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A neuroeconomic theory of memory retrieval☆

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ABSTRACT

We propose a theory of "optimal memory management" that unveils *causal* relationships between memory systems and the characteristics of the information retrieved. Our model shows that if the declarative memory is more accurate but also more costly than the procedural memory, then it is optimal to retrieve exceptional experiences with the former and average experiences with the latter. The theory provides other testable predictions: (i) decisions are closer to original experiences when the declarative memory is invoked, and (ii) the declarative memory is more likely to be invoked when the importance of recalling information accurately increases.

1. Introduction

Bounded memory is arguably one of the most important limitations in humans, an aspect that has received considerable attention from researchers. Formal mathematical models of limited memory can be found in fields as diverse as statistics (Cover and Hellman, 1970), artificial intelligence (Narendra and Thathachar, 1989), psychology (Anderson and Milson, 1989) and computation theory (Feder, 1991), just to name a few. There is also a literature in economics (see e.g., Piccione and Rubinstein, 1997; Mullainathan, 1998; Benabou and Tirole, 2002; Bernheim and Thomadsen, 2005; Frey, 2005; Kocer, 2012; Monte, 2014), although it is fair to say that it has received less attention than other aspects of bounded rationality.

Bounded memory is multifaceted. In order to concentrate on some aspects, all the formal models we know have overlooked one important finding in neuroscience: memories can be encoded by different systems and each system has some special properties. The goal of this paper is to build the (to our knowledge) first model of bounded memory in economics or any other science where experiences are *optimally encoded by different systems* depending on their characteristics. More precisely, our model unveils causal relationships between the memory system employed and the type of the information retrieved. To better understand the building blocks of the theory, we first present a brief overview of the existing neurophysiological evidence on memory (these findings are well-known in neuroscience but possibly less familiar for economists).

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Table 1
Taxonomy of declarative and procedural memory systems.

Memory system	Declarative	Procedural
Characteristics	Fast and conscious Flexible and temporary Effortful Precise	Slow and unconscious Rigid and durable Effortless Vague
Uses	Facts and events Unique features	Skills and habits Common features
Brain areas	Medial temporal lobe (hippocampus)	Basal ganglia (striatum)

Memory refers both to the conscious recollection of facts and historic events and also to the unconscious and automatic retrieval of information necessary to perform some habitual actions. However, the processes involved in storing, learning and retrieving these different types of information differ largely. The literature in neuroscience reports findings indicating the existence of different memory systems in the brain (see e.g. Poldrack and Foerbe, 2008 for a review). An accurate classification of memory systems has been obtained by correlating the types of information memorized with the underlying biological mechanisms involved in the memory processes (see e.g. Squire, 2004 for a review). Memory can be broadly classified into two main classes.

Declarative memory refers to the capacity to recollect information in a conscious way. It is based on the ability to detect and encode what is unique about an event (Ullman, 2004). Learning occurs fast (with few exposures) and the learned material is consciously known and easily verbalized. Learning is effortful and engages working memory resources (Craik et al., 1996). The knowledge acquired with the declarative memory system is flexible and can be used in a variety of contexts, but it also tends to erode. Declarative memory engages the hippocampus and surrounding structures. These structures are involved in the formation of memories but also in the ability to retain and recall them (Gabrieli and Kao, 2007). The lateral Prefrontal cortex (lPFC) is engaged in the memory process of contextual details of an experience. The left dlPFC is activated when memories are formed while the right dlPFC is activated when memories are retrieved (Kapur et al., 1997) and these structures are also more active during the encoding of unexpected facts (Fletcher et al., 2001). The amygdala is involved in the encoding and retrieval of emotionally charged memories (Adolphs et al., 1997).

Non-declarative memory refers both to learned skills and habits and perceptual learning or conditioning. Non-declarative memory detects what is common to several situations. Learning is gradual and slow, the decision-maker learns through trial-and-error, and requires feedback. The learned material is also unconscious and difficult to verbalize. Learning requires effortless attention. Learned knowledge is rigid, used in specific contexts, and durable. It engages a variety of structures depending on the finer subclassification of memories. Closest to the specific interest in this article, the part of the non-declarative memory that refers to skills and habits is placed under the umbrella of *procedural memory*. It engages structures like the striatum (Kreitzer, 2009). Also, conditioning is linked to the amygdala and the cerebellum (see Squire, 2004 for a detailed classification).

This classification suggests a tight connection between memory system and type of information. We can think of the different systems as tools to solve different problems. For instance, the declarative system helps find a solution to problems like “in which spot did I park today?” while the procedural system solves best problems like “when I come to school where do I usually park?”. A summary of the major differences between the declarative and procedural memory systems is presented in Table 1.

The relationship between memory systems and types of memories is still imperfectly understood. Yet, existing studies provide interesting findings. Firstly, memory systems are *substitutable*. Bayley et al. (2005) show that subjects with impaired procedural memory improve over time their performance in the weather prediction task by repeatedly exercising their declarative memory, even though this is a paradigmatic example where procedural memory works best. Also, what is learned depends crucially on which system is engaged (Dagher et al., 2001). Overall, systems are tailored to certain types of memories and act as ‘imperfect substitutes’ (Poldrack and Packard, 2003). Secondly, systems are selected depending on task demands. In particular, there is evidence that neurobiological mechanisms are in place to make sure behavior is *optimized*, that is, it employs the memory system most suitable to the experience (Poldrack et al., 2001; Foerbe et al., 2006).

Substitutability and optimization are key properties in decision making. The evidence reviewed here suggests that the resort to a given memory system is an endogenous decision: (i) several systems can be employed to retrieve memories, (ii) different systems have different properties which make them suitable for the encoding and retrieval of different experiences, and (iii) the choice of one system over another will be the result of an optimization process. Starting from these premises, the purpose of this study is to build a theory of optimal memory management, that is, one that predicts the choice between competing memory systems as a function of the experience to memorize.

Combining the findings reported above, we build a simple model in which a decision-maker (hereafter DM) learns a piece of information relevant for future choices. DM has imperfect memory, so the exact information received may not be correctly recalled at the time of the future decision. The information is stored and retrieved using either the declarative memory system or the procedural memory system. We work under the hypothesis that these systems differ in their *accuracy* and *cost*. Accuracy corresponds to the degree to which DM can recover the precise experience, while cost refers to the