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4 || Some Remarks on a Theory of Memory¹

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A system of human memory is described in terms of theoretical constructs involving information representation, storage, and retrieval. The system reflects a synthesis of ideas regarding some controversial issues in the analysis of memory. Information in memory is processed in several different "stores", each with different storage and retrieval characteristics; within these stores information can be coded in a number of alternative forms. Control processes act to regulate coding and information transfer so that optimally the system performs its activities in the most efficient way in a given task context. The system is intended to support a broad range of cognitive functions, from simple perceptual and memory tasks to complex activities like language understanding.

I. Introduction

This paper is an attempt to integrate several theoretical constructs about memory. We have considered certain ideas that seem central to current research in memory and have tried to determine their relation to one another by placing them within the theoretical description of a memory system. This is not a review paper and no attempt will be made to trace the development of these ideas in the literature; we refer only to research that seems particularly important for understanding the constructs of the memory system. A more complete consideration of several of the ideas to be discussed here is presented in an earlier paper (Atkinson, Herrmann, and Wescourt, 1974). The memory system to be described is extremely general. The intent is that it be capable of supporting a broad range of cognitive activities, from perception to language comprehension, that, in

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common, depend on the utilization of stored information. No one of these activities requires the full complexity of the system for its theoretical analysis; the complexity exists because of our desire to endow the system with a capability to serve as an analytic tool for a wide range of experimental work.

The central theoretical elements of the system have appeared in other theories. The most basic construct in the system is the *feature*. Features are values on dimensions in terms of which information can be represented. Ordered sets of features comprise *information codes*. A code is an internal representation that defines a unit of experience—most simply an object in the system's environment. Codes are *linked* (connected, associated) together to form *memory structures*. These structures "represent" knowledge and events within the system. Codes and structures are stored in the different *memory stores* of the system. These stores are characterized by their internal structures and by the storage and retrieval processes that are used to manipulate information. The system also has *control processes* that regulate the representation, storage, and retrieval processes with respect to the context of the system's activities. Control processes act to develop efficient strategies for performing tasks under changing conditions. As these concepts are developed in the paper, mention will be made of how they represent a synthesis of views on certain issues: "boxes-in-the-head" v. levels-of-processing models of memory, single- v. multi-copy representation of information, and "distance" (structural) v. "process" (associationist) notions of information relatedness.

Our description of the system will be general and almost schematic in places. Certain aspects of the system intersect with more general issues: what is the nature of features; how does pattern recognition occur; how are inferences made from stored information? While we have ideas about these problems, they are beyond the scope of this chapter; our purpose here is to describe how certain constructs can be interrelated, and not to speculate about particular implementations of these constructs. Further, this chapter reflects no strong convictions that the ideas presented are the "correct" ones. Our motivation stems from a belief that there is value in theorizing about memory outside the context of particular tasks. This chapter attempts to integrate principles that have proved successful in one domain into a vocabulary of theoretical constructs that may be applied to other domains. Hopefully, the memory system we describe will prove to be a useful tool for thinking about a broad range of memory phenomena; but, we do not view it as a replacement for the type of careful, formal theorizing that characterizes research on some well-defined problem.

The discussion begins by describing the structural aspects of the memory system. These have been developed in detail elsewhere (Atkinson and Shiffrin, 1968, 1971) and the present account will be brief. The major part of the discussion, then, considers the representation of information

as codes, the organization of codes into memory structures, and the nature of the processes involved in the manipulation of information within memory.

II. Structural Aspects of the Memory System

The three main divisions of memory are the *sensory register* (SR), *short-term store* (STS) and *long-term store* (LTS). Information enters the system via its receptors and is transmitted to the SR in a relatively unprocessed form. The mosaic of sensory information in the SR is subject to *pattern recognition processes* that extract features and synthesize them to form codes. The information in the SR is lost rapidly either by decay or by being "written over" by new input. The STS is a working memory of limited capacity. Information is copied into STS either from the output of the pattern recognition processes or from LTS. Information is lost from STS unless maintained by particular control processes like rehearsal or imagery. The contents of STS may be thought of as a person's "current state of consciousness". Information in STS is immediately available to the system's processes without the need for a *directed search*; later the notion of a directed search will be developed with regard to its role in LTS.

The LTS is a large and essentially permanent memory bank. The memory structures stored there are normally never lost from the system, but the effectiveness of search and retrieval processes determines their availability for further use. These processes involve algorithms for content-addressable or heuristic search necessary for the practical operation of a large memory. Such algorithms are sensitive to changes in the contents of the store and so the storage of new information can affect the accessibility of old information (Newell and Simon, 1972).

Most activities of the memory system require many information transformations and transfers between the different memory stores. The activation of the SR, STS, and LTS need not occur sequentially during these operations. Instead, the different stores may be active *concurrently* during the processing required by some task. There is evidence, for example, that in certain recognition tasks STS and LTS are searched simultaneously for information needed to make a decision (Wescourt and Atkinson, 1973; Mohs, Wescourt, and Atkinson, 1973). Also, the different stores may be engaged in different tasks at the same time; consider the experience of driving a car over a familiar route while engrossed in other thoughts and subsequently realizing that all the turns and stops were made "unconsciously". It seems that the SR and LTS can be involved in driving the car, while at the same time STS and LTS can be active in other processes.

Although the SR, STS, and LTS have been referred to as "structural" elements of the memory system, they need not correspond to different neurological systems. Rather, the different memory stores may represent

different phases of activation of a single neurological system. The notion of degrees of activation is also consistent with theories of memory that account for certain results in terms of "levels-of-processing" (Craik and Lockhart, 1972; Restle, 1974), rather than in terms of different stores. From a levels-of-processing viewpoint, information entering memory is subject to a continuous process of organization and integration with other information; retention depends upon the degree of processing such that new sensory information is available only briefly, whereas highly processed information (e.g., at a semantic level of representation) is available for long durations. By itself, the idea of levels-of-processing (that information can be processed into different types of internal codes) is attractive because it can account for a large range of results from recognition tasks (e.g., Posner, 1969).

However, the assumption that there is a strict correspondence between coding level and availability of information in memory seems unwarranted (Posner and Warren, 1972)—as are assumptions that restrict particular coding levels to particular memory stores in a system like the one described here; for example, supposing that STS can contain only phonemic information. The present system incorporates both constructs of memory stores and of levels of coding. Information is represented by different types of codes which in some sense correspond to different levels of organization, and the various types are available for representation in both STS and LTS. The duration of information availability in memory depends primarily on the storage and retrieval processes that operate within the different stores, and is not directly determined by the coding format of the information.

II. Representations of Information in Memory

Information is represented in the memory system as codes. Each code is an ordered list of features that define an arbitrary unit of experience (an object, a relation, an abstract concept) on some set of dimensions. Two main classes of codes are distinguished on the basis of the types of features that comprise them: *perceptual codes* (p-codes) and *conceptual codes* (c-codes). The p-codes are generated from the mosaic of sensory information in the SR by pattern recognition processes. The effect of these processes is to "parse" sensory information into units characterized along dimensions which past experience and current context indicate as marking important distinctions. For example, information in the SR produced by the reception of spoken English contains components that have to do with whether the sounds were "voiced" or "unvoiced" and "aspirated" or "unaspirated"; while the former distinction is important for the correct perception of some consonant sounds, the latter distinction is not—English consonants are not distinguished by aspiration. The p-codes

produced by pattern recognition of spoken English contain only information about features like "voicing" that make useful distinctions. In general then, much of the information in a sensory pattern will not be encoded in p-codes, and as a result different patterns may be analyzed into the same p-code. On the other hand, past experiences and context can affect pattern recognition such that a given pattern of sensory information is parsed into different p-codes; referring to the previous example, a trained linguist, studying English dialects, would encode aspiration in his perception of speech.

As another example, consider a printed word. A printed word is an object distinct from its referent, if any. It has size, contours, colour, etc. A word is also composed of letters which themselves may be taken as distinct objects. Experimental evidence indicates that words are perceived differently in different contexts. In a visual search for a particular letter (Gibson, Tenney, Barron and Zaslou, 1972) each letter of a word seems to be perceived as a unit (each letter is represented by a p-code). In word recognition, larger units like spelling patterns (Gibson, 1969) or vocalic centre groups (Spoehr and Smith, 1973) seem to be the perceptual units (each unit is represented by a p-code). In reading (Manelis and Atkinson, 1974), the words themselves may be the perceptual units (there is a p-code for each word). In each of these cases, the p-codes, though they preserve different amounts of sensory information, could still be composed from the same set of features. However, it is possible that even the set of features which comprise codes changes with context; for instance, the features that characterize music are probably different from those for speech. That there are different sets of features even within sensory modalities serves to complicate notions about the organization of LTS and about storage and retrieval processes that will be described subsequently. For the sake of clarity in this discussion we assume that there is but a single set of perceptual features in each modality; that is, across contexts, a given sensory pattern may be pattern recognized into different p-codes, but the features of these p-codes are values on a single set of perceptual dimensions.

The p-codes play an important role in the internal representation of objects and relations in the environment. However they are not sufficient for the operation of human memory. The p-code for an object and the p-code of the written or spoken word that denotes an object are quite different types of information. The p-code of the word "table" conveys no information about the characteristics of a table, whereas the p-code(s) produced while looking at an actual table does represent the table's physical characteristics. One idea is to say that "table" is a symbol that has as its meaning the p-codes generated when one looks at, feels, smells, and tastes a table. However, this formulation is not adequate for defining the meaning of all words. Consider the word "justice"; it certainly has a meaning

and yet there is no single object or relation it refers to as in the case of "table".

An alternative idea is that there is a higher-order type of code that we will call a c-code. Let a *concept* be a collection of memory structures containing information about a particular object, relation, or another concept; for example, the concept of table is the information stored in memory from experiences with various tables. Then, a c-code is a characterization of a concept as an ordered list of conceptual features—it is, in a sense, an abbreviation of the concept. The system makes sense of the p-codes for words by retrieving the c-codes of the concepts the words refer to. Our intuition is that conceptual features that comprise c-codes indicate the types of relations a concept characteristically forms with other concepts. This idea can best be illustrated in terms of a conceptually based language representation (Fillmore, 1968; Schank, 1972). To qualify as the *actor* of some conceptualization, a concept (in our case, its c-code) must have a feature that marks it as denoting some animate object. Also certain *acts*² may require certain features of their *actors*, *objects* and other cases; for example, the *act* underlying the verb "to write" has in its representation that its *actor* should be "intelligent" and that its *instruments* must also have certain features.

How might memory be structured to allow rapid access to c-codes when words denoting concepts or objects are perceived? The perceptual features of the p-code produced when a table is seen could be similar to the conceptual features of the c-code of the concept table, but there could be no such relation between the c-code and the word "table" since the word is an arbitrary symbol for the concept. Thus, there must be arbitrary links between the c-code and the p-codes of its symbols. Such links are defined in a functional partition of LTS that we call the *conceptual store* (CS). Located in the CS are special memory structures called *nodes*. Each CS node is a collection of the alternative p-codes for the word and object (if any) that correspond to the c-code that is also stored at the node. For example, the node for *table* contains the c-code that is an abbreviation of the concept table and linked to it are the various p-codes that are produced when a table is seen, when the printed word "table" is seen, when the auditory word "table" is heard, etc.³

The CS has the property of being content-addressable on the basis of features comprising codes; there is an overall structure to the CS such that each node is stored at a location that has an address determined by all the features of all the codes stored there. Given a p-code or c-code, retrieval

²*Acts* are primitive concepts that underlie verbs. Schank (1972) has proposed that all English verbs map onto about 15 such acts.

³This means that p-codes for homographs and homophones are stored at more than one CS node with different c-codes. Also, p-codes of synonyms are represented at different nodes that contain identical c-codes.

of the node containing it is a process of generating an address from the code. This storage and retrieval scheme has the property of allowing rapid access to an abbreviated coding of the concept symbolized by a word, as well as to alternative p-codes.

The CS and c-code are useful constructs for explaining certain memory phenomena. First, the CS may be taken as a major locus for many types of "familiarity" effects observed in memory experiments. These effects are typified by subjects being able to make relatively rapid and preconscious recognition judgments. These judgments seem to reflect the existence of a "strength" value associated with each to-be-remembered item that is practically independent of how the items were learned (Atkinson and Juola, 1974). Many of the familiarity effects in memory experiments may reflect the activity of CS nodes. Whenever an item is perceived, the p-code leads to location of the CS node that contains it. The activity or "strength" of that node is then evaluated. The assumption is that accessing a node (regardless of context) temporarily raises its activity, relative to some base-line value. Very high or very low activity is evidence that the item represented at a node was or was not perceived recently, perhaps during study of a list of to-be-remembered items. At least two findings indicate that CS nodes are a locus of familiarity effects. First, the effects are independent of the modality in which the items are presented (Juola, 1973). Second, the effects are sensitive to perception of items outside the specific task context; specifically, the inclusion of certain words in the instructions to the subject can affect performance if these words are then used during the experiment as distractor items (Atkinson, Herrmann, and Wescourt, 1974).

The notion of c-codes composed of conceptual features is also consistent with data and models of semantic decision time (Rips, Shoben, and Smith, 1973). In tasks where subjects verify the truth value of predictions like "A canary is a bird" or "A canary has wings," decision time varies with normative judgments of the "typicality" or "relatedness" of the subject and predicate: for true statements times become faster with increasing relatedness, whereas for false statements the inverse relation holds. This result is difficult to account for with a semantic memory model that verifies statements by searching through a network representation of the concepts involved (e.g., Collins and Quillian, 1969). An alternative model (Rips *et al.*, 1973) proposes that predications are verified by comparing the features of the subject and predicate. If relatively many features match or mismatch, then a rapid true or false response can be made with reasonable accuracy. If, however, there is some intermediate degree of similarity, further information about the concepts involved must be considered in order to make a decision. In applying the present system to this model, the features used in the initial comparison are those of c-codes retrieved from the CS when the predication is presented.

The CS is also a useful construct in thinking about human language

understanding. Memory plays a central role in understanding, and a striking aspect of the process is its high speed. During at least the initial stages, which involve parsing the input, there is rapid access to the "meaning" of linguistic symbols. In terms of the constructs developed here, parsing involves using p-codes produced from the input stream to locate CS nodes and in turn retrieve the c-codes. The features of the c-codes suggest the conceptual relations that exist between the concepts symbolized in the input. This provides a basis for building an internal meaning representation that is then elaborated by reference to particular events and knowledge stored in memory.

There can be little doubt that coding is an important construct in understanding memory (cf., Melton and Martin, 1972). We have suggested a scheme for the generation and organization of alternative coding forms in the memory system. This scheme seems reasonable both in terms of experimental results and logical considerations of how the system operates. In the next section we will present some ideas about the use of codes to represent knowledge and events in memory and about the relation of the memory processes themselves to the other aspects of the system.

IV. Structure of Knowledge and Events in Memory

New information is stored in memory by linking together copies of codes that represent physical or conceptual events to form *memory structures*.⁴ Memory structures are first built in STS and are then copied into LTS. Memory structures (as distinct from nodes) are stored in a functional partition of LTS called the *event-knowledge store* (EKS). The EKS is distinguished from the CS in two main ways. First, memory structures in EKS represent a wide range of relationships between different code types, as compared to CS nodes. A CS node represents a simple linking of the abbreviated meaning of a concept to the alternative internal codings produced by perception of physical symbols or exemplars of that concept. An EKS memory structure, on the other hand, may have many internal organizations that reflect the relations between physical referents and/or abstract concepts in events and knowledge.⁵

The second distinction between EKS and CS involves storage, search

⁴A conceptual event is a conscious thought; for example, retrieval of a memory structure from LTS into STS.

⁵An event involves a particular set of referents in a particular spatio-temporal context. Knowledge represents relations between concepts that involve information abstracted from a number of events. For example, "John's dog bit Mary" is a statement generated from the representation of a particular event, whereas "Dogs can bite" is generated from knowledge abstracted from a number of events involving dogs. This latter type of memory has been called semantic memory (Tulving, 1972) and has been viewed as a partition of LTS distinct from episodic (event) memory.

and retrieval processes. A CS node is content-addressable through the features of any of the codes it contains. This type of storage organization is possible because of the restricted format of CS nodes; they contain only a single c-code and a p-code for each feature set, and therefore a node can have but a single value on any feature dimension. In contrast, EKS memory structures are composed of any number and variety of c-codes and p-codes. However, search through EKS is also directed; otherwise, search for a particular memory structure would be too time-consuming for the system to function. What we suggest is that only some of the features of some of the codes in a memory structure are used to determine the storage location of that structure. For example, a phone number may be stored on the basis of features of its owner's name and not on the basis of the number itself or the context in which it was learned. Alternatively, a structure might be stored on the basis of features of the context in which it was built and yet this context information may not be included in the actual memory structure. Consider a hypothetical example where a person is unable to retrieve an historical fact until he is cued with the information that his sixth grade teacher once made him stay after school for failing to answer the same question. Given this type of storage and retrieval, it follows that there are processes active at storage and search which select a subset of features to use in generating an EKS address. Further, the successful retrieval of a particular memory structure depends on whether the features selected at retrieval are the same as those selected at initial storage of the structure. Therefore, factors that encourage this consistency, for example, the availability of "retrieval cues" (cf., Tulving and Thomson, 1971), will aid retention and vice-versa.

The internal structure of EKS is similar to that of the CS; locations in the store are organized and addressable in terms of dimensions that represent the range of feature values of both p-codes and c-codes. On the average then, memory structures representing similar information tend to be stored at locations with similar addresses. The internal organization of CS and EKS is to be distinguished from the organization within memory structures. These two types of organization correspond to two different ways that information may be scaled as "related": either by being stored at locations with similar addresses (being stored "close together") or by being linked within a memory structure that is stored at a single location.

The organization of codes within a memory structure reflects the relations that existed between the units of experience of some event, or the relations between concepts in the encoding of abstract knowledge. The possible types of organization are perceptual and conceptual. By perceptual organization we mean that the codes representing an experience are linked by perceptible (spatio-temporal) relations (e.g., b is x units to the left of c ; or, d is y units more intense than e). Such organization is most

useful for encoding details of visual scenes or sound sequences.⁶ Conceptual organization links codes by conceptual relations. The idea of a conceptual representation has had extensive development in recent theories of language and memory (Anderson and Bower, 1973; Rumelhart, Lindsay, and Norman, 1972; Schank, 1972). Conceptual representation links units of experience and concepts with a restricted set of dependencies, cases, and causal relations (cf., Schank, 1972). One way of representing conceptual organization in memory is to link concepts and internal representations of particular physical referents into labelled associative networks. (A labelled association between two internal codes is a relation between them.) The system described here allows only simple (unlabelled) links between codes, and represents relations themselves as codes; that is, the relation "x is the subject of act y," is represented by linking the code for x to a code for "subject of" to a code for y. Features of the codes for relations serve to indicate the codes in the structure that are linked by that relation. However, there must still be a relatively fixed ordering of the codes so that the "meaning" stored in the structure can be interpreted by following links between adjacent codes (i.e., the structure would be interpreted incorrectly if codes were examined in the wrong order). Therefore, while the codes within a memory structure may assume various conceptual organizations, the actual links between codes are undifferentiated and connect them to form a linear array.

A major rationale for suggesting that all memory structures are linear arrays of codes reflects the representation of processes in the memory system. In our view, the processes that manipulate information in memory— inference, decision, abstraction, generalization, rehearsal, imagery, pattern recognition—are themselves stored in LTS and in the same format as the "data" they operate on (Rumelhart, Lindsay, and Norman, 1972). These processes are considered as "programs" stored in EKS with codes as individual "instructions". These particular codes may represent a set of mental actions that underlie events and linguistic statements involving the communication of information.⁷ For example, the concept of "comparison" can be described as the transfer of codes into STS followed by a feature matching operation. This meaning of comparison is stored in a memory structure(s) in EKS and may be entered as a procedure to compare two arrays of information stored elsewhere in memory. Alternatively,

⁶Note that either p-codes or c-codes representing units of experience may be organized perceptually. The organization of the structure must initially develop from p-codes, but before storage in EKS the corresponding c-code can be retrieved from CS and substituted into the structure. It is also the case that stored information can be similarly recoded when retrieved from EKS into STS. However, such recodings probably will not be the same as ones generated at the time of storage, since the contextual information that influenced generation of the-original p-codes will be different.

⁷See Schank, Goldman, Rieger, and Riesbeck (1972) for the description of such a set of mental actions.

this structure can be used as data for some other process as it was above when we gave its "definition." How the stored information is used depends upon the control process that accesses it.⁸ Further, since the processes are stored in memory, they can be accessed by other processes and modified so that they will operate differently the next time they are used as a procedure. This approach, though relatively unexplored, seems to be a powerful way to think about the development and change of task strategies. It also provides a mechanism for the ontological development of complex cognitive functions. The linear linking of codes within memory structures is reasonable if the structures are accessed as procedures that are executed to achieve some processing function. From a formal viewpoint, this type of internal organization is equivalent to a labelled associative network for the representation of events and knowledge.

Several additional remarks need to be made about EKS. Each memory structure in EKS is a discrete entity stored at an addressable location. The amount of information stored in any one structure depends upon the control processes that operate at storage, and perhaps by the limited capacity of S'IS since new structures are built there and then copied into EKS. Particular codes are stored in many different memory structures. In addition, the same event or knowledge may be represented in more than one memory structure and with alternative forms of codes, thus increasing the likelihood that the event or knowledge can be retrieved. The modification of information already in EKS involves copying old structures into S'IS, changing them, and then recopying the new structure into a location in EKS; the old structures are not erased from the system. This view of LTS contrasts with theories that suppose that each unit of experience or concept is represented by a single node in memory, and that events and knowledge are recorded by linking these nodes with relational associations (Anderson and Bower, 1973). In the present system, such organizations exist within each memory structure, but no links exist between these structures. To retrieve a structure, the address of its storage location must be generated. The individual codes within the structure are then available by a search along the links between them.

V. Concluding Remarks

We have presented a view of how different theoretical constructs, each developed from a consideration of some aspect of memory, can be integrated into a system that, in principle, is capable of accounting for a broad range of cognitive activities. The constructs of the system are in

⁸The control processes are themselves stored in EKS. The operation of memory therefore involves processes that invoke processes that invoke other processes, etc. Complex processes like language understanding may therefore be a hierarchical organization of more basic processes.

accord with both data and logical considerations of how memory must operate. The work of Sperling (1960) in vision and Massaro (1972) in audition agree with the notions of a SR and pre-perceptual representation. The idea of alternative internal codes is central to the explanation of studies of same-different recognition (Posner, 1969). The CS and c-codes reflect studies of recognition memory (Atkinson, Herrmann, and Wescourt, 1974), semantic decision time (Rips, Shoben, and Smith, 1973), and the requirements of a language understanding system that must have rapid access to the information needed to parse input (Schank, 1972). Other constructs (for example, those involving content-addressable storage and the representation of processes) reflect the influence of research in computer science and artificial intelligence.

One may ask what useful purpose such a general conception of memory serves, especially since no effort has been made to implement the system as a whole and investigate its operation over a range of tasks. This would constitute a basis for criticism if our goal were to offer a finished and testable theory of memory. However, our purpose here is more modest. We feel that the description of the memory system serves to introduce a language that is generally useful for thinking about memory. The memory system reflects that perception, simple retention, and complex cognitive activities all require the representation, storage and retrieval of information and it constitutes a way of talking about them in terms of these commonalities. Thus, it provides a means for thinking about different problems with a single vocabulary.

What we have presented then is not a theory of memory, but instead a language for formulating specific models of memory. While our own research has led us to test several models that seem well stated in this language (Atkinson, Herrmann, and Wescourt, 1974), the system might equally well be used to represent other models that lead to somewhat different predictions.

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