcile perception with unitarity:** Model perceptual "self-measurements" as quantum instruments embedded in unitary agent-environment dynamics, analogous to decoherence distributing coherence via environmental entanglement (Zurek, 2003).
- **Resolve issues of energy non-conservation:** Demonstrate that self-measurements conserve energy, for example when perception instruments $\{\mathcal{I}_j\}$ commute with the total system Hamiltonian H (i.e., $[\mathcal{I}_j, H] = 0$), potentially avoiding artifacts such as the quantum Zeno effect (Itano et al., 1990).

It is intriguing to investigate this in light of recently proposed quantum extensions of established theories in the neuroscience of consciousness, for example, quantum versions of integrated information theory (Albantakis, Prentner, & Durham, 2023; Kleiner & Tull, 2021; Zanardi, Tomka, & Venuti, 2018). The theory, rather than postulating a metaphysical (reductive) identity between physical (quantum) systems and consciousness, could be interpreted as specifying an interface to consciousness on the quantum level, for example, providing a criterion for associating the interface with a minimal notion of self "intrinsic" to it (featuring a non-zero amount of Φ). An open question is whether or how such a system could be seen to trigger actions that feedback to its own experiential structure, effectively combining a first-personal "consciousness-first" approach with a "third-personal" action-oriented framework.

Empirically, QIT predicts that signatures of quantum coherence in a biological substrate will correlate with consciousness only if they modulate an agent's interface dynamics, a testable criterion. The framework also suggests new targets for AI research: constructing artificial agents whose "self-measurements" obey the quantum-instrument calculus.

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