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Bohr complementarity in memory retrieval

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HIGHLIGHTS

- We use quantum techniques to model overdistribution in the human episodic memory.
- The previously built Quantum Episodic Memory model has a classical equivalent.
- We use Bohr complementarity to build a truly non-classical alternative (CMTmodel).
- Bohr complementarity is the one distinguishing feature of the quantum formalism.
- The data fit with the CMT is comparable with that of the QEM model.

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ABSTRACT

We comment on the use of the mathematical formalism of Quantum Mechanics in the analysis of the documented subadditivity phenomenon in human episodic memory. This approach was first proposed by Brainerd et al. in Brainerd et al. (2013). The subadditivity of probability in focus arises as a violation of the disjunction rule of Boolean algebra. This phenomenon is viewed as a consequence of the co-existence of two types of memory traces: verbatim and gist. Instead of assuming that verbatim and gist trace can combine into a coherent memory state of superposition as is done in the QEM model, we propose to model gist and verbatim traces as Bohr complementary properties of memory. In mathematical terms, we represent the two types of memory as alternative bases of one and the same Hilbert Space. We argue that, in contrast with the QEM model, our model appeals to the one essential distinction between classical and quantum models of reality namely the existence of incompatible but complementary properties of a system. This feature is also at the heart of the quantum cognition approach to mental phenomena. We sketch an experiment that could separate the two models. We next test our model with data from the same word list experiment as the one used by Brainerd et al. While our model entails significantly less degrees of freedom it yields a good fit to the experimental data.

1. Introduction

In this article we will extend the work done in Brainerd, Wang, and Reyna (2013) in using the quantum formalism to explain phenomena in human memory. In Brainerd et al. (2013), a memory analogue to the superposition principle of quantum mechanics is proposed and formally tested. The phenomenon that is studied concerns a two step experiment dealing with human episodic memory, where autobiographical memories are stored. In the first step participants memorize various word lists. In the second step participants are asked to accept or decline statements about these memorized word lists. These can be specific statements, asking the agent if they remember a word being part of a specific list or be more general statements, regarding the presence of a word on any of the remembered lists. Participants are shown to exhibit episodic subadditivity, a violation of the classical disjunction rule, which is attributed to the episodic memory consisting of two distinct memory types: verbatim memory and gist memory. We will discuss these two memory types more extensively in Section 2. The authors of Brainerd et al. (2013) view this experiment as a memory analogue to the classic double slit experiment in Physics. We will summarize and discuss this approach in section three and use it as an example to introduce the quantum formalism.

In Section 4 we propose an alternative view on subadditivity, where we view different types of human episodic memory as complementary properties of human memory. This idea was

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first proposed in Lambert-Mogiliansky (2014) and chapter 6 of Busemeyer and Bruza (2012) and was used as an example of the importance of non-orthogonal vectors as the distinction between quantum and classical models presented in Denolf (2015). Here we will flesh out this view in the form of a new model, called the Complementary Memory Types (CMT) model. We will fit this model to the data of an experiment discussed in Section 2. In our view, this CMT model elegantly models the overdistribution. We also claim that the CMT model is easily adjustable to be applied to other datasets, which might express different forms of additivity in their disjunction rule. We briefly suggest an extension of the previously discussed experiment, where we include the possibility of measuring order effects. These order effects are viewed as an expression of the non-classical nature of human memory and are naturally modeled within the CMT model.

2. The source memory experiment and overdistribution

Experiments and literature concerning human episodic memory are classically divided into two types, item memory and source memory. The former deals with the ability to remember previously acquired information, e.g., if a word was previously seen, the latter also deals with contextual information, e.g., where a word was previously seen. In these episodic memory experiments participants are asked to memorize different sets of words and recollect these afterward. Doing so, two types of memory distortions are exhibited, false memories and overdistribution.

To define these two memory distortions, we will expand on an example by Brainerd et al. concerning item memory. Suppose participants memorized a list of target words containing, amongst others, the words *Pepsi, 7up* and *Sprite* and are presented the test word *Coke*. They are then asked to categorize the given test word as a target word, where a target word denotes a word that was studied, a related distractor or an unrelated distractor. Since *Coke* was not on the list of target words, but shares semantic features with target words, it should be categorized as a related distractor. When a participant wrongly remembers *Coke* as a target word but not as a related distractor, we denote this distortion as false memories.

In addition to false memory, it can occur that participants remember *Coke* as both a target word and a related distractor. Here, memory retrieval is distorted by past experience, which are in this case, other memorized words. This form of memory distortion is denoted as overdistribution.

These two forms of memory errors are fundamentally different since the total error can be divided in these two types of mistakes, as shown in Brainerd, Reyna, and Aydin (2010).

Since participants know that a word cannot be both a target word and a related distractor, overdistribution cannot be directly observed. We have to rely on the classic disjunction rule to measure the amount of overdistribution participants exhibit. Therefore, after presenting the participant a test word, the participant is also presented with one of three possible recognition statements. The participant is then asked to either accept or reject the statement they received. The three possible statements are: (a) the test word is a target word, (b) the test word is a related distractor and (c) the test word is a target word or related distractor. This way, the following quantities can be defined and measured for each test word: $P_w(T)$ as the proportion of participants remembering the test word w as a target word, $P_w(R)$ as the proportion of participants remembering the test word w as a related distractor and $P_w(T \cup R)$ as the proportion of participants remembering the test word w as a target word or a related distractor, without specifying which of the two. This way the probability that a participant would remember the test word w as both a target word and a related distractor can be defined as:

$$P_w(T \cap R) = P_w(T) + P_w(R) - P_w(T \cup R). \quad (1)$$

With this definition, the overdistribution phenomenon can be mathematically expressed as a violation of the disjunction rule, since participants with perfect memory would exhibit $P_w(T) + P_w(R) - P_w(T \cup R) = 0$ for each test word w. Viewing overdistribution as a disjunction fallacy, Brainerd and Reyna showed in Brainerd and Reyna (2008) and Brainerd et al. (2010) that overdistribution can be seen as a consequence of dual-trace distinctions from Fuzzy-Trace Theory developed in Reyna and Brainerd (1995). This theory postulates that human episodic memories are stored in two different types of memory. The first memory type is referred to as verbatim memory, encompassing the presentation and phonology of a memorized word. The second memory type is referred to as gist memory, encompassing the semantic meaning of a memorized word. Target words and related distractors can share the same gist trace (e.g. *coke* and *sprite* are both soft drinks). Since both verbatim and gist traces are used in deciding if a word is a target word, these gist traces account for words being viewed as both target words and related distractors, resulting in episodic overdistribution. For a more complete overview of episodic distribution, including the implementation of other theories than the Fuzzy-Trace theory, see Kellen, Singmann, and Klauer (2014).

In this paper we will focus on an experiment reported in Brainerd and Reyna (2008) and extended in Brainerd, Reyna, Holliday, and Nakamura (2012), concerning the overdistribution of the source memory. As this experiment concerned source memory, participants were tasked not only with remembering if a word was studied, but also with remembering where (e.g. which list) the word was first presented on.

Seventy participants were asked to memorize three distinct word lists, containing different words. Each of these lists contain 36 words (2-word starting and ending buffers, 32 target words), a different background color and a different font in which the words were printed, to ensure that each list was distinctive. Each of these participants was then presented a list of 192 test items. A test item comprises a combination of a test word and a recognition statement. These test words originated from 1 out of 4 different sources: one of the three memorized lists or a non-memorized list of unrelated distractors. The four possible recognition statements were, (a) the test word is on list 1, (b) the test word is on list 2, (c) the test word is on list 3 or (d) the test word is on one of the lists. Each of these test words was presented with 1 out of these 4 recognition statements, such that, across all participants, each test word had probability.25 of being presented with each of the recognition statements. The experiment also varied the test words between word concreteness (abstract/concrete) and word frequency (high/low frequency use in common language), resulting in 4 different word types. These manipulations were done for theoretical reasons, since it was predicted that abstract and low frequency words create weaker verbatim traces than concrete high frequency words, resulting in a clearer overdistribution for abstract low frequency words, see Brainerd and Reyna (2005) and Brainerd et al. (2012) for more details. This gives us 16 experimental conditions (4 word types × 4 possible sources), each with four possible measurements (the four recognition statements).

For the participant responses, the following proportions were calculated, for each type of test word: p_1, p_2, p_3 which were the proportions of accepted statements of resp. type (a), type (b) and type (c) and p_{123} which was the proportion of accepted statements of type (d). These proportions are seen as the probability of the event that an agent thinks that the test word is on a certain list for proportion p_i (similar to $P(T)$ and $P(R)$ from the item version of overdistribution) or the probability of the event that the agent thinks that the test word is on any of the lists, for p_{123} (similar to