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Can quantum probability help analyze the behavior of functional brain networks?

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Abstract

Pothos and Busemeyer (2013) argue how key concepts of quantum probability, e.g., order/context, interference, superposition and entanglement, can be used in cognitive modeling. Here, we suggest that these concepts can be extended to analyze neurophysiological measurements of cognitive tasks in humans, especially in functional neuroimaging investigations of large-scale brain networks.

We agree in general with the views expressed in the target article by Pothos and Busemeyer (PB) about the application of quantum probability (QP) to cognitive science. Moreover, we believe that the mathematical framework of QP can be used as well to interpret brain network interactions underlying cognitive tasks and that this should be further explored in the future. Here, we emphasize that the concept of functional brain network embodies notions similar to those of QP such as entanglement, interference and incompatibility.

Modern neuroimaging experimental designs are often based on the idea of studying a complex cognitive task as a sum of multiple sensory/cognitive factors that have corresponding processing modules in the brain (Sternberg 2011). For example, to study auditory-visual integration one would design unimodal control tasks (factors) employing visual and auditory stimuli separately, and examine the change of brain responses during presentation of combined visual-auditory stimuli (Molholm et al. 2004). Another example comes from investigating the neural correlates of bimanual coordination - execution of movements with both limbs, e.g. two hands or two feet. Here, unimanual movements (movement with one limb at a time) serve as factors for studying the neural correlates of bimanual movements (Debaere et al. 2001, Banerjee et al. 2012a).

A fundamental problem with factor-based approaches is that they implicitly assume each cognitive component triggers an additional neural correlate that is the same irrespective of the cognitive or physiological context (Banerjee et al. 2008). For example, while studying multisensory integration, one often assumes the same brain response during an auditory stimulus presentation is expected to be triggered in auditory areas when a visual stimulus is tagged with the auditory stimulus presentation as a combined auditory-visual stimulus

(Molholm et al. 2004). The reader of PB will note that this assumption is identical to the concept of “compatibility” and is not appropriate for studying the neural basis of human sensory and cognitive processes that are adaptive to even subtle changes of context (McIntosh 2004).

Furthermore, an implicit assumption in factor-based neuroimaging designs is that any residual (e.g., bimanual – sum of left and right unimanual) brain activity comes from recruitment of additional brain areas related only to the missing factor not addressed by the control tasks (Banerjee et al. 2008). Hence, the possibility of “interference” of control related networks during the active cognitive task is ignored by factor-based designs. This approach thus disregards the “degenerate” nature of cognitive neural systems – different networks can coordinate to perform the same tasks (Price & Friston 2002; Tononi et al. 1999). Degeneracy is an omnipresent phenomenon of complex biological systems and the search for measures to characterize degenerate neural systems is an ongoing area of research (Tononi et al. 1999; Edelman & Gally 2001). Current neuroscience research indicates that there are two distinct conceptualizations of neural degeneracy – structural & functional. The same neural structures can give rise to different functions (structural) and different neural structures can generate the same function (functional) (McIntosh 2004; Price & Friston 2002). An example of the former was observed in an electroencephalographic (EEG) study of bimanual coordination (Banerjee et al. 2012a) where participants were asked to move their left or right fingers independently and simultaneously in different trials at specific frequencies by syncing with a rhythmic visual stimulus. During execution of stable bimanual coordination patterns, neural dynamics were dominated by temporal modulation of unimanual networks. An example of functional degeneracy occurred in an investigation of the temporal microstructure of a long term memory retrieval process (Banerjee et al. 2012b). Here magnetoencephalographic (MEG) data were used to examine the network recruitment of auditory areas during a visual-auditory paired associate task compared to a visual-visual paired associate task. It was found that visual–visual and visual-auditory memory recollection involved equivalent network components without any additional recruitment during an initial period of the sensory processing stage, which was then followed by recruitment of additional network components for modality specific memory recollection.

PB point out that the QP concept of “entanglement” plays a crucial role in understanding cognitive behavior. The mathematical framework of expressing “entanglement” involves quantifying the evolution of correlated state variables and hence is pertinent for the study of functional brain networks. Indeed, data acquired by functional neuroimaging (i.e., functional magnetic resonance imaging (fMRI) and EEG/MEG) are being investigated by cognitive neuroscientists using a variety of network-based mathematical tools, such as functional connectivity (Horwitz et al. 1992; Beckmann et al. 2005), effective connectivity (McIntosh et al. 1994; Friston et al. 2003) and graph theory (Bullmore & Sporns 2009). A critical point with respect to functional networks is that since all nodes are functionally linked to one another, any alteration in even a single link results in alterations throughout the network (Kim & Horwitz 2009). In essence, one can say that brain network nodes (regions) that may not be anatomically connected and are physically separated by large distances can become “entangled” with one other to facilitate task execution. This aspect of network behavior has

important ramifications for the way in which functional brain imaging data are interpreted in comparing tasks or patients and healthy subjects (Kim & Horwitz 2009).

To conclude, we think the insights that QP brings to cognitive science, as reviewed by PB, are likely to be as significant when used for interpretation of brain network analysis. Indeed, an examination of the recent brain imaging literature suggests that such an approach already is under way (Banerjee et al. 2012a,b; Noppeney et al. 2004). Although the words used by functional brain imagers to describe their methods differ from the language of QP, we have attempted to point out that there are strong similarities in the fundamental mathematical problem each strives to solve.

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