around. Quantum models of cognition offer formal exercises that might produce impressive fits to data but, by their founding assumptions, cannot offer some of the most basic insights into the causes, effects, and relevant factors that underlie the workings of human cognition.

Jaynes (1993, p. 269) puts the physicists' epistemological dissent bluntly, saying "I am convinced, as were Einstein and Schrödinger, that the major obstacle that has prevented any real progress in our understanding of Nature since 1927, is the Copenhagen Interpretation of Quantum Theory. This theory is now 65 years old, it has long since ceased to be productive, and it is time for its retirement." It would be unfortunate if a theory ready for retirement in its professional field of physics were to enjoy a second hobbyist career in psychology.

Grounding quantum probability in psychological mechanism

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Abstract: Pothos & Busemeyer (P&B) provide a compelling case that quantum probability (QP) theory is a better match to human judgment than is classical probability (CP) theory. However, any theory (QP, CP, or other) phrased solely at the computational level runs the risk of being underconstrained. One suggestion is to ground QP accounts in mechanism, to leverage a wide range of process-level data.

Pothos & Busemeyer (P&B) make clear that quantum probability (QP) theory offers a rich array of theoretical constructs, such as superposition, entanglement, incompatibility, and interference, which can help explain human judgment. The authors illustrate how these concepts, which are strongly contrasted with the basic tenets of classical probability (CP) theory, can be used to accommodate aspects of human choice that deviate from normative CP accounts. For example, the conjunction fallacy is explained in terms of incompatible questions requiring sequential evaluation, which induces an interference effect.

Although new frameworks can provide novel insights, one worry is that QP will recapitulate some of the shortcomings of rational CP approaches by sticking to a computational-level analysis. To the authors' credit, they acknowledge how notions of optimality in CP approaches can be impoverished and not match the goals of the decision maker. However, these criticisms largely serve to question CP's status as the preferred normative account rather than question the wisdom of eschewing process-level considerations in favor of a computational-level analysis.

In a recent article with Jones (Jones & Love 2011), we, too, critiqued rational (Bayesian) CP approaches to explaining human cognition, but our critique was broader in scope. Although many of our points are particular to the rational Bayesian program (which we refer to as "Bayesian Fundamentalism"), some of the central critiques apply equally well to any approach largely formulated at the computational level. The basic issue is that such accounts wall off a tremendous amount of related data and theory in the cognitive sciences, including work in attention, executive control, embodiment, and cognitive neuroscience, as well as any study using response time measures. It seems unlikely that a complete theory of cognition or decision making can be formulated when neglecting these insights and important constraints.

The suggestion offered in Jones and Love (2011), which we referred to as "Bayesian Enlightenment," is to integrate probability and mechanistic approaches. In the context of QP, one could imagine construing operations, such as projections to subspaces, as psychological operations that unfold in time, may have brain correlates, be limited in capacity, and change over development. Such an approach would retain the distinctive characteristics of QP while linking to existing theory and data.

Grounding QP in mechanism may offer a number of other advantages, such as better motivating the assumptions (that are psychological in nature) that make QP successful. Many of the effects considered in the target article require assumptions on the order in which statements are considered and the role context plays. These topics may be addressed in a principled manner when situated within a mechanism that aims to explain shifts in focus or attention. Such mechanistic models would also make clear what role QP plays in accounting for the results, as opposed to the ancillary assumptions.

The authors note that one key challenge is to anticipate new findings rather than simply accommodate existing data. Grounding QP ideas in mechanism may facilitate making a priori predictions. Once the move to mechanism is made, second generation questions can be asked, such as which QP model best accounts for human judgment. My guess is that moving away from evaluating general frameworks to testing specific proposals will hasten progress. As the authors note, it is very difficult to invalidate an entire framework, as ancillary assumptions can always be made (e.g., CP models can be modified to account for the main findings in the target article). In contrast, particular models can be evaluated using model selection procedures.

My prediction is that moving toward evaluating particular models grounded in mechanism will lead to a rapprochement between QP and CP approaches. For a view that allows for superposition, many aspects of the QP are very rigid. For example, according to the approach advocated by the authors, statements are either compatible or incompatible. One possibility is that successful models will be more fluid and include a mixture of states, which is a notion from CP. Given the complexities of human cognition and decision making, it would be surprising if one unadulterated formalism carried the day. Although physics undergraduates may complain about how confusing QP is, human cognition will likely prove more vexing.

Cognition in Hilbert space

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Abstract: Use of quantum probability as a top-down model of cognition will be enhanced by consideration of the underlying complex-valued wave function, which allows a better account of interference effects and of the structure of learned and ad hoc question operators. Furthermore, the treatment of incompatible questions can be made more quantitative by analyzing them as non-commutative operators.

Pothos & Busemeyer (P&B) argue for the application of quantum probability (QP) theory to cognitive modeling in a function-first or top-down approach that begins with the postulation of vectors in a low-dimensional space (sect. 2.1), but consideration of the high-dimensional complex-valued wave function underlying the state vector will expand the value of QP in cognitive science. To this end, we should import two premises from quantum mechanics. The first is that the fundamental reality is the wave function. In cognitive science, this corresponds to postulating spatially distributed patterns of neural activity as the elements of the cognitive state space. Therefore, the basis vectors used in QP are basis functions for an infinite (or very high) dimensional Hilbert space. The second premise is that the wave function is complex valued and that wave functions combine with complex coefficients, which is the main reason for interference and other non-classical phenomena. The authors acknowledge this (sects. 2.3, 3.3, Appendix), but they do not make explicit use of complex numbers in the target article.

There are several possible analogs in neurophysiology of the complex-valued wave function, but perhaps the most obvious is the distribution of neural activity across a region of cortex; even a square millimeter of which can have hundreds of thousands of neurons. The dynamics are defined by a time-varying Hamiltonian, with each eigenstate being a spatial distribution of neurons firing at a particular rate. The most direct representations of the magnitude and phase (or argument) of a complex quantity are the rate and relative phase of neural impulses.

The target article specifies that a decision corresponds to measurement of a quantum state, which projects the cognitive state into a corresponding eigenspace, but it is informative to consider possible mechanisms. For example, the need to act definitely (such as coming to a conclusion to answer a question) can lead to mutually competitive mechanisms, such as among the minicolumns in a macrocolumn, which create dynamic attractors corresponding to measurement eigenspaces. Approach to the attractor amplifies certain patterns of activity at the expense of others. Orthogonal projectors filter the neural activity and win the competition with a probability proportional to the squared amplitude of their inner products with the wave function. (In the case in which impulse phases encode complex phases, matching occurs when the phases are delayed in such a way that the impulses reinforce.) The winner may positively reinforce its matched signal components while the loser negatively reinforces its matched components. Regardless of mechanism, during collapse, the energy of the observed eigenstate of the question (measurement) operator captures the energy of the orthogonal eigenstates (this is the effect of renormalization). The projection switches a jumble of frequencies and phases into a smaller, more coherent collection, corresponding to the outcome (observed) eigenspace. This competition also explains the prioritization of more likely outcomes (sect. 3.1).

The target article (sect. 2.1) suggests that a QP model of cognition begins by postulating basis vectors and qualitative angles between alternative question bases (significantly, only real rotations are discussed). As a consequence, a QP model is treated as a low-dimensional vector space. This is a reasonable, top-down strategy for defining a QP cognitive model, but it can be misleading. There is no reason to suppose that particular question bases are inherent in a cognitive Hilbert space. There may be a small number of "hard-wired" questions, such as fight-or-flight, but the vast majority is learned. Certainly this is the case for questions corresponding to lexical categories such as (un-)happy and (un-)employed.

Investigation of the dynamics of cognitive wave function collapse would illuminate the mechanisms of decision making, but also the processes by which observables are organized. This would allow modeling of changes in the question bases, either temporary through context effects, or longer lasting through learning. Furthermore, many question bases are ad hoc, as when we ask, "Do you admire Telemachus in the *Odyssey*?" How such ad hoc projectors are organized requires looking beneath a priori basis vectors to the underlying neural wave functions and the processes shaping them.

Certainly one of the most interesting consequences of applying to QP to cognition is the analysis of incompatible questions. The approach described in the target article (sect. 2.2) begins by postulating that incompatible questions correspond to alternative bases for a vector space. The qualitative angle between the question bases is estimated by a priori analysis of whether the questions interfere with each other.

In quantum mechanics, however, the uncertainty principle is a consequence of non-commuting measurement operators, and the degree of non-commutativity can be quantified. Two measurement operators P and Q commute if $PQ = QP$, that is, if the operator $PQ-QP$ is identically 0. If they fail to commute, then $PQ-QP$ measures the degree of non-commutativity, which is expressed in quantum mechanics by the *commutator* $[P,Q] = PQ-QP$. It is relatively easy to show that this implies an uncertainty relation: $\Delta P \Delta Q \geq |\langle [P, Q] \rangle|$. That is, the product of the uncertainties on a state is bounded below by the absolute mean value of the commutator on the state. Suppose H is a measurement that returns 1 for $|\text{happy}\rangle$ and 0 for $|\text{unhappy}\rangle$, and E is a measurement that returns 1 for $|\text{employed}\rangle$ and 0 for $|\text{unemployed}\rangle$. If

$$|\text{employed}\rangle = a|\text{happy}\rangle + b|\text{unhappy}\rangle,$$

$$\text{then the commutator is } [H, E] = ab\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

and the magnitude of the commutator applied to an arbitrary state $|\psi\rangle$ is $\| [H,E] |\psi\rangle \| = |ab|$.

Might we design experiments to measure the commutators and so quantify incompatibility among questions? Certainly there are difficulties, such as making independent measurements of both PQ and QP for a single subject, or accounting for intersubject variability in question operators. But making such measurements would put more quantitative teeth into QP as a cognitive model.

Processes models, environmental analyses, and cognitive architectures: Quo vadis quantum probability theory?

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Abstract: A lot of research in cognition and decision making suffers from a lack of formalism. The quantum probability program could help to improve this situation, but we wonder whether it would provide even more added value if its presumed focus on outcome models were complemented by process models that are, ideally, informed by ecological analyses and integrated into cognitive architectures.

In the cognitive and decision sciences, much research suffers from a lack of formalism. This is particularly the case for qualitative accounts of behavior proposed, for instance, within the heuristics-and-biases framework (Kahneman et al. 1982), or within related dual process theories of cognition (Sloman 1996). We applaud Pothos & Busemeyer's (P&B's) attempt to promote a formal framework that contributes to remedying this shortcoming and that has a high potential for being innovative and useful. With that being said, we take issue with three aspects of the quantum probability (QP) program.

First, we posit that outcome models should be complemented by process models. What level of description do P&B envision for QP models? One of the central goals of many psychological theories is to describe cognitive processes. In contrast, behavioral economists and cognitive scientists working with, for example, Bayesian models (e.g., Griffiths et al. 2008) focus on predicting the outcomes of behavior, without necessarily aspiring to provide plausible accounts of the underlying processes (Berg & Gigerenzer 2010). We worry that the QP program falls into this class of outcome-oriented (or *as-if*) models, banishing algorithmic-level accounts of memory, behavior exhibits properties such as incompatibility, interference, and entanglement, we believe that the answer is yes.

Lee & Vanpaemel present another objection to quantum theory. They note the extent to which a limited number of physicists have objections to quantum theory. They provide a telling quote from Jaynes, in which he strongly questions the value of quantum theory in physics. (However, we recommend reading Bub [1999] rather than Jaynes, for a more comprehensive interpretation of quantum theory.) To clarify this issue, physicists do not object to the formal (mathematical) form of quantum theory. They debate its interpretation. Our applications to cognition have used the mathematics, and we have avoided taking any stand on the interpretation of quantum theory. Leaving aside the fact that no other physical theory has had such a profound impact in changing our lives (e.g., through the development of the semiconductor and the laser), few if any physicists think that quantum theory is going into retirement soon. For completeness, it is worth noting that Aspect's work famously and definitively supported quantum theory against Einstein's classical interpretation of Bell's hypothetical experiment (e.g., Aspect et al. 1981). Any introductory quantum mechanics text will outline the main ideas (e.g., see Isham 1989). Quantum theory is a formal theory of probability: it remains one of the most successful in physics and we wish to explore its possible utility in other areas of human endeavor.

In conclusion, the wide variety of thought-provoking comments, ranging across criticisms to empirical challenges to debates about fundamental aspects of cognition, attest to Sloman's view that "quantum theory captures deep insights about the workings of the mind" (this is part of his review for Busemeyer & Bruza's 2012 book, Busemeyer & Bruza 2012).

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[The letters "a" and "r" before author's initials stand for target article and response references, respectively]

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