The structure of long-term memory

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A Connectivity Model of Semantic Processing

Wolfgang Klimesch
University of Salzburg


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Preface

The purpose of this book is to describe a new theory about long-term memory, the connectivity model for semantic processing (chaps. 8 and 9). In addressing the question of the way that complex semantic codes are represented, searched, and retrieved, the model tries to answer the following key problem. Which are the representational assumptions that allow us to predict that complex knowledge stored in long-term memory does not slow down activation and search processes in a systematic way? When the principles of the connectivity model were first published in 1987, my primary concern was the experimental evaluation of the model within the domain of semantic memory. During a research visit at the University of California in Davis, I worked on this topic together with Professor Neal E. A. Kroll. In the following years he has carried out a series of well-designed experiments in order to test several crucial assumptions and predictions of the model (see the brief summary of this work in section 9.7). I am grateful for his contributions, suggestions, and the many enlightening discussions we had together.

The basic logic and procedure which led to the foundations of the connectivity model is characterized by the attempt to define representational assumptions as explicitly as possible and to evaluate their plausibility or empirical validity whenever feasible (chaps. 1–5). Thus, it was a logical consequence to focus also on the implementation of the model. I wish to thank F.G. Winkler who wrote the simulation program CONN1. His work has led to important new insights which are discussed in chap. 10.

When pursuing the representational problem, it gradually became clear to me that the issue of how information is encoded in the brain must also be

considered. The more I focused on the elaboration of a connecting bridge between theoretical and neurophysiologically based representational assumptions (chap. 11), the more I became convinced that the future of cognitive psychology lies in the further development of cognitive neuroscience. I am grateful to Professor Jaak Panksepp (from Bowling Green State University, Ohio, where I stayed during a research visit in 1991) for his encouragement to follow-up this approach and for the valuable suggestions he made when reading parts of the manuscript. Chapters 10 and 11 are additions to the English edition which were not included in the original German publication.

Last but not least, I wish to thank Patrick O'Mahony who has translated the German edition into English. His skills and collaborative mind have been invaluable in the prompt completion of the English manuscript.

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Introduction

An important but controversial issue in memory research concerns the way in which the complexity of semantic structures influences processing time and memory performance. Traditional memory theories such as HAM, ACT, or ACT* assume that memory load increases and processing time slows down as more semantic components are processed. This assumption amounts to what is known as the paradox of retrieval interference: The more information is stored in memory, the slower it works. Chapters 6 and 7 give an extensive review of this issue. Chapter 8 includes the mathematical basis for a new, nonconnectionist memory model, the connectivity model, which refutes the paradox of retrieval interference. The basic assumption here is that—in contrast to conventional computers—the speed of search processes in human memory increases as the complexity of interconnected knowledge increases. This prediction, which contradicts all presently existing memory models, explains a variety of different memory phenomena that are discussed in chap. 9. A simulation program is presented in chap. 10. This program allows for a better understanding of the complex predictions of the connectivity model. Neurophysiological evidence is also in close agreement with the predictions of the connectivity model. This issue is addressed in chap. 11, where it is shown that the well-known properties of postsynaptic signal transmission lead to the conclusion that converging neural activity speeds up processing time, and that the stronger a neural signal is, the faster it can be transmitted. Besides other evidence, this fact is also confirmed through reaction time experiments, which show that reaction times decrease as stimulus intensity increases. Finally, chap. 12 gives

a brief summary and addresses how the connectivity model differs from connectionist approaches.

One of the fundamental principles on which the connectivity model is based is the assumption that any comprehensive memory theory must explicitly define the format of a code. If explicit representational assumptions are avoided, misleading and contradictory theories about memory or cognitive processes emerge. After a brief historical review about the representational problem in chap. 1, this argument is developed and explained in chaps. 2, 3, and 4. Here, theories and experiments about forgetting show why misleading representational assumptions are responsible for the failure of traditional memory theories. In chap. 5, those theories that define the format of a code explicitly are shown to assume a hierarchical structure. The chapters that follow demonstrate that the assumption of a hierarchical coding format is at the core of retrieval interference. It is argued that only the suggested connectivity model is capable of overcoming this paradox.

To my wife Therese and my daughter Christine

Contents

1 The Representational Problem: A Historical Perspective

Those who concern themselves with the history of experimental psychology will no doubt conclude that the topics this discipline has dealt with in the last 100 years have not changed much (cf. with this the synoptic works of Boring, 1950; Flugel, n. d.; Lück, Miller, & Rechtien, 1984). In cognitive psychology, for example, there are many experimental paradigms and theoretical concepts that have been dealt with in similar fashion, but under different titles, over many historical periods. Consider the cognitive-psychological concept of a limited capacity of short-term memory (STM). James McKeen Cattell had already carried out studies on the attention span at the Leipzig Institute of Wilhelm Wundt and observed that in a simultaneous, tachistoscopic display of several stimuli only 4 to 6 units—be they lines, letters, or words—could be understood and remembered (Flugel, n. d., p. 157). The terms *capacity of STM* and *attention span* (cf. Ebbinghaus, 1885) refer to one and the same empirical phenomenon. Where they differ is in their historical context and in the ways in which they happen to be embedded in overlapping theoretical relations (e.g., Bahrick, 1985). There is a long list of historical concepts and empirical phenomena that have been redeployed. Here, however, we content ourselves with a few references and, in doing so, recall the historical relations between the following concepts:

- the similarity between Donder's "subtractive procedure" (Donders, 1868; cf. Massaro, 1975, p. 44; Sanders, 1971, p. 17) and the experimental paradigms in cognitive psychology (Posner, 1978; Posner, Boies, Eichelman, & Taylor, 1969);
- the importance that reaction time paradigms have assumed in

experimental psychology ever since Wilhelm Wundt conducted his extensive experiments at the Leipzig Institute;

- the continued importance of verbal association paradigms, which have been an important feature in memory psychology since Ebbinghaus (1885; e.g., McGeoch, 1942; Slamecka, 1985a, 1985b);
- the experimental documentation concerning the superiority of visual memory over verbal memory, which has been known since Kirkpatrick (1894) and Calkins (1898), and not just since Shepard (1967) or Paivio (1971);
- and, within the confines of cognitive psychology, the "rediscovered" findings—dating back to Cattell (1886)—that words can be identified more quickly than images (Potter & Faulconer, 1975).

Seen in this light, it is not surprising that critical voices continually claim that little, if any, scientific progress is being made in our discipline. We attempt to show that this view is misleading because it ignores important recent developments. It can be seen from the comparison of the most important historical approaches that it is the specific preoccupation with the representational problem that is in fact the new contribution of cognitive psychology as it emerged in the Anglo-American sphere. Only the explicit consideration of the representational problem can build a foundation on which to arrive at a consistent interpretation of memory phenomena. Chapters 2, 3, and 4 consider this question in greater detail.

The name *cognitive psychology* has often led to misunderstandings about the actual concerns of this comparatively young field of research. A more precise and specific description would be "the psychology of information processing." Those critics who claim that the "cognitive trend" will soon turn into an "action trend" (Graumann, 1983, p. 68) or "emotional trend," are not taking into consideration the specific contribution made by cognitive psychology. Its task is to examine how information is encoded, represented, and processed. The type of information involved—whether "cognitive," "emotional," or "action relevant"—has no immediate impact on the study of the representational problem. Cognitive psychology is not the counterpart of an "emotional" or "action" psychology. Nevertheless, it emphasizes the cognitive content, because for methodical reasons emotional processes are much more difficult to examine empirically than cognitive processes.

The next section considers the fundamental concepts needed to explain and elucidate the representational problem. Subsequent sections are then devoted to the historical development of the representational problem. Based on these sections, we show that the consideration of the representational problem leads to new and important discoveries.

1.1 DEFINING THE REPRESENTATIONAL PROBLEM: CODE, CODING, AND THE CODING FORMAT

Which processes enable sensory information to be recognized, stored, and recalled? This is the main research topic in cognitive psychology, and characterizes what is generally understood by the encoding or representational problem. *Encoding* or *coding* is the transformation of sensory information into a certain format of a memory representation, resulting in the formation of a memory code. The form, composition, and structure of the internal representation, on the other hand, is known as the coding format. It is precisely this interest in how information is "represented" (i.e., how information is stored in memory) that has led to the preeminent position of memory research in the field of cognitive psychology. Because coding is considered a process of transformation—reflecting different stages of information processes, such as perception, recognition, and selective attention—it becomes clear that memory can be described only if empirically validated assumptions regarding the entire information-processing system are made. This idea of a close interdependence between the properties of the encoding format and the structure of the entire information-processing system is discussed in chap. 4.

The description of the elementary properties of codes is crucial here. Consequently, memory research is the main focus of the following historical survey.

1.2 MEMORY RESEARCH: A HISTORICAL PERSPECTIVE

It is worth noting that Ebbinghaus, as the founder of empirical memory research, had no interest in representational assumptions. Following his description of the "Mangelhaftigkeit des Wissens über das Gedächtnis" (The inadequate knowledge about memory), Ebbinghaus (1885) wrote:

> And because all our knowledge is so uncertain and imprecise, it has remained unfruitful for an understanding of a theory of memory, recall, and association processes. In our ideas on its physical basis, we use different metaphors such as stored images, imprinted ideas, and encarved traces etc., of which we only know that one thing is certain that they are not correct. (p. 7)

Ebbinghaus could hardly have expressed his rejection of the representational problem more clearly. Nevertheless, it would be wrong to assume that memory psychology could have managed without representational assumptions in its early stages. These were more implicit than explicit in nature and

were based on the fundamental conceptions of associationism, which was the predominant psychological trend in the second half of the 19th century. Ebbinghaus saw the goal of his work not as an attempt to empirically examine associationistic representational assumptions, but rather to substantiate the scientific claim of his experimental approach in psychology. The status of implicit and explicit representational assumptions within memory psychology is discussed in chaps. 2 and 3.

In order to evaluate the importance of Ebbinghaus' work, we must consider the historical factors that influenced it. Two factors need to be taken into consideration: On the one hand, there was the dismissive attitude toward psychology as an experimental science and, on the other hand, the limited prospect of ever arriving at an empirically validated theory of memory. Ebbinghaus, like other empirical psychologists of his day, was primarily concerned with showing that mental processes—like physical and biological processes—could also be examined and understood using scientific methods. His approach to the problem was therefore primarily one of method as opposed to content. It consisted of the classical scientific procedure of proving what effect the specific variation of one or more independent variables has on one or more dependent variables. The dependent variable was memory performance or the extent of forgetting. Among the most important independent variables were the number of repetitions and the retention interval (i.e., the time that elapses between presentation and test), as well as the nature and amount of material to be learned. Ebbinghaus arrived at a series of rules governing the examined variables, whereby the rule governing the length of the retention interval and memory performance, known as the "forgetting curve," is only one of the better-known examples.

From the perspective of the then-dominant school of thought, these results were a sweeping success. Ebbinghaus was now able to prove that the study of higher mental processes was also possible for a psychology using scientific methods. Thus, together with Wilhelm Wundt, Ebbinghaus made a significant contribution toward the founding of a scientifically and experimentally oriented psychology. It is interesting to note, however, that Wundt had a negative attitude toward the study of higher mental processes—as they represented memory performance—and seven years after first publishing *Philosophische Studien* (the journal founded by Wundt in 1890) Ebbinghaus published *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, which to a certain extent provided a forum for independent researchers outside of the Wundtian School (Boring, 1950; Flugel, n. d., p. 167).

Müller, Jost, and Pilzecker (Jost, 1897; Müller & Pilzecker, 1900) followed a procedure similar to Ebbinghaus, but even this was completely derived from associationism (e.g., Müller, 1917). The first 30 years of

empirical memory research are thus essentially characterized by two factors: on the one hand, by the methodical-scientific orientation that predominates, and, on the other hand, by simple associationistic conceptions of memory. As a result, one finds a wealth of important rules that up to now remain untouched in applied memory psychology. What was missing, however, were approaches to general, overlapping memory theories. Therefore, within the framework of classic memory psychology, it was not the investigation of representational assumptions that predominated, but in effect only the question of how associations develop between memory contents.

After this first classical period of memory research, the emphasis of scientific research shifted from Germany to the Anglo-American sphere. Even there the focus remained for a long time—up to the early 1960s—within the framework of associationism and behavioristic approaches. There were, however, a few important exceptions. For example, F. C. Bartlett, then a Cambridge psychologist, was among the first to introduce the concept of a mental "schema" into memory psychology. Bartlett (1932) assumed that sensory information is structured and stored alongside these mental schemas, which are themselves represented in memory. Schemas, which are derived by means of abstraction, represent the essential characteristics of a whole class of stimuli. The similarity to the Gestalt concept, but also to Rosch's (1975) "typicality concept" in the area of concept formation, should not be overlooked. According to Bartlett, the associationistic viewpoint of memory as a passive store was abandoned, and the active, structuring character of memory came to the fore. Bartlett assumed that schemas are of crucial importance for perception and thinking as well as memory. Thus it became clear that memory could not be studied and understood in isolation from other phenomena of the human mind.

Oldfield joined others in adopting Bartlett's schema concept, which Evans and his colleagues (Evans, 1967; Evans & Arnoult, 1967; Evans & Edmonds, 1966) subsequently applied in the area of concept formation (Homa & Cultice, 1984). Seen from our perspective, Bartlett's works occupy a special position, because they were among the first ideas that—after 50 years of empirical memory research—started out with clearly drawn representational assumptions. It was all the more surprising, therefore, that these important ideas—apart from those exceptions mentioned earlier—did not receive widespread attention.

In the late 1940s, Shannon's information theory and Wiener's cybernetics theory stimulated new interest among researchers in psychology and in other scientific disciplines (see Wiener, 1968). In the hope of a promising and fruitful approach to the study of perception, memory, and thinking, information theory and cybernetics were frequently introduced into psychology with a lack of critical insight. The number of works relating to the