Quantum Structure in Cognition: Why and How Concepts Are Entangled

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Abstract. One of us has recently elaborated a theory for modelling concepts that uses the state context property (SCoP) formalism, i.e. a generalization of the quantum formalism. This formalism incorporates context into the mathematical structure used to represent a concept, and thereby models how context influences the typicality of a single exemplar and the applicability of a single property of a concept, which provides a solution of the Pet-Fish problem and other difficulties occurring in concept theory. Then, a quantum model has been worked out which reproduces the membership weights of several exemplars of concepts and their combinations. We show in this paper that a further relevant effect appears in a natural way whenever two or more concepts combine, namely, entanglement. The presence of entanglement is explicitly revealed by considering a specific example with two concepts, constructing some Bell’s inequalities for this example, testing them in a real experiment with test subjects, and finally proving that Bell’s inequalities are violated in this case. We show that the intrinsic and unavoidable character of entanglement can be explained in terms of the weights of the exemplars of the combined concept with respect to the weights of the exemplars of the component concepts.

Keywords: Concept combination, Bell’s inequalities, entanglement, quantum cognition.

1 Introduction

Understanding the mechanism of how concepts combine to form sentences and texts so that it is possible to communicate meaning among human minds is one of the major challenges in the psychological studies on human thought. None of the existing theories on concepts explains however ‘how concepts combine’. This combination problem was manifestly revealed by Hampton’s experiments [12] which measured the deviation from classical set theoretic membership weights of exemplars with respect to pairs of concepts and their conjunction or disjunction. Hampton’s investigation was motivated by the so-called Guppy effect in concept conjunction found by Osherson and Smith [3]. These authors considered the concepts Pet and Fish and their conjunction Pet-Fish, and observed that, while an exemplar such as Guppy was a very typical example of Pet-Fish, it was
neither a very typical example of *Pet* nor of *Fish*. Hence, the typicality of a specific exemplar with respect to the conjunction of concepts shows an unexpected behavior from the point of view of classical set and probability theory. As a result of this work, the problem is often referred to as the *Pet-Fish problem* and the effect is usually called the *Guppy effect*. Hampton identified a Guppy-like effect for the membership weights of exemplars with respect to pairs of concepts and their conjunction [1], and equally so for the membership weights of exemplars with respect to pairs of concepts and their disjunction [2]. Several experiments have since been performed (see, e.g., [4]) and many approaches have been propounded to solve the Pet-Fish problem (see, e.g., fuzzy set based theories [5,6,7] and to provide a satisfactory mathematical model of concept combinations (see, e.g., explanation based theories [8,9,10]). But none of the currently existing concept theories provide a satisfactory description or explanation of such effects [4,9,10].

Inspired by a formalism providing an operational foundation of quantum mechanics [11,12,13,14], one of the authors has elaborated, together with some co-workers, a *State Context Property (SCoP)* formalism to model and represent concepts [15,16,17,18]. In the SCoP formalism each concept is associated with well defined sets of states, contexts and properties. Concepts change continuously under the influence of a context and this change is described by a change of the state of the concept. For each exemplar of a concept, the typicality varies with respect to the context that influences it. Analogously, for each property, the applicability varies with respect to the context. This implies the presence of both a *contextual typicality* and an *applicability effect*. The Pet-Fish problem is solved in the SCoP formalism because in different combinations the concepts are in different states. In particular, in the combination *Pet-Fish* the concept *Pet* is in a state under the context *The Pet is a Fish*. The state of *Pet* under the context *The Pet is a Fish* has different typicalities, which explains the Guppy effect. On the basis of the SCoP formalism, a mathematical model using the formalism of quantum mechanics in Hilbert space has been worked out which allows one to reproduce the experimental results obtained by Hampton on conjunctions and disjunctions of concepts. This formulation identifies the presence of typically quantum effects in the mechanism of combination of concepts, e.g., contextual influence, superposition, interference, emergence, etc. [19,20,21,22,23,24,25].

In this paper we show that another relevant effect which is usually considered as characteristic of quantum mechanical entities, that is, *entanglement*, is present whenever two or more concepts combine. The presence of entanglement is explicitly revealed by considering two concepts, i.e. *Animal* and *Acts*, and their combination *The Animal Acts*, together with some exemplars *Horse*, *Bear*, *Tiger*, *Cat* (for *Animal*) and *Growls*, *Whinnies*, *Snorts*, *Meows* (for *Acts*), and constructing some Bell’s inequalities in the version derived by Clauser, Horne, Shimony and Holt [26] (Sec. 2). We then test these Bell’s inequalities in a real experiment with 81 test subjects and analyze the obtained data (Sec. 3). The experiment shows a significant violation of Bell’s inequalities, hence it proves the entanglement between the concepts *Animal* and *Acts* when they form the sentence *The Animal Acts* (by the term *entanglement* we actually mean the presence of nonclassical correlations...