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Quantum cognition: An epistemological challenge for naïve and local realism

Quantum cognition is an innovative and interdisciplinary emerging field within the cognitive sciences as, *inter alia*, evidenced by a recent theme issue published in the Philosophical Transactions of the Royal Society. It is independent from the widely debated Orch-OR (Orchestrated Objective Reduction) theory formulated by Sir Roger Penrose and Stuart Hameroff which postulates that quantum processes at the microtubular neuronal level are causative for the emergence of consciousness. Quantum cognition, on the other hand, applies the abstract formalism of quantum mechanics to cognitive processes (e.g., decision-making, perception, memory, conceptual reasoning, language, etc.). The vast majority of contemporary models (e.g., those utilising Bayes' theorem) are grounded on Kolmogorovian probability axioms which stipulate that operators obey commutativity, i.e., $P(A \cap B) = P(B \cap A)$. By contrast, quantum probability theory is not limited by these aprioristic structural constraints and is able to parsimoniously account for numerous empirical results which appear, *prima facie*, irrational and paradoxical in the orthodox framework. Recent empirical evidence from experimental quantum physics is highly pertinent for psychology, neuroscience, and computer science, and challenges some of the unquestioned assumptions which underlie most of current theorising, viz., naïve and local realism. This presentation will briefly review these paradigm-shifting findings and their epistemological and ontological implications. Moreover, I will discuss conceptually related psychophysics experiments conducted in India and the UK during my PhD. Finally, neurochemical processes (specifically 5-HT_{2A} receptor agonism) which underpin open-mindedness and intellectual curiosity will be addressed, as these personality traits are indispensable to appreciate the extensive ramifications of the novel and epistemically challenging results.

A conceptuel primer on superposition

“In atomic science, so far removed from ordinary experience, we have received a lesson which points far beyond the domain of physics.”
Niels Bohr, “Physical Science and Man’s Position,” (Presented at the United Nations International Congress on Peaceful Use of Atomic Energy, Geneva, August, 1955), Volume IV, p. 171.

According to most formal models (computational or mathematical) used in the cognitive sciences, the cognitive system changes on a moment to moment basis, but at any specific point in the temporal sequence it is assumed to be in a definite determined state. Models based on this assumption are for instance:

- Bayesian network models (e.g., Pearl, 2000),
- Production rule models (e.g., Klahr, Langley, & Neches, 1987),
- Connectionist network models (e.g., McClelland & Rumelhart, 1986).

Let us consider a specific example. Random walk models assume that evidence (information) is accumulated incrementally over time until a specific critical decision-threshold is reached. In this class of models, the weight associated with each option increases diachronically in a progressive manner. However, at each discrete point in the temporal sequence the system is assumed to be in a definite and determinable state. In principle, this state can be accessed by taking a measurement. Moreover, it is assumed that the act of measuring does not influence the state under investigation. That is, classical models presuppose that a given system is consistently in a specific state (even though the observers' cognition of this state might be uncertain).

This deterministic (Newtonian) assumption stands in sharp contrast with one of the main ideas of quantum probability (QP) theory which provides the axiomatic foundation of quantum theory. A crucial and profound insight derived from quantum theory is that taking a "physical measurement" of a "physical system" actively creates rather than passively records the property under investigation. In the context of decision-making, quantum cognition replaces the term "physical measurement" with "human decision" and "physical system" with "cognitive system".

By contrast, classical theories assume that taking a measurement merely reads out an already pre-existing state of a system. Moreover, QP is incompatible with the classical notion that a given system (be it physical or psychological) is always in a determinable state at any point in time. By contrast, QP allows for the possibility that a system can be in a superpositional state in which *n* possibilities can exist simultaneously as unrealized potentials (the technical terminus is state amplitudes; Heisenberg, 1958). It is only when a measurement is taken that these undetermined potentialities collapse into determinate actualities. In other words, measurements actively create rather than passively record the property under investigation. From a quantum cognition perspective, attitudes and opinions are not simply retrieved from memory – they are often constructed online. From a cognitive economy point of view, it seems to be very inefficient to store a vast number of opinions about reality in our brain/mind (e.g., sparse coding of memory). Santiago Ramón y Cajal postulated over 100 years ago that our neuronal morphology is shaped by "laws of conservation for time, space, and material" (Cajal, 1895). This notion is supported by recent neuroscientific simulation studies, which focus on the energy dynamics of neural network structures (Sporns, 2014). Following this line of thought, it seems plausible that most cognitive states are created in real time "on the fly". Quantum theory provides an elegant framework to formalize this intuition (see Busemeyer & Bruza, 2011).

A simplified real-world example

Consider the following generic decision scenario:

Suppose you have to decide an important question that can be answered either with yes or with no (you can imagine any scenario which fits this description). From a classical information processing point of view the answer entails a binary decision (1 or 0) and these values might change over time. Importantly, at any moment in time, you are assumed to be in a definite state (see Figure 1). However, it seems plausible that your answer to the question does not jump from one discrete binary state to the other (like a flip-flow). Instead, you might experience ambiguity about both states simultaneously (see Figure 2). That is, until you make decision you are in a superpositional state.

The concept of superposition differs from the classical concept of a mixed state. According to the latter, you are either exactly in state 0 or exactly in state 1, but we do not know which it is (because it is a latent/hidden variable). Therefore, probabilities are assigned to each possibility. By contrast, from a QP point view, you are *neither* in state 0 *nor* in state 1. You are in an indefinite ambiguous state, simultaneously entertaining both possibilities. An interesting aspect of QP theory is that it ascribes a constructive role to the process of disambiguating a superposition state (this is closely related to the Kochen-Specker theorem; Kochen & Specker, 1967). When you finally make the decision, the superposition instantly transforms into a determinate state (the quantum mechanical designation is “wave function collapse”). That is, the quantity being measured changes from a superimposed state into an eigenstate[1] (definite state). Note that the process of measurement itself causes this change. This is the basic tenet of superposition and collapse in QP theory from an intuitive point of view.

Figure 1. Classical sequential model (Markov)

Observe state i at time t where p_i = probability of state i

$p(t \mid i) = [1,0,..,1,..0]'$

$p(t + s) = T(s) \cdot p(t \mid i)$

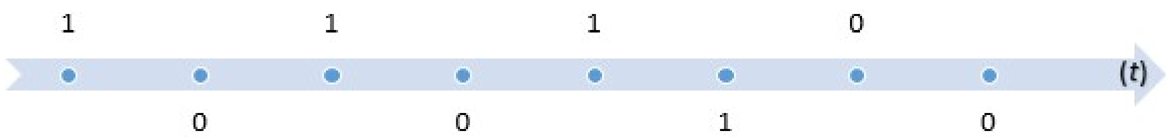
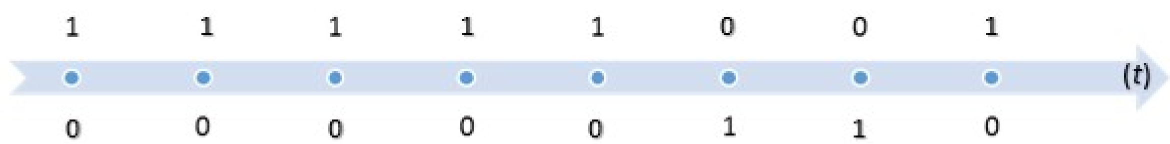


Figure 2. Quantum probability model (Schrödinger)

Observe state i at time t where ψ_i = amplitude of state i

$\psi(t \mid i) = [1,0,..,1,..0]'$

$\psi(t + s) = U(s) \cdot \psi(t \mid i)$



Micro vs. macro?

Fascinatingly, quantum effects are not just observable at the atomic scale but also at the macroscopic level of physical matter. For instance, quantum entanglement (an extremely active cutting-edge research topic in the physics community (e.g., Handsteiner et al., 2017)) has been demonstrated experimentally with large molecules (Arndt, et al., 1999) and even small diamonds (Lee et al., 2011). It becomes clear that the demarcation criterion between

[1] The word "eigenstate" is derived from the German word "eigen", meaning “own”, "inherent", or "characteristic".

micro and macro is highly arbitrary. The hitherto unanswered question is: At which scale do the quantum laws stop?

As Professor Anton Zeilinger (inaugural recipient of the Isaac Newton Medal) puts it in his 2008 Newton lecture: "*The experimenter decides whether a system is classical or quantum by choosing the apparatus, there is no objectivity … there is no border between the classical world and the quantum world, it depends on your experiment*" (Zeilinger, 2008).

This topic is not just of theoretical interest but has far-reaching real-world implications. For instance, quantum computation (Gottesman & Chuang, 1999), quantum AI (Dunjko & Briegel, 2017), quantum encryption (Lum et al., 2016), and quantum teleportation (Ren et al., 2017) are innovative fields of scientific research. Soon we might all be surfing in the "quantum internet" (Pirandola & Braunstein, 2016)…

References

Arndt, M., Nairz, O., Vos-Andreae, J., Keller, C., Van der Zouw, G., & Zeilinger, A. (1999). Wave-particle duality of C60 molecules. *Nature*, *401*(6754), 680-682.

Busemeyer, J. R., & Bruza, P. (2011). *Quantum models of cognition and decision making*. Cambridge, UK: Cambridge University Press.

Cajal, S. R. (1895). *Histology of the nervous system of man and vertebrates*. NY: Oxford University Press.

Gottesman, D., & Chuang, I. L. (1999). Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature, 402(6760), 390–393. https://doi.org/10.1038/46503
Gottesman, D., & Chuang, I. L. (1999). Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature, 402(6760), 390–393. https://doi.org/10.1038/46503
Handsteiner, J., Friedman, A. S., Rauch, D., Gallicchio, J., Liu, B., Hosp, H., … Zeilinger, A. (2017). Cosmic Bell Test: Measurement Settings from Milky Way Stars. *Physical Review Letters*. https://doi.org/10.1103/PhysRevLett.118.060401

Klahr, D., Langley, P. and Neches, R. (1987). *Production System Models of Learning and Development. Cambridge*, MA: The MIT Press.

Lee, K. C., Sprague, M. R., Sussman, B. J., Nunn, J., Langford, N. K., Jin, X.-M., … Walmsley, I. A. (2011). Entangling Macroscopic Diamonds at Room Temperature. *Science*, *334*(6060), 1253-1256.
Gottesman, D., & Chuang, I. L. (1999). Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature, 402(6760), 390–393. https://doi.org/10.1038/46503
McClelland, J., & Rumelhart, D. (1986). Parallel distributed processing: Explorations in the microstructure of cognition. Vol. 1. Cambridge, MA: MIT Press.

Pearl, J. (2000). *Causality: Models, Reasoning, and Inference*. Cambridge: Cambridge University Press.

Pirandola, S., & Braunstein, S. L. (2016). Physics: Unite to build a quantum Internet. Nature. https://doi.org/10.1038/532169a

Pothos, E. M., & Busemeyer, J. R. (2013). Can quantum probability provide a new direction for cognitive modeling. *Behavioral and Brain Sciences*, *36*, 255-274.

Gottesman, D., & Chuang, I. L. (1999). Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature, 402(6760), 390–393. https://doi.org/10.1038/46503

Kochen, S. and Specker E.P. (1967). The problem of hidden variables in quantum mechanics, *Journal of Mathematics and Mechanics*, *17*, 59-87.

Sporns, O. (2014). Cost, Efficiency, and Economy of Brain Networks. In Michael A. Gazzaniga (Ed.), *The Cognitive Neurosciences*, 5th ed,. Cambridge, MA: MIT Press.: 91-99.