Progress in Biophysics and Molecular Biology 130 (2017) 53–60

Contents lists available at ScienceDirect

Progress in Biophysics and Molecular Biology

journal homepage: www.elsevier.com/locate/pbiomolbio

Neural implementation of operations used in quantum cognition[☆]

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ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form
26 April 2017
Accepted 27 April 2017
Available online 6 May 2017

ABSTRACT

Quantum probability theory has been successfully applied outside of physics to account for numerous findings from psychology regarding human judgement and decision making behavior. However, the researchers who have made these applications do not rely on the hypothesis that the brain is some type of quantum computer. This raises the question of how could the brain implement quantum algorithms other than quantum physical operations. This article outlines one way that a neural based system could perform the computations required by applications of quantum probability to human behavior.

Contents

Although quantum mechanics is a theory of physics, the mathematics underlying this theory provides the foundation for a general theory of probability (Pitowski, 2006; Suppes, 1966). Most applications of probability theory outside of physics are based on classical theory Kolmogorov (1933/1950). Until recently, quantum probability theory has rarely been applied outside of physics to fields such as the behavioral and social sciences. However, a body of researchers in the new field called "quantum cognition" have made a reasonably convincing case that quantum probability theory provides a viable new way to formulate theoretical explanations for puzzling behavior that have resisted explanation by classical probability theories (Busemeyer and Bruza, 2012; Khrennikov, 2010). See Ashtiani and Azgomi (2015) for a recent survey of the field.

There are two different views that a quantum cognition researcher can hold regarding the use of quantum probability theory to model human behavior. One view is that quantum

☆ This research was supported by NSF MMS (SES-1560554 and AFOSR FA9550-15-1-0343).

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http://dx.doi.org/10.1016/j.pbiomolbio.2017.04.007
0079-6107/

probability rules are simply useful for predicting human behavior, and they do not have to be represented at a neurophysiological level (see, e.g., Atmanspacher and Filk, 2010). The other view is that the brain actually implements these procedures. In particular, the state vector is somehow physically present in the brain.

Researchers who take the view that brain actually implements quantum computations have at least two different ideas about how this can be done. One hypothesis (e.g., Hammeroff, 1998; Jibu and Yasue, 1995)[1] proposes that the brain is using quantum physical mechanisms to represent cognitive states and produce operations. Another hypothesis (e.g., Eliasmith, 2013) proposes that classical neural network models can implement the computations required by the quantum probability rules. The purpose of this article is to describe a classical neural network that implements quantum computations.

1. Confidence judgments during signal detection

To motivate this presentation, it is helpful to begin with an empirical example that illustrates the kind of evidence used to support the application of quantum probability to human judgment and decision making. One of the key types of findings used to support a quantum interpretation are interference effects, which are essentially violations of the law of total probability.

We recently found evidence for interference effects obtained from a human decision making experiment using a signal detection type task in which a decision maker must decide on each decision trial whether a target is present or absent based on noisy and uncertain information (e.g., to decide whether or not an enemy is located at a position based on a poor and fuzzy image). Decisions are made across several hundred trials – on some trials the signal is present, and on other trials, no signal is present. Accuracy, decision time, and confidence are measured on each trial. Performance on the signal detection task has traditionally been modeled using classical Markov type of random walk/diffusion models of decision-making (see, e.g., Ratcliff and Smith, 2004). The basic idea is that the decision maker accumulates evidence for each hypothesis until the accumulated evidence reaches a threshold. The first hypothesis to reach the threshold is chosen, the time to reach the threshold determines the decision time, and the difference in evidence soon after the decision determines the confidence (Pleskac and Busemeyer, 2010).

Alternatively, Busemeyer et al. (2006) developed a quantum walk model for signal detection (summarized later), which assumes that a person's evidence state is represented by a quantum wave function that evolves across levels of confidence in the direction driven by the presented information. Busemeyer and Bruza (2012) derived a key prediction that provides a critical method to empirically distinguish and test the two theories. The experiment consists of two conditions: In the choice-confidence condition, the person makes a choice (makes a binary decision between signal present versus signal absent) at time t_1 and then rates confidence at time t_2; in the confidence-alone condition, the person only provides a confidence rating at time t_2. For both conditions, the focus is on the marginal distribution of confidence ratings that are obtained at time t_2. Confidence is defined as the judged probability that a signal is present rated on a 0% (certain signal not present) to 100% (certain signal is present) scale. The Markov model obeys the Chapman-Kolmogorov equation, which is a dynamic form of the law of total probability, and it predicts no difference between the two conditions. The quantum model predicts an interference effect produced by the choice on the confidence rating, which makes the confidence distributions differ between the two conditions.

Kvam et al. (2015) empirically tested for the predicted interference effects by comparing confidence ratings produced by the choice-confidence versus confidence-alone conditions. They obtained strong support for the interference effect predicted by the quantum model. Confidence judgments were, on average, lower in the choice-confidence condition ($M = 83.96$; $SD = 15.56$) than in the confidence-alone condition ($M = 85.15$; $SD = 14.95$), and a Bayesian statistical analysis of the difference resulted in a 95% highest density interval that did not cover zero.[2] Fig. 1 shows the result for one of the nine participants. The horizontal axis represents the degree of confidence, and the vertical axis represents the relative frequency of reporting a particular level of confidence. Notice the large bump produced by the choice in choice-confidence condition, which is absent for the choice-alone condition. Also notice that the confidence seems to oscillate as it moves up the scale in agreement with the quantum model and contrary to the predictions of the Markov model.

2. Quantum probability basics

Quantum theory was originally developed by a brilliant collection of scientists including Planck, Einstein, de Broglie, Bohr, Heisenberg, Born, Schrödinger and many others, but a firm mathematical foundation was not established until the axiomatic works by Dirac and von Neumann (Von Neumann, 1932/1955; Dirac, 1930/1958). Of course, the theory has evolved extensively since that time to include new concepts, such as quantum noise decoherence produced by open systems (Nielsen and Chuang, 2000). However, here we simply describe the very basic ideas. To keep the mathematics at an elementary level, we will restrict our discussion to finite spaces. Although the dimension of the space is finite, it could be very large, e.g., 10 billion, which is less than the number of neurons in the brain! We can translate classical into quantum probability theory as follows.

We start by replacing the classic *sample space* (a finite set of cardinality N) with a quantum *Hilbert space* (a finite vector space of

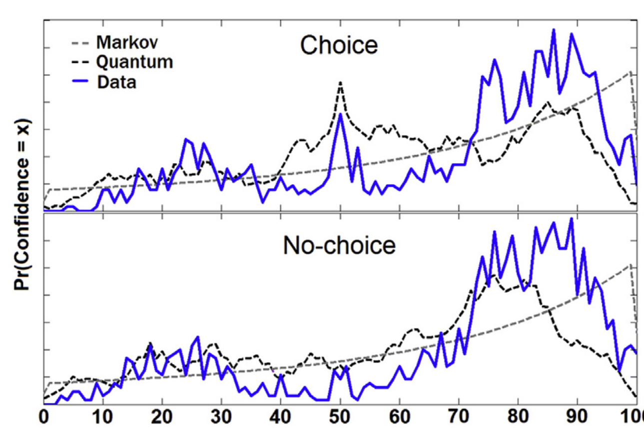

Fig. 1. Interference effects for one participant. Top panel shows choice-confidence condition, bottom panel shows confidence-alone condition. Horizontal axis represents confidence on a 0 = certain absent to 100 = certain present scale. Vertical axis shows relative frequency of a confidence rating. Blue curve shows data, black curve shows quantum predictions, grey curve shows Markov predictions.

[1] The quantum field models of memory by Freeman and Vitiello (2006) seem to lie someplace between an abstract mathematical model and a physical brain model.

[2] This is the Bayesian version of 95% confidence interval.