23 Human Memory: A Proposed System and Its Control Processes

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It is hard to imagine how understanding memory could not be important for the field and for humanity generally: Memory is what we are, and what defines us as individuals. Despite an ever-increasing reliance on external aids to memory (e.g., looking up forgotten material on the web), we rely on our memory for almost all decisions and interactions in our daily lives. Everyone is particularly aware of the tragedy of memory failure due to diseases such as Alzheimer's. With memory so fundamental, with such a broad scope, and with such great complexity, it is essential that its components be delineated carefully, and it helps enormously if such delineation is made precise with the use of formal theorizing and especially quantitative modeling.

Such delineation was what we put forth in our 1968 chapter, and is the primary reason we regard it as our most important contribution, despite its age and the fact that one of us was a graduate student at the time of its publication. This chapter has served as a template and inspiration for about fifty years of research since.

Our theory has been called the "modal model" of memory and it remains so: Almost all of its insights into memory can be found in contemporary publications. It represented a turning point in the evolution of memory theory because it took many of the concepts proposed since the field of psychology began, as exemplified by William James in his 1890 book *Principles of Psychology*, and formalized them in a comprehensive framework that was backed up by empirical research (much of it original) and quantitative modeling. The theory has undergone many elaborations over the years, in our hands and those of students and colleagues, and has served as a starting point for the development of alternative models, though most of them instantiated the same basic concepts in alternative verbal and computational machinery.

What are these core concepts? We divided the concepts into structural components of the memory system and processes that controlled memory storage and retrieval. It was primarily the second of these that led us to the theory's formulation and its general acceptance: It seemed obvious to us that the control of memorial processes such as storage, retrieval, and decision was responsible for much of the observed phenomena of memory, and such control processes were in need of exposition, delineation, and formal modeling. These control processes acted upon and resided in the three structural components: the short-lived sensory memories, the short-term store(s), and the relatively permanent long-term memory. We used the term "working memory" to describe the control processes that primarily reside in the short-term component of the system; this theme persists today. The various memories were construed to consist of separate traces, a common theme that is also prevalent in categorization research in the form of exemplar theories.

Both the basic structures and the concepts of control processes have remained core concepts as the field has evolved, as empirical studies have grown in huge numbers, as models have proliferated, and as neural measurements have become ever more important and tied to behavioral data. In the 1968 model, we focused on rehearsal as the most apparent and easily modeled of the control processes, but made it clear that this was just one example and that there were a host of other control processes that were in use in working memory, particularly including those used in memory retrieval via memory search.

The chapter was replete with new empirical studies and mathematical modeling of the results. Now it is almost fifty years since its appearance and few scientists have read it or are aware of its contents, other than through a few core ideas that have appeared in secondary and tertiary sources such as textbooks. Yet the chapter and the theory in it would never have achieved the reputation it did without the scientific validation conferred by those studies and their predictions by the models.

The theory presented has become the basis for further research and modeling ever since. In various publications in the 1970s we elaborated on the role and uses of short-term store, working memory, and control processes. Raaijmakers and Shiffrin elaborated the theory by focusing on the role of various kinds of context in storage and retrieval. They showed how a vast array of recall results, both successes and failures (memory loss), could be explained in a simple and coherent fashion, within the framework established by the original theory. This focus on context was a key to further development and has appeared in different guises, but with similar concepts, in recent years (e.g., in modeling by Mike Kahana and his students and colleagues). In 1984, Gillund and Shiffrin extended the model to include recognition; that approach has become the standard way to model recognition decisions based on "familiarity." What is familiarity? A test item and its context are used to probe memory. Traces are activated due to similarity to the memory probe (these are the same activations that are sampled in recall tasks). The activated trace strengths are in effect summed to produce a measure of familiarity, and strong enough familiarity is used to produce a positive recognition decision. In 1997 and 1998, Steyvers and Shiffrin placed the whole system on a more firm probabilistic footing. Traces were implemented as collections of features. Bayesian modeling was used to define trace activation strengths in terms of the probability that a given trace could have been produced by the memory probe. In 2001 Huber and Shiffrin showed how short-term priming operates: A prime (or primes) presented prior to a test word adds features to short-term memory; these features join with features of the test word, and both are used to probe memory. The theory explained how both positive and negative priming comes about based on the way the evidence returned from memory is evaluated. In 2013, Angela Nelson and Shiffrin extended the model of storage in and retrieval from long-term store by showing how event traces could accumulate to form knowledge, and how knowledge is used to encode events. Among other things, this recent research elaborated on the point we made in 1968 that storage produces a long-term memory trace, that further storage adds to and changes that trace, and that later retrievals of a trace changes the trace yet again. This theme presaged much recent research on malleability of memory and development of false memories (e.g., the research of Elizabeth Loftus).

One reason the theory has withstood the test of time is the way its components match "common sense" and are easy to understand. As many theorists have noted, all models and theories are wrong, but are nonetheless useful in various ways (the statistician Box is well known for this observation). Theories lead to future experimentation, alternative theorizing, and critical tests. Perhaps most importantly, they lead to increases in understanding and a concomitant increase in ability to communicate that understanding to others. The importance of our chapter and our theory was certainly enhanced by the way it incorporated many prior concepts and put them together in an easy to understand conceptual framework. That chapter had no lack of technical rigor, presenting new experimental data analyzed in sophisticated ways to validate formal models that were formulated to fit the conceptual framework. Yet the chapter would not have achieved its renown had it not been accessible and understandable.

This characterization helps explain the origin of the idea behind the research. It took concepts prevalent and common in the field since its inception, organized and formalized them, and applied them to a wide range of old and new findings. Both of us began working on these ideas simultaneously, and initially independently. In his first year of graduate study Shiffrin started working with Gordon Bower, developing a model of free recall based on short- and long-term memory, with a strong emphasis on control processes. At the same time Atkinson was working across the Stanford campus on development of short-term memory models with similar themes. When Gordon left to take a sabbatical in England, he sent Shiffrin to work with Atkinson. There was a seamless and natural convergence of our ideas and approach, leading to a number of publications in addition to the 1968 chapter, but the chapter represented a synthesis of all the ideas together in a broad and comprehensive framework.

The successes of the Atkinson and Shiffrin framework, its continued development over the years since, the incorporation of similar concepts in neural modeling, and all the experimentation that has bolstered this approach have hardly exhausted our understanding of memory. We have uncovered only the tip of the iceberg, and we expect many new insights to emerge in the future. Only time will tell if the Atkinson and Shiffrin general theoretical framework will remain the best functional approach to understanding the enormously complex system we describe with the term "memory."

REFERENCES

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence and J. T. Spence (eds.), *The psychology of learning and motivation: Advances in research and theory* (vol. 2, pp. 89–195). New York: Academic Press.

Nelson, A. B., & Shiffrin, R. M. (2013). The co-evolution of knowledge and event memory. *Psychological Review, 120*(2): 356–394.

Raaijmakers, J. G. W., & Shiffrin, R. M. (1980). SAM: A theory of probabilistic search of associative memory. In G. H. Bower (ed.), *The psychology of learning and motivation* (vol. 14, pp. 207–262). New York: Academic Press.