MODELS OF MEMORY

Models of memory are theories of how information is represented in memory and the processes by which information is stored in and retrieved from memory. To develop a model that successfully accomplishes these goals is a daunting task. Thousands of experiments have been done to investigate memory, and there are hundreds of phenomena to explain. Theoretical progress in understanding memory is made by trying to map a wide range of phenomena onto a model that specifies what processes operate on what kinds of information for each phenomenon. So, for example, questions are asked like the following: Are the processes used in recognizing that a string of letters is a word the same processes that are used in recalling that the word appeared in a sentence? Do the processes operate on a common memory representation of the string of letters or on different representations? While progress can be made on such questions experimentally by using intuitive notions of process and structure, models provide more insightful ways of addressing these issues and integrate our understanding across different kinds of experiments.

The first issue is "Why develop models at all; are the data alone not enough?" Several papers have addressed the need to use theory in guiding research; here some major points are summarized (Estes, 1975; Hintzman, 1991). Models are useful because they bring out relationships among sets of data that would not otherwise have been apparent to us, because they allow reclassifications of phenomena that are not obvious in the data alone, and because they allow specific predictions about processing and representation to be formulated and tested against data. Both Estes and Hintzman provide excellent examples of these and other reasons for the use of models. In cognitive psychology, models usually are relatively simple in structure and make use of accessible and well-understood mathematics. Thus the domain is exciting for a researcher because it is possible to develop new models and to make major contributions in a relatively short time. This stands in contrast with many domains of research in the physical sciences.

Representation

The key to understanding and modeling human cognition is representing knowledge. While there has been a great deal of work on representation (e.g., see SEMANTIC MEMORY and CONCEPTS AND CATEGORIES, LEARNING OF), it is clear that definitive answers have not been found. One structure that has been proposed for representing knowledge is a semantic network (e.g., Anderson, 1983) in which each concept is a single node and relationships among concepts are shown by labeled links between nodes. Similarity between two concepts can be measured as the distance between the concepts in number of links or the number of common concepts directly linked to the two concepts. A second method for representing knowledge uses a feature representation in which each concept is made up of a number of semantic features, and similarity is measured by the number of features in common.

Most current memory models have less to say about representation than about processing. However, all the models make use of either semantic networks or feature representations, but without spelling out exactly what kinds of information are carried in the nodes, links, or features.

Process

Several memory models do a good job of explaining a number of phenomena from a number of different tasks, and of explaining multiple aspects of the data from each task. One model is presented in moderate detail and another is presented briefly.

The SAM (search of associative memory) model of Gillund and Shiffrin (1984) is designed to account for performance on recognition tasks and recall tasks. Subjects are presented with a list of words (or other materials) that they are to study. Then, in recall, they are asked to write down all of the words from the list that they can remember. In recognition, subjects are shown a list of test words and are asked to indicate which of the words on the test list were on the study list. For these tasks, the SAM model can predict the effects of a number of variables, such as presentation time per study word, number of repetitions of study words, forgetting over time or by interference from other learning, effects of rehearsal of the study words, effects of the context of other words in the test list, effects of the frequency with which the words occur in English, and so on. The aim is to explain how the accuracy of recognition and recall varies as a function of these variables. The model uses the same representation of the study words in memory for both tasks, and to account for the effects of all the variables. However, recall and recognition are assumed to employ different retrieval processes. The SAM model assumes that each study item is represented separately in memory. At encoding, a simple buffer model builds a retrieval structure that contains strengths of connections between cues (potential test items) and images (representations of items in memory). The parameters of this encoding process are expressed in terms of units per second, and measure the strength that accumulates per second. The parameter *a* refers to the strength built up between the context in which an item is presented and the item, *b* refers to interitem strengths (the strengths between the items that are in the buffer at the same time), *c* refers to the strength built up between an item as a cue and its own image in memory, and *d* refers to the residual strength that exists between any item as cue and any other item in memory independently of encoding.

The process that operates on information in memory for the recognition task is a global parallel matching process whereby the test word is compared against all words in memory. The test word is combined with the test context to be compared against memory; the result of this comparison is a match value, a number that indicates how well the test word matches memory. The value is calculated as the sum over all items in memory of the products of the strength between the test word (the cue) and each image in memory. If the value is large (larger than some criterion value), then the response to the test item will be that it is from the studied list; if the value is smaller than a criterion value, then the response will be that the word was not from the list. Consider a numerical example. If the strengths of connections between the test context and the test item (what memory is probed with) and each item in memory are as shown in Figure 1 (.2 for context to item 1, .9 for test item to item 1, etc.), then the value of the match is the sum of products as shown in the figure. Real subjects make errors in recognition; in the SAM model, these errors result from variability at encoding. During study, some words will be encoded extremely well, others not so well, and others very poorly. A poorly encoded word may have a small match value when presented as a test word, and so the response to it may be incorrect. Similarly, some words not on the list may match memory better than the criterion value, and so be responded to incorrectly. To model the time taken to make a response, the value of the match between test and memory can be used to determine the rate at which information is accumulated over time (Ratcliff, 1978). Such an evidence accumulation process predicts a range of phenomena including the behavior of the average response

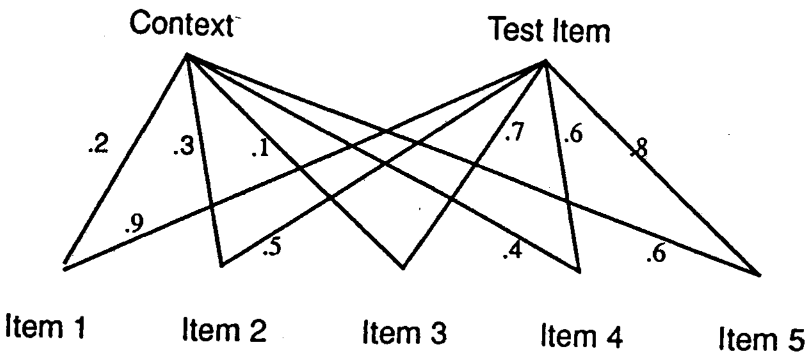

Figure 1. Items 1–5 are in memory; the numbers represent the strengths between context and memory and between the test item and memory. The match between the test item plus context (familiarity) = .2 × .9 + .3 × .5 + .1 × .7 + .4 × .6 + .6 × .8 +. . . .

time, the shape of the response time distribution, and the average accuracy of responses.

In recall, a search process recovers items one after another. First, memory is probed with the test context in order to find an item. Then, if the strength is high enough, the item will be recovered (i.e., recalled). Then this item, along with context, probes memory again in an attempt to recover another item. This process is repeated until the process runs out of time or cannot recover any more items.

SAM represents memory as a network of strengths connecting items. A contrasting model is Hintzman's MINERVA2 model, in which items are represented in memory as sets of features (items are represented separately, i.e., an instance-based model; other models are composite, all items entering a common memory. See Murdock, 1982). For recognition, a test item (which is also represented as a list of features) is matched against all the items in memory. When a feature in the test item matches a feature in an item in memory, the match value is increased by 1; when they do not match, the match value is decreased by 1. All of these match values between the test and individual items in memory are then cubed and pooled to produce an overall match value. Hintzman's (1986, 1988) model has been applied successfully to a range of phenomena including recognition, cued recall, frequency judgments, and categorization.

Comparison of Models

What is interesting about current memory models is that although their structures are different in many ways, they make remarkably similar predictions in their common domains of application. In one sense, this should be expected; if they did not, one model would be right and another wrong. But in another sense, the question becomes "What are the mechanisms that give rise to similar predictions?" For example, to explain better accuracy in recognition as study time per word increases, the MINERVA2 model assumes an increase in the probability of a feature's being encoded into memory. Similarly, in the SAM model, greater retrieval strength is accumulated as a function of study time. The major characteristic that makes the models produce similar predictions in recognition is that they compute an overall match value between the test item and all items in memory.

Application to Other Phenomena

One important use of the global memory models is to serve as either a qualitative or a quantitative metaphor for processing, and thus to serve in other research domains. An example is the application of the models to priming. Priming occurs when one test item speeds responses to the next test item by virtue of the relation between them. The most popular current view of this phenomenon is that the first item sends spreading activation through a semantic network of concepts and the second item is responded to more quickly because it is partially activated before it is actually presented. Ratcliff and McKoon (1988) and Dosher and Rosedale (1989) developed an alternative, compound cue, model using the mechanisms that already existed in the global memory models.

These models emphasize parallel retrieval and have mechanisms for matching pairs of test items against memory in parallel. Thus the new compound cue model assumes that a test probe to be matched against all of memory consists of the first and second items together. If the two items are related in memory, then the value of the match will be larger than if they are not (through the standard mechanisms of the global models). This provides a counterinterpretation to the popular, spreading activation theory.

Connectionist Models

Many connectionist/neural network models are advertised as having associative memory, and many of these models can be successfully used to store and retrieve information from a content-addressable memory (see PARALLEL DISTRIBUTED PROCESSING MODELS OF MEMORY). Few of the models, however, have been seriously applied to the same range of experimental data in memory as the global memory models. It has been shown (e.g., McCloskey and Cohen, 1989; Ratcliff, 1990) that it is far from trivial to get models of this class to account for more than a few of the major trends in experimental data. However, the application of connectionist models to memory data is sure to be a major area of research in the future.

Conclusions

Models of memory have a number of uses and are an end in themselves. They attempt to organize and predict a large number of phenomena within their single framework. They also form the basis for developing new and different accounts of other phenomena in related domains. Finally, the models provide a basis for competition with connectionist models and an impetus for development of future models.

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Roger Ratcliff