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# Quantum Cognition: Key Issues and Discussion

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**Abstract**

Quantum cognition is an emerging field that uses mathematical principles of quantum theory to help formalize and understand cognitive systems and processes. The topic on *the potential of using quantum theory to build models of cognition* (Volume 5, issue 4) introduces and synthesizes its new development through an introduction and six core articles. The current issue presents 14 commentaries on the core articles. Five key issues surface, some of which are interestingly controversial and debatable as expected for a new emerging field.

*Keywords:* Quantum theory; Cognitive models; Probability; Order effects; Compatibility; Commutativity; Uncertainty

Quantum cognition is an emerging field that uses mathematical principles of quantum theory to help formalize and understand cognitive systems and processes. The topic on *the potential of using quantum theory to build models of cognition* (Volume 5, issue 4, of *Topics in Cognitive Science*) introduces and synthesizes its new development. Following a general introduction to quantum cognition theory and a brief review of the field, the topic presents six core articles of concrete theoretical development and empirical testing of quantum cognitive models. The core articles cover diverse topics, including ambiguous perception, concepts and semantics, concepts combinations, episode memory, order effects of psychological measurements, and decision making. They aim to test how cognitive models based upon quantum probability theory (QP), instead of classical probability theory (CP), can be developed to explain paradoxical empirical findings or challenging questions in psychological literature.

The current issue includes 14 commentaries on these core articles, including a reply to one of the commentaries. Some raise general issues regarding quantum cognition, and others

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are more specific to one or two articles. Several key issues surface. As expected for a new emerging field, some of the questions are interestingly controversial and debatable.

First, what is the contribution of quantum cognition and where is it going? Commentaries by Sloman and Hampton discuss these. In his commentary, Sloman defends quantum cognition against Lee and Vanpaemal's earlier criticisms. He emphasizes that both QP and CP have it right that causes are never sufficient for explaining psychological effects nor that Probability (effect | cause) = 1. He points out that utilizing QP, quantum cognition is about a kind of uncertainty that differs from crisp probability as formalized in CP cognitive models. The inevitable uncertainty presented in cognition and decision is from imprecision and vagueness of measurements and language, or ambiguity and limited information that is ubiquitous in psychology. In sum, he proposes there are different kinds of judgments that lend themselves to distinct psychological analyses. One analysis describes computations in a similarity space and involves parallel multi-attribute comparisons; the other involves rules that count and combine sets. This distinction maps cleanly onto at least one dual-system theory (Sloman, 1996). Using conceptual combination models as examples, Hampton makes an important point in his commentary on how to move the field forward: "For progress to be made, it should be a common goal to make closer links between the parameters within the mathematical model and measurable aspects of the concept intensions." Indeed, a close marriage between the mathematical and theoretical rigor of quantum theory, and the substantive and intuitive psychological conceptions is the aim of quantum cognition scholars.

Second, when is a phenomenon quantum and when is a theory a quantum theory? More comprehensive discussion can be found in Busemeyer and Bruza (2012), and the introduction to the topic (Wang, Busemeyer, Atmanspacher, & Pothos, 2013). Commentaries here focus on several key quantum conceptions—interference, entanglement, compatibility/commutativity, and measurement orders. La Mura discusses physical versus abstract mathematical quantum models, and the nature of non-physical interference phenomena in human decision making. Lambert-Mogiliansky discussed another important concept in quantum theory—compatibility. She specifically suggests developing alternative models assuming incompatibility of the episodic memory measures to account for the empirical interference effects presented in one of the core articles. One of the strengths of quantum cognitive models is their high empirical testability. For example, whether the episodic memory measures should be assumed to be compatible or incompatible in fact can be empirically tested using a measurement order paradigm developed in quantum cognition research. If order effects occur, then the models need to take their incompatibility into account. In his commentary, beim Graben provides interesting discussion on various cognitive phenomena of the order effects and the relation to language, and the crucial role of noncommutativity of mental operations upon cognitive states.

Third, commentaries by Basieva and Khrennikov, and by Yukalov and Sornette address the issue of incompatibility of measurements and why this is important for decision theory. Basieva and Khrennikov, and Yukalov and Sornette present alternative theoretical approaches that are quite different from the models included in the topic. Khrennikov and colleagues have developed a general method for constructing a quantum-like wave function representation of probabilistic data that relaxes the law of total probability. Yukalov and Sornette summarize some of the basic ideas behind their general quantum decision theory, which uses a superposition called a prospect to represent decision uncertainty.[1]

Fourth, what are the neural implementations of quantum cognition? There are two different perspectives. One perspective is discussed by Hameroff, and by H. Wang and Sun. Both propose a quantum (computer) brain and encourage integrating the quantum brain approach and the quantum cognition approach. Very differently, the other perspective proposes classical neural models that can be efficiently modeled using quantum dynamics. Related issues are discussed by Takahashi and Shankar, although Shankar has some reservations about the neural plausibility of the model presented by Fuss and Navarro (2013). Consistent with the second perspective, an interesting view has been proposed by beim Graben and colleagues (beim Graben & Atmanspacher, 2006; beim Graben, Filk, & Atmanspacher, 2013): Coarse measurements of a classical dynamic system, such as neural systems, typically generate incompatible observables that result in unresolvable uncertainty relations and entangled correlations, such as our cognitive behavioral observables. In other words, even if the brain is classical, the observed cognitive behaviors and processes may be better modeled by QP.

Last, several commentaries discuss other ways to formulate probability models for cognition. Narens develops a generalized probability theory called intuitionistic theory, which relaxes the complementation axiom of classical Kolmogorov theory. In his commentary, he emphasizes how event space properties can impact probability concepts and thus the ways we model human cognition. Dzhafarov and Kujala's approach remains within classical Kolmogorov theory but extends it by allowing for stochastically unrelated sample spaces and random variables. They developed general conditions for testing existence of joint distributions of events and point out the importance of marginal selectivity to be tested as well as the Bell/CHSH inequalities for testing existence of joint distributions. In their commentary, Dzhafarov and Kujala connect the issue of testing existence of joint distribution of events to the concept of selective influences in psychology. Aerts comments on their commentary.

Bohm (1957, p. 103) said, "The most fundamental theory now available is probabilistic in form, and not deterministic." Now the question faced by cognitive scientists is: What kind of probabilities better describe our human cognition? We wish the topic on quantum cognition and the commentaries presented here fuel our exploration along this amazing journey.

## Note

1. A small but important detail that we need to point out concerns an issue brought up at the end of Yukalov and Sornette's commentary on the Z. Wang and Busemeyer (2013) article. Z. Wang and Busemeyer present a test of the quantum model of measurement order effects using a *q*-test equality, called QQ equality. Yukalov

and Sornette claim that the classical model also predicts this equality. However, the latter is true *only if* there are no order effects of the measurements; and the whole point of Z. Wang and Busemeyer's article is to develop and test a quantum model of measurement order effects, and all the datasets that they used to test the model using the QQ equality show significant order effects. It is important to note that when there are measurement order effects, the classical model does not predict the QQ equality, but the quantum model does. Exactly based on this, QQ equality is the critical test on the quantum measurement order model, as shown by Z. Wang and Busemeyer.

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