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Episodic memory does not add up: Verbatim–gist superposition predicts violations of the additive law of probability

C.J. Brainerd [a,*], Zheng Wang [b], Valerie F. Reyna [a], K. Nakamura [a]

[a] Department of Human Development, Cornell University, United States
[b] School of Communication and Center for Cognitive and Brain Sciences, The Ohio State University, United States

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ABSTRACT

Fuzzy-trace theory's assumptions about memory representation are cognitive examples of the familiar superposition property of physical quantum systems. When those assumptions are implemented in a formal quantum model (QEMc), they predict that episodic memory will violate the additive law of probability: If memory is tested for a partition of an item's possible episodic states, the individual probabilities of remembering the item as belonging to each state must sum to more than 1. We detected this phenomenon using two standard designs, item false memory and source false memory. The quantum implementation of fuzzy-trace theory also predicts that violations of the additive law will vary in strength as a function of reliance on gist memory. That prediction, too, was confirmed via a series of manipulations (e.g., semantic relatedness, testing delay) that are thought to increase gist reliance. Surprisingly, an analysis of the underlying structure of violations of the additive law revealed that as a general rule, increases in remembering correct episodic states do not produce commensurate reductions in remembering incorrect states.

Introduction

Historically, an enduring feature of judgment-and-decision-making research has been the availability of pre-existing normative models for human reasoning. Specifically, the axioms of formal logic and classical probability theory have long been implemented in such research as prescriptive benchmarks against which reasoning is gauged. As decades of experimentation in the heuristics and biases tradition have shown, reasoning routinely violates the most basic axioms. Examples of decision making tasks that exhibit such violations include various forms of preference, such as intertemporal choice (e.g., Killeen, 2009; Scholten & Read, 2010) and choices among risky prospects (e.g., Tversky & Fox, 1995). Examples of judgment tasks that exhibit such violations include probability judgment (e.g., Rottenstreich & Tversky, 1997; Tversky & Kahneman, 1983) and frequency judgment (e.g., Fiedler, Unkelbach, & Freytag, 2009), with the literature on probability judgment being quite extensive (see Busemeyer, Pothos, Franco, & Trueblood, 2011; Pothos & Busemeyer, 2013). Owing to the availability of a normative model, such violations have deep psychological significance, inasmuch as they demonstrate that reasoning is neither logical nor rational, in a formal sense.

Memory research, in contrast, has not drawn upon formal logic or classical probability theory as a normative framework. For that reason, experiments that assess whether memory conforms to axiomatic criteria of logic and rationality have been rare (for an exception, see Hicks, Marsh, & Cook, 2005). We have argued, however, that experiments of that ilk can answer fundamental theoretical and empirical questions about memory (Brainerd, Holliday, Nakamura, & Reyna, 2014; Brainerd, Reyna, &

* Corresponding author at: G331 MVR Hall, Cornell University, Ithaca, NY 14853, United States.
E-mail address: cb299@cornell.edu (C.J. Brainerd).

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Aydin, 2010). On the theoretical side, they can deliver tests of competing principles of representation and retrieval, principles that differ in their predictions as to whether memory data will align with particular axioms. On the empirical side, whether our memories are distorted in specific ways can be shown to turn on whether memory follows certain axioms.

These issues are elaborated in the first section, below. There, we consider one of the central axioms of classical probability, the additive law, which specifies that the probabilities of the components of any partition of a set of possible events must sum to 1. We note some known violations of this law in human judgment and discuss what the general significance of parallel violations in the domain of episodic memory would be. As theoretical motivation for the latter, we show that nonadditivity of episodic memories is predicted by a quantum probability model that implements a memory representation principle (superposition of verbatim and gist traces) and a retrieval principle (description dependency). The model has been used to explain false memory phenomena and can identify conditions that should influence observed levels of nonadditivity. Experiments are then reported that evaluated those predictions using two types of designs, item false memory and source false memory.

Superposition and additive probability

Measuring violations of the additive law

Suppose that some set S of events has been partitioned into i subsets; that is, the subsets $S_1, S_2, \ldots, S_i$ are mutually exclusive and exhaustive. Suppose that the sampling probabilities of these subsets are known to be $p_1, p_2, \ldots, p_i$; that is, the probability of selecting an event from S_1 on a random draw is p_1, the probability of selecting an event from S_2 is p_2, and so on. Although individual sampling probabilities are free to vary over the unit interval, the additive law constrains the possible values that can be observed for the components of the partition such that $p_1 + p_2 + \cdots + p_i = 1$ must be satisfied. For instance, imagine that S is an urn containing a large quantity of marbles, whose partition is S_1 = white marbles, S_2 = red marbles, and S_3 = blue marbles. If the sampling probabilities of the white and red subsets are known to be .35 and .45, respectively, then by the additive law, the sampling probability of the blue subset must be .20.

However, when subjects make probability judgments about partitions of sets of real-life events, those judgments fail to obey the additive law. Instead, the judged probabilities of the subsets are normally subadditive ($p_1 + p_2 + \cdots + p_i \geqslant 1$; e.g., Redelmeier, Koehler, Liberman, & Tversky, 1995), although they are occasionally superadditive ($p_1 + p_2 + \cdots + p_i \leqslant 1$; e.g., Macchi, Osherson, & Krantz, 1999). In an early illustration of subadditivity, Redelmeier et al. presented the case history of a hospitalized patient to physicians and asked different groups of them to estimate the probability of one of the following outcomes: (a) the patient dies during the current hospitalization; (b) the patient is discharged alive, but dies within 1 year; (c) the patient is discharged alive and lives more than 1 but less than 10 years; or (d) the patient is discharged alive and lives 10 years or more. Note that these four outcomes are mutually exclusive and exhaustive with respect to patient mortality. Thus, the additive law applies—so that the actual objective probabilities of these outcomes, based on mortality statistics for patients with this history, must sum to one. However, Redelmeier et al. found that physicians' probability estimates summed to much more than one, 1.64 to be precise. This pattern is not restricted to high-stakes risky events—such as death, gambling, stock market investment, and so forth—because judgments about partitions of more prosaic events are also subadditive.

The psychological significance of subadditive probability judgments is both simple and fundamental: As a general rule, people perceive the probabilities of real-life events to be higher than their objective probabilities; they believe that events are more likely to happen than they are. An important consequence is that this can lead to a number of distortions in life-altering decisions. For instance, people may fail to take appropriate risks because they perceive the chances of a negative outcome to be higher than they are, or conversely, they may take inappropriate risks because they perceive the chances of a positive outcome to be higher than they are.

Turning to memory, our concern in this article lies with whether episodic memory also violates the additive law of probability and with the psychological significance of such an outcome. To illustrate this possibility, consider two familiar paradigms that figure in hundreds of prior experiments, false memory for items and false memory for sources (e.g., Hicks & Starns, 2006; Tse & Neely, 2004). In a typical item false memory experiment, subjects encode some target items (e.g., a word list), and then test cues of three types are administered: old targets (O; e.g., *sofa*; true memory measures), new-similar items (NS; e.g., *couch*; false memory measures), and new-dissimilar items (ND; e.g., *ocean*; controls for guessing and response bias). Subjects make a single episodic judgment about each of these types of cues: Is it old (O?)? In a typical source false memory experiment, on the other hand, subjects encode target items that are presented in one of two distinct contexts (e.g., List 1 or List 2), and then test cues of three types are administered—namely, targets from the first context (L1), targets from the second context (L2), and new-dissimilar items (ND). Subjects make one or both of two episodic judgments about each type of cue. First, they decide whether it is an old target (usually called an item judgment), and if the response is "old," they decide which context it appeared in (usually called a source judgment). The true memory index is the rate at which correct contexts are selected for L1 and L2 cues that are recognized as old, the false memory index is the rate at which incorrect contexts are selected for the same cues. Both can be corrected for bias using the rate at which the two contexts are selected for ND cues that are recognized as old.

Consider some simple variants of the memory tests in these two paradigms, variants that are capable of detecting violations of additive probability but that, to the best of our knowledge, have not been studied. In the item design,