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DEPARTMENT OF PSYCHOLOGY

The University of Michigan, Ann Arbor

How Associations are Memorized

JAMES G. GREENO

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Technical Report No. 12
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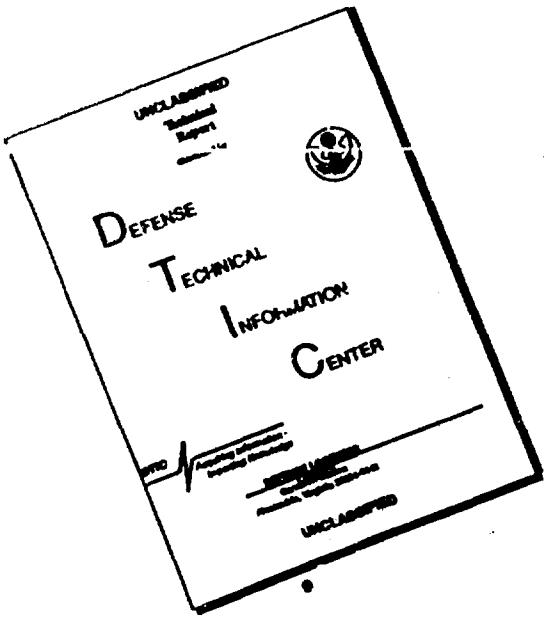

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THE UNIVERSITY OF MICHIGAN

COLLEGE OF LITERATURE, SCIENCE AND THE ARTS

DEPARTMENT OF PSYCHOLOGY

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HUMAN PERFORMANCE CENTER--TECHNICAL REPORT NO. 12

December, 1968

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THE HUMAN PERFORMANCE CENTER

DEPARTMENT OF PSYCHOLOGY

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Learning theory as we know it today probably was founded in the Seventeenth Century, when Hobbes and Locke revived Aristotle's attack on the doctrine of innate ideas. Hobbes and Locke and other empiricist philosophers took the view that knowledge comes from experience. This view requires a learning mechanism, and the empiricists proposed that learning is a process of combining impressions that occur near one another in space and time, or are similar, or contrast with one another. Empiricists argued for the plausibility of a human organism endowed only with elementary sensory (and, presumably, motor) capacities. Complex concepts and sequences of ideas were assumed to develop as combinations of sensory impressions. Thus, the mechanism of association between ideas played an important role in the argument for empiricism, and was therefore part of the justification of the scientific method itself.

It seems safe to say that the belief in association as the elementary learning event has dominated theories of learning and thinking for at least three centuries. The early view that associations form between ideas has been replaced in this century by the idea that associations connect stimuli and responses. But in one form or another, the hypothesis of associationism has enjoyed nearly doctrinal status for most scientific psychologists. Most theorists interested in learning have asked how associations are formed--not whether the basic learning process might be rather different from that described by association theory.

Under the presumption that all learning probably is based on formation of associations, paired-associate memorizing seems to provide the paradigm case of learning in its simplest and purest form. In the framework of association

theory, achievements of recall and recognition require relatively elaborate explanations. Learning to recall is sometimes viewed as the formation of connections between responses and some general stimuli--for example, the properties of an experimental room. And recognition is sometimes said to depend at least partly on a learned connection between a stimulus and some general recognizing response which is evoked when the stimulus reappears.

The discussions of recall and recognition included in this volume do not emphasize associationistic ideas. The operative concepts in most of the theories presented here are encoding, storage, and retrieval of items. Rather than asking how associations are formed between stimuli and responses, most of the theories in this volume consider how graphic and auditory stimuli are encoded, how records of stimuli are stored in the subject's working or acquisition memory, and how these records are retrieved and used to generate responses on tests of retention. The theory of memory based on concepts of storage and retrieval evidently gives a rich and illuminating explanation of the processes of recall and recognition, as these are understood at present.

We are faced with an awkward theoretical situation. For tasks involving recall or recognition of lists, concepts of storage and retrieval seem more appropriate than concepts of associative connection. But for paired-associate memorizing it may seem simpler to theorize using concepts of stimulus-response associations.

In this chapter I will present evidence suggesting that the concepts of storage and retrieval are also more appropriate than concepts of stimulus-

response connections for paired-associate memorizing. The view to which I have been tentatively persuaded is that the task of memorizing associations is not paradigmatic for learning processes in their simplest form. On the contrary, I believe that paired-associate memorizing involves processes that are revealed in simpler form in experiments where subjects memorize lists for recall or recognition. I will not try to discuss these processes in detail--that is the task undertaken by many other contributors to this volume. What I hope to do is to present some of the data that encourage me to believe that their discussions probably describe the basic properties of paired-associate memorizing

A remark is needed to avoid a misinterpretation. Every theory of paired-associate memorizing has to be an associative theory in that it must explain how subjects come to learn correct responses for stimuli. However, classical association theory makes a specific claim about the nature of the learning process. The theory that this article disputes claims that stimuli and responses are independently manipulable units, and the learning of an association is the formation of a connection between otherwise independent mental entities. In situations that will be considered here, the basic process of forming connections does not provide a complete theory, and we will be concerned with association theory amended to include processes of response acquisition and unlearning of interfering connections

The alternative theory that I will consider takes a view of association that is basically Gestalt in character. Kohler (1941, p. 493) expressed the idea when he said, "Association is...simply coherence within the unitary trace of a unitary experience." I propose that the first stage of memorizing an association involves storing a representation of the stimulus-response

pair in memory as a unit. Depending on the materials used, the stimulus or the response or both may already be in the subject's long-term or permanent memory. Borrowing concepts used by Feigenbaum and Judith Reitman in this volume, the process of storing a pair results in a structure which represents the pair in the subject's working or acquisition memory.

In some situations, successful storage of an item may be all that is needed for successful retention. But in other situations, storage of an item in memory may not guarantee that the subject will be able to perform successfully on tests. In these situations, I propose that the second stage of memorizing involves learning to retrieve the stored item from memory reliably. The process of learning to retrieve could involve changing the stored representation of an item, or discovering relationships among stored items to permit better organization, or some other process.

Consider an example. Suppose that one of the items in a paired-associate list is the pair SPIRAL-VIVID. At the beginning of the experiment, the subject has no idea that these two words are supposed to go together--the item is not known. Then at some time the subject stores a representation of the pair SPIRAL-VIVID in memory. When the stimulus SPIRAL is presented on tests there is some chance that the subject will be able to retrieve the stored memory structure and give the correct response. But there may also be failures of retrieval, due perhaps to other stored items with stimuli similar to SPIRAL, or to requirements for fast responding. If the representation of SPIRAL-VIVID does not permit rapid and reliable retrieval, then further learning is needed, and this is what I am calling learning to retrieve. Once a retrieval strategy

for SPIRAL-VIVID is acquired, the subject will be able to respond correctly on tests, and the item will be learned.

I am primarily concerned to argue that there are two main sub-processes in memorization of associations, and that these involve storage and learning to retrieve. I am less concerned in this paper with issues about the exact nature of storage and retrieval processes. However, some discussion of possibilities is helpful in clarifying the general ideas.

First, regarding the process of storing pairs in memory, Neisser (1967) has argued that storage of information should be viewed as a constructive process relating to a cognitive act. Neisser's argument seems cogent-- the mind cannot really be a blank tablet. Furthermore, the nature of the stored memory structure for an item can vary a great deal depending on what the subject does when he studies it. For example, in studying the pair SPIRAL-VIVID a subject might form a visual image of a brightly colored design that could appear on a psychedelic poster. Or he might construct an associative mnemonic such as "spiral-viral-vivid". He might select some part of the stimulus, such as its first letter and code "S-vivid". Or he might simply rehearse the pair as it was presented. The information stored by the subject would be different in each of these cases, and questions about the form in which information is stored are very important and interesting. But the notion of storage as it is used in this paper is intended to refer to any representation of the paired associate in memory. The important claim is that an item is stored as a unit, rather than as a connection.

Now, suppose that an item has been stored. On a test, the subject sees the stimulus term of the pair and he has to give the correct response. There seem to be two ways of thinking about his problem. One common way of

thinking about memory involves an analogy with a library or a filing system, or using Miller's (1963) idea, a junk box. An item may well be in memory and not be found on a given occasion If memory is like a junk box or a filing system, then the process of learning to retrieve could be accomplished by getting the item separated from the rest of the contents of memory in some way, or by getting the contents of memory organized in some systematic way so the subject knows where to look for things.

There is another way of thinking about memory that may be more realistic. Analogies to filing systems or junk boxes make memory seem spatial, with information stored and waiting passively to be found. Another possibility is that memory structures or engrams are functional as well as structural features of the mind. On this view, a stored memory structure becomes active when an appropriate signal is received--the engram may be thought of as waiting for its number to be announced before coming forward. If memory storage involves establishing engrams then the question of retrieval is the question of whether the engram becomes active when the stimulus is presented on a test. And if it does not with sufficient reliability, then the subject has to set or tune the engram more efficiently so that it will be activated reliably by the presentation of the stimulus

While these remarks about storage and retrieval processes are entirely speculative, they demonstrate that reasonable general views of the nature of memory are consistent with the claim that memorizing could easily involve two stages that can be called storage and learning to retrieve. Later sections of this paper present evidence that supports this conceptualization

Statistical Methods

The evidence that will be presented uses measurements of the difficulty of learning in each of two stages in various paired-associate memorizing experiments These measurements are obtained by estimating the parameters of

a Markov model, using results presented in detail elsewhere (Greeno, 1968). The model has four states:

O, the state of an item at the beginning of an experiment, applying until the item is stored in memory.

E, the state of an item which is stored in memory, but a reliable retrieval strategy has not been acquired and the subject fails to retrieve the item from memory.

C, the state of an item which is stored in memory without a reliable retrieval strategy, but the subject succeeds in retrieving the item from memory.

L, the state of an item which is stored in memory with a reliable retrieval strategy.

The initial and transition probabilities of the chain are[1]

$P(L_1, E_1, C_1, O_1) = (t,\ (1-s-t)r,\ (1-s-t)(1-r),\ s)$,

$$P = \begin{array}{c|cccc} & L_{n+1} & E_{n+1} & C_{n+1} & O_{n+1} \\ \hline L_n & 1 & 0 & 0 & 0 \\ E_n & d & (1-d)q & (1-d)p & 0 \\ C_n & 0 & q & p & 0 \\ O_n & ab & a(1-b)e & a(1-b)(1-e) & 1-a \end{array} \qquad (1)$$

[1] In this discussion I am ignoring the problem of identifiability. The version of the model given in Eq. 1 is not identifiable in the form given, but in every application that will be presented there are acceptable simplifying restrictions that make Eq. 1 identifiable. The assumption that $P(L_{n+1}|C_n) = 0$ is used as an identifying restriction here. In effect, it is assumed that learning to retrieve stored items is a process of strategy selection that occurs only after failures to retrieve.

It will be recognized that this model ignores important temporal features of the memorizing process, discussed in this volume by Norman and Rumelhart and by Judith Reitman, and elsewhere by numerous authors (e.g., Atkinson & Shiffrin, 1968, Greeno, 1967; Peterson, 1966). Present evidence seems to indicate that learning occurs during an interval of time including and following the presentation of the item to be learned. In the experiments to be discussed here, individual items were almost never repeated within short enough intervals to produce effects due to short term memory.

In the general form of Eq. 1, the model is a little unwieldy. Some simplifications often are acceptable. One simplification results if the first test comes after a single study trial on which the transition parameters are the same as on later trials. Then

$$t = ab, \; r = e, \; s = 1-a \tag{2}$$

Further simplifications are possible if the probabilities of acquiring a retrieval strategy and retrieving stored items are the same on the first trial after an item leaves State 0 as they are on later trials. In that case,

$$b = d, \; e = q \tag{3}$$

If the simplifications in Eqs. 2 and 3 are acceptable, the measurements of difficulty in the two stages of learning are straightforward. There are just three parameters, a, d, and p. The value of a measures the difficulty of learning in the first stage. The value of d measures the difficulty of learning in the second stage. And the value of p is the probability of retrieving a stored item from memory before a reliable retrieval strategy is acquired. If the simplifications are not all acceptable the measurements of difficulty in the two stages of learning are less simple. However, summary

measures give reasonable indices of the difficulty in each stage. Let Z_1 be the number of trials spent in the State O, and let Z_2 be the number of trials spent in States E and C. The expected values of these variables are

$$E(Z_1) = 1+\frac{s}{a} \quad , \quad E(Z_2) = (1-s-t)\left[1+\frac{1-rd}{qd}\right] + s(1-b)\left[1+\frac{1-ed}{qd}\right].$$

To obtain the measurements of difficulty needed for the analyses we need estimates of the parameters of the model. These can be obtained using the method of maximum likelihood. Suppose one item shows a sequence of correct responses (0) and errors (1)

$$X = 1\ 1\ 1\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ \ldots$$

Using Eq 1, the likelihood of X is

$$L(X) = (1-s-t)r(1-d)^3q^3p^2d + sa(1-b)e(1-d)^2q^2p^2d$$
$$+ s(1-a)a(1-b)e(1-d)qp^2d + s(1-a)^2a(1-b)(1-e)qpd$$

Of course, this is only an illustration. The likelihood of any sequence can be calculated using Eq. 1, in a form similar to the above equation. The likelihood of all the data is the product of the likelihoods of the separate sequences. The estimates of the parameters are those values that maximize the likelihood of the data. For the model we are considering, maximum likelihood estimates cannot be obtained algebraically, but the maximum can be found using a computer search program. We have used Stepit (Chandler, 1965) which uses only a few seconds of computer time to obtain a set of estimates.

To determine whether one or more simplifications of the model are acceptable, likelihood ratio tests are used. The procedure involves finding maximum likelihood estimates of the parameters of the general model, and

then finding maximum likelihood estimates of the parameters with a restriction imposed The value of the likelihood obtained with the restriction will be lower than the maximum likelihood obtained without the restriction, and the ratio of the two values (restricted over general) is called λ If the restricted version is correct, the value of $-2 \log_e \lambda$ is asympotically distributed as chi square with degrees of freedom equal to the number of restrictions In the discussion that follows, when a restriction is called acceptable for a set of data, this means that the likelihood ratio rest for that restriction gave a test statistic with probability greater than 05

The main analyses involve tests of significance comparing different experimental conditions in the difficulty of the two stages of learning Likelihood ratio tests are also used in these analyses Suppose for example, that we want to test whether two groups differ in the value of a A maximum likelihood value is obtained for all the data of both groups, with all of the parameters free to vary A second maximum likelihood value is obtained with a single value of a used for both sets of data The restricted value of the likelihood divided by the maximum likelihood without the restriction gives a likelihood ratio λ In this case $2 \log_e \lambda$ is asymptotically distributed as chi square with one degree of freedom if the two groups really have equal values of a Tests can be carried out using more than one parameter, and the degrees of freedom for the chi square distribution equal the number of parameters involved in the test In this way, we can test whether two groups differ in the difficulty of the first stage of learning, or in the difficulty of the

second stage of learning, or in performance during the intermediate stage of the learning process, or in any combination of these characteristics.

Effects of Stimulus and Response Difficulty

Michael Humphreys conducted an experiment varying the difficulty of responses and the similarity among stimuli. The materials he used are listed in Table 1. The four lists were learned by separate groups, using the anticipation method. Subjects were asked to spell the responses. Some summary statistics are given in Table 2. Note that both the stimulus variable and the response variable had reasonably strong effects in the experiment.

Table 1

Lists Used in Humphreys' Experiment

EE	EH	HE	HH
1-HAZ	1-HPF	11-RAS	11-GPS
2-MAK	2-IPW	12-MAK	12-HPF
3-GAW	3-NPE	13-JAV	13-BPC
4-RAS	4-GPS	21-BAQ	21-IPW
5-BAQ	5-JPV	22-HAZ	22-NPE
6-LAN	6-MPA	23-FAC	23-XPO
7-DAP	7-BPC	31-DAP	31-RPK
8-JAV	8-XPO	32-GAW	32-MPA

Table 2

Summary Data for Humphreys' Experiment

Group	Mean Errors Before First Correct	Mean Errors After First Correct	Mean Trial of Last Error
EE	3.10	1.17	5.71
EH	5.06	1.57	8.01
HE	5.28	1.85	8.28
HH	6.64	2.82	11.79

The data of this experiment allow us to test the theory of storage and retrieval learning Recall that in the theory, the first stage of learning is storage of the stimulus-response pair as a unit We should expect that this process should be affected by both stimulus and response variab es. Then, in Eq 1, the value of a should be influenced by both of the variables in Humphreys' experiment. On the other hand, the theory says that the second stage involves learning to retrieve items reliably In Humphreys' experiment, the main difficulty in retrieval might well be elimination of confusion among items with similar stimuli In this case, the second stage of learning should be influenced mainly by the stimulus variable In Eq 1, the values of b and d should be higher for groups with easy stimuli than hard stimuli, but should not be influenced by the response variable

Now suppose that the theory of storage and retrieval learning is wrong, and associations are really memorized by forming connections between stimuli and responses. A primitive version of association theory would not allow for response effects at all, but association theorists have extended the theory to include an additional process The most comprehensive treatment of the extended theory is given by Underwood and Schulz (1960) In the extended theory, paired-associate memorizing has two stages In the first stage, the subject acquires the response term of the paired associate For a nonsense syllable response, the response learning phase probably would involve forming associations among the components of the response For responses that were already well integrated, the response learning phase would be a process of increasing the availability of the response in the experimental situation--a process sometimes called formation

of a contextual association. The formation of an associative connection or hookup between the response and its stimulus occurs in the second stage of learning.

According to the theory of response-strengthening and hookup learning, the first stage of paired-associate memorizing should be affected mainly by response variables. This means that in Humphreys experiment, we should expect the value of a in Eq. 1 to be different for groups with different responses, but a should not be influenced by the stimulus variable. In Underwood and Schulz' theory, the difficulty of forming stimulus-response hookups depends on properties of both the stimuli and the responses. This means that in Humphreys' experiment, the values of b and d in Eq. 1 might well depend on both the stimulus and the response variable. A summary of the predictions suggested by the storage-retrieval theory and the response-hookup learning theory is given in Table 3.

Table 3

Summary of Predictions for Humphreys' Experiment

Parameter	Storage-Retrieval	Response-Hookup
a	Depends on Stimulus and Response Variables	Depends only on Response Variables
b and d	Depends Only on Stimulus Variable	Depend on Stimulus and Response Variables

The main question, then, is how the parameters of the model varied depending on the experimental conditions. But this question is not meaningful

unless the model is approximately accurate as a description of the learning that went on in the experiment We want to use the parameter estimates as psychological measurements, and as with any psychological measurements we have to be concerned with the question of validity For example, the predictions summarized in Table 3 depend partly on assuming that the stages of learning are approximately discrete and sequential For example, if the response-hookup learning theory were true, but the stages overlapped, then the model would be wrong but the estimate of a would probably be influenced by both stimulus and response variables.

We cannot prove that the measurements obtained with a model are valid, because we can never prove that a model is accurate What we can do is to perform tests that have the possibility of rejecting the model if it is substantially wrong The tests carried out in this case involved comparisons between frequency distributions of statistics in the data with distributions calculated using Eq 1 with maximum likelihood estimates of the parameters

For the groups in this experiment, the simplification given as Equation 3 was not acceptable in one of the groups Eq 2 was acceptable Therefore, the goodness of fit of the model was tested using maximum likelihood estimates of five parameters a, b d, e, and q

An illustration of the tests will be given using the group with hard stimuli and easy responses Fig 1 shows the distribution of the number of errors made after the first correct response on each item Fig 2 shows the number of trials between the first correct response and the criterion of three consecutive correct responses, which was taken as showing learning The agreement between the data and these theoretical distrib-

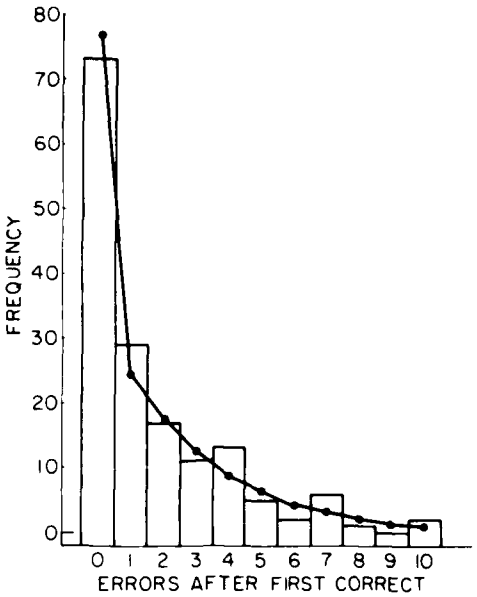

Fig. 1 Theoretical and empirical distributions of the number of errors after the first correct response for Group HE in Humphreys' experiment. The histogram represents the data, and the connected dots show the theoretical frequencies.

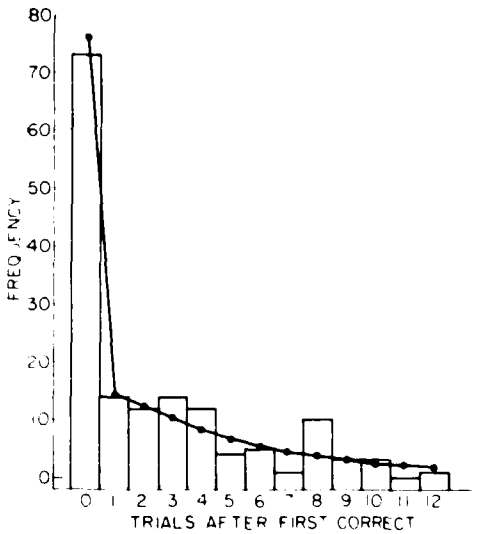

Fig. 2 Theoretical and empirical distributions of the number of trials between the first correct response and the criterion for Group HE in Humphreys' experiment.

ution seems excellent. These distributions involving performance after the first correct response have considerable importance because the model says that an item has to have completed the first stage of learning before a correct response can occur. According to the model, learning that occurs after the first correct response must be all-or-none in nature. The distributions shown in Figs. 1 and 2 test this feature of the data.

There are two kinds of sequences that need to be separated for purposes of estimation; sequences that have no errors after the first correct response and sequences that have some errors after the first correct response. Fig. 3 shows the empirical and theoretical distributions of the number of errors before the first correct response separated into components.

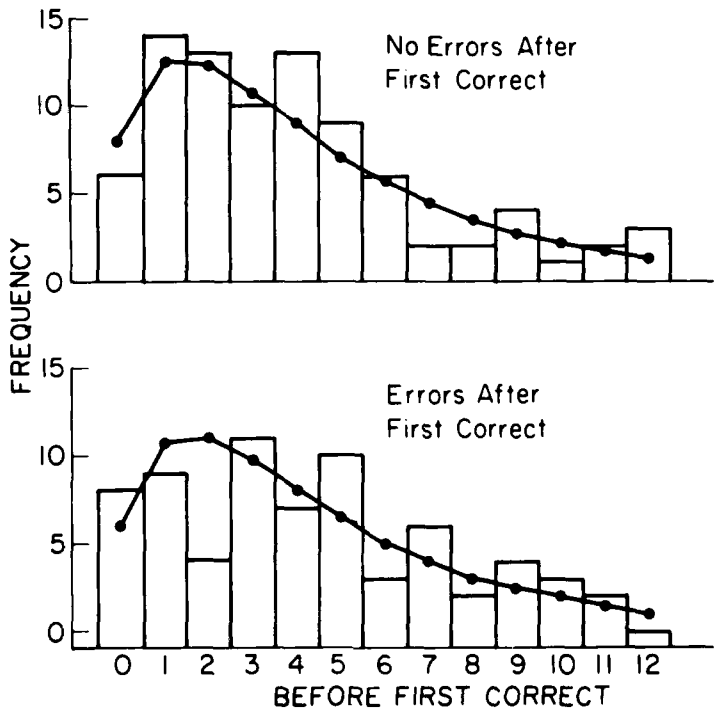

Fig. 3 Theoretical and empirical distributions of the number of errors before the first correct response. The upper panel shows frequencies of sequences with no errors after the first correct response, and the lower panel shows frequencies of sequences with one or more errors after the first correct response.

The upper panel has sequences with no errors after the first correct response. For example, a sequence that contributes to the fourth column in the upper panel would be 1 1 1 0 0 0 The lower panel has sequences with one or more errors after the first correct response. For example, a sequence contributing to the fourth column in the lower panel might be 1 1 1 0 0 1 0 1 0 0 0 ... The agreement in Fig. 3 is not as striking as in Figs. 1 and 2, partly because these distributions are based on fewer cases. But it is still satisfactory.

Figs. 4 and 5 show the distributions of errors and trials of the last error for all trials. In effect, these test the assumptions in the model about how the distributions in Figs. 1 and 2 combine with the distribution in Fig. 3. These empirical distributions were not smooth, but the theoretical curves seem to follow the main contours of the data fairly well.

The results shown from Group HE do not include the cases of greatest disagreement between data and theory, but they do not include the best cases either. In any event, the real question of the model's validity depends on the overall agreement between all the empirical distributions and all the predicted distributions. Because maximum likelihood estimates of the parameters were used, we know something about the distributions of goodness-of-fit chi square statistics. Let n be the number of cells in a frequency distribution, and let m be the number of parameters estimated from the data and used in calculating the theoretical distribution, then the asymptotic distribution of the chi square statistic is bounded by $\chi^2(n-1)$ and $\chi^2(n-m-1)$ (Chernoff and Lehman, 1954). For the four experimental groups, a total of 20 chi square tests were carried out. One of

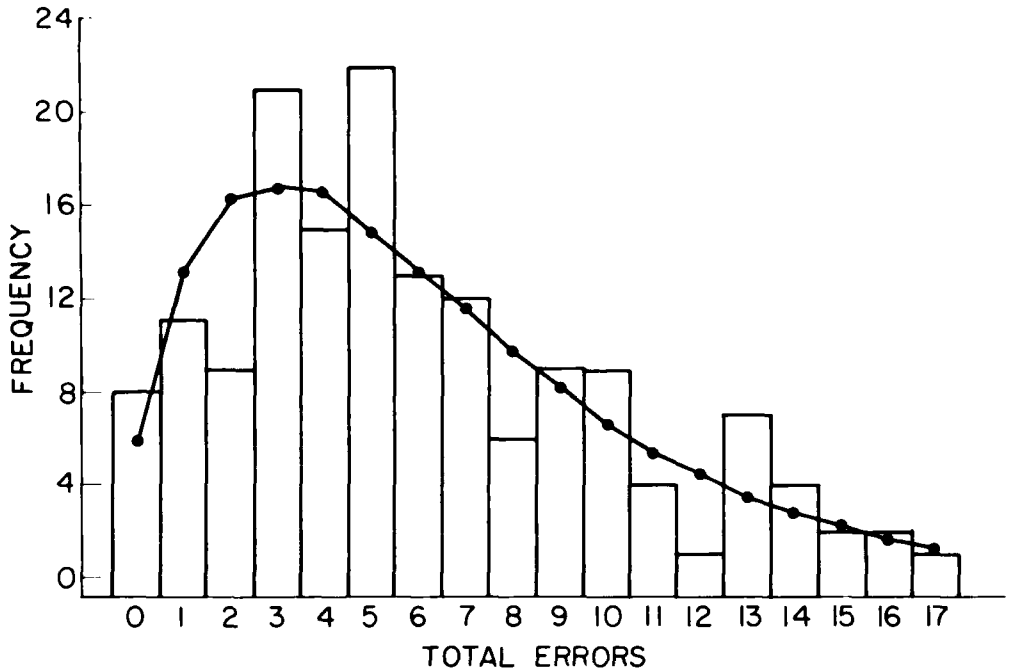

Fig. 4 Theoretical and empirical frequencies of the total number of errors.

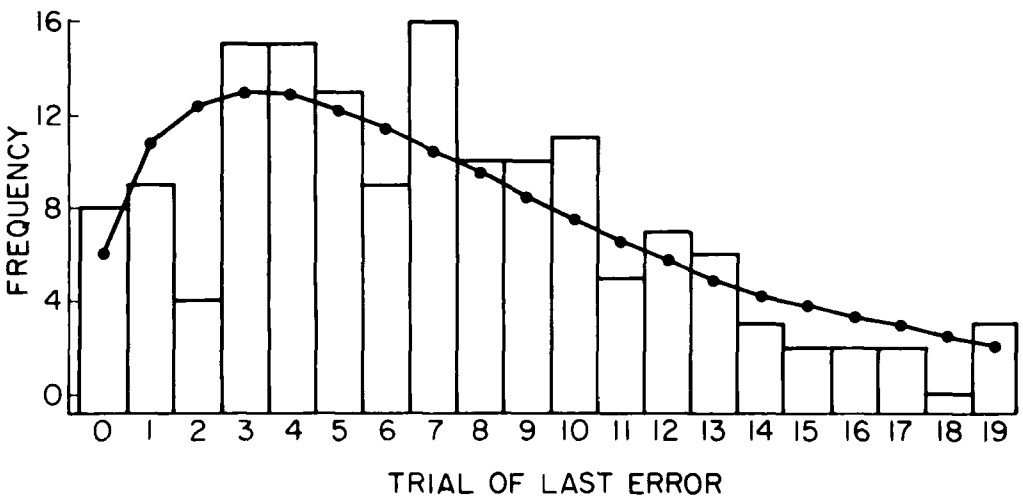

Fig. 5 Theoretical and empirical frequencies of the total number of trials before criterion.

them was significant at the .05 level using the upper bounds of degrees of freedom, and three were significant using the lower bounds. Statistically, then, the predictions of the model weem to agree to an acceptable approximation with the data. At least, we probably can have reasonable confidence that the parameter values and tests of hypotheses about parameters using the model will not be grossly misleading.

Now recall that the main target of the analysis is to obtain evidence for a choice between two theories of memorizing. One theory says that the first stage is response learning, and should be hard or easy depending on the responses that have to be learned. Another theory says that the first stage is storage of the stimulus-response item, and should depend on both the stimulus and response variable. If the response-hookup theory is correct, we should find that a can be held constant across groups with the same responses. But if the storage-retrieval learning theory is correct, then values of a probably should depend on stimulus as well as response variables. Table 4 has the results of testing the invariance of a across pairs of conditions, using likelihood ratio tests. For example, one null hypothesis is that a has the same value in groups EE and HE -- the two groups with easy responses. The test statistic was 5.97, which has probability .015 under the null hypothesis, indicating rejection of the null hypothesis. A similar result was obtained for the test of invariance of a across groups EH and HH -- the two groups with hard responses. The tests involving groups with the same stimuli are included for completeness--they permit rejection of the hypothesis of invariance even more strongly. Since the groups with the same responses cannot be

described with the same values of a , the results in Table 4 favor the storage-retrieval theory over the response-hookup learning theory

Table 4

Tests of Invariance of a

Conditions	$-2 \log \lambda$	p
EE vs HE	5.97	.015
EH vs HH	6.69	.010
EE vs EH	14.23	.0002
HE vs HH	16.23	.00006

The other test involves the prediction suggested by the storage-retrieval theory about b and d If the second stage of memorizing is learning to retrieve stored items, then b and d should depend on the stimulus variable, but not on the responses. But if the second stage of memorizing is formation of a stimulus-response connection, then the values of b and d probably should depend on both stimulus and response variables The result to be reported uses the data from all four groups In addition to testing invariance of b and d , we test the hypothesis that b and d were equal The theory is required to fit the data of all four groups with any value of a in each group, one value of b and d for groups EE and EH, and a different value of b and d for groups HE and HH The performance parameters p and e were allowed to vary freely The null hypothesis is that b and d were equal, and depended only on the stimulus

variable. The alternative hypothesis is that all the parameters including b and d differed among all four groups. The test has six degrees of freedom.

The result of the test is in Table 5. The value obtained for $-2 \log \lambda$ was 4.37, which has probability greater than .60 under the null hypothesis. What we found in the statistical analysis is that we can reject the hypothesis of equal values of a across groups with the same responses, but we cannot reject the hypothesis of equal values of b and d across groups with the same stimuli. This fits with expectations based on the storage-retrieval learning theory, and thus favors a choice of that theory over the theory of response strengthening and hookup learning.

Table 5

Parameter Estimates and $-2 \log \lambda$ Testing $b = d$, Depending Only on Stimulus Difficulty

Condition	a	b=d	p	1-e
EE	.29	.34	.46	.32
EH	.18	.34	.36	.62
HE	.21	.26	.40	.34
HH	.13	.26	.36	.90

Note -- $-2 \log \lambda = 4.37$, $p > .60$.

The results of Humphreys' experiment have been presented using the literary device of giving the hypotheses first and then the data. This was done for reasons of clarity, rather than historical accuracy. Actually,

Humphreys and I had expected to obtain a confirmation of Underwood's theory when we began the analysis, because we had not thought of any reasonable alternative to it. We developed the theory of storage and retrieval learning because the data seemed to disagree with Underwood's theory, at least in the simplified form that we were considering. When a new hypothesis is developed because of a complicated statistical result, it is wise to replicate the study. This was done at Indiana in an experiment carried out with the assistance of Herbert Marsh. We used the same design as Humphreys did, but different materials and procedures were used. The lists learned by the subjects are given in Table 6. Note that the lists were shorter (six instead of nine items), the stimuli were letters rather then numbers, and the responses were words rather than nonsense syllables. Whereas Humphreys' experiment was run using a memory drum with subjects speaking their responses, our replication was run in a computer-based laboratory with stimuli presented on crt displays and responses typed on keyboards. Table 7 shows summary data for the replication of Humphreys' experiment. Apparently the changes in materials and procedures did not eliminate the overall differences due to stimulus similarity and response difficulty, although the effect of response difficulty seems to have been smaller here than in Humphreys' data.

In testing simplifying assumptions of the general model, we found that the simplifications of Eq. 3 were acceptable only for groups EE and EH. The simplifications of Eq. 2 were acceptable for group HH, and nearly acceptable for group HE ($.025 < p < .05$); Eq. 2 was not acceptable for groups EE and EH. Rather then applying the model in its most general (and weakest)

Table 6

Lists Used in Replication of Humphreys' Experiment

EE	EH	HE	HH
P--Touch	P--Delft	FQ--Touch	FQ--Delft
V--Night	V--Blear	VF--Night	VF--Renal
F--Grain	F--Renal	VQ--Grain	VQ--Anode
C--Stand	C--Houri	QV--Stand	QV--Houri
L--Earth	L--Ingot	QF--Earth	QF--Ingot
S--Offer	S--Anode	FV--Offer	FV--Blear

Table 7

Summary Data for Replication of Humphreys' Experiment

Group	Mean Errors Before First Correct	Mean Errors After First Correct	Mean Trial of Last Error
EE	2.66	1.59	4.56
EH	3.93	1.16	5.84
HE	5.02	5.61	13.68
HH	6.19	4.83	13.97

form, we used the model with the restrictions that were acceptable in the various groups The model did not fit as well in this experiment as it did for Humphreys' data. Of 20 tests of goodness of fit, six could be rejected at the .05 level using upper bounds on degrees of freedom, and eight could

be rejected at .05 using the lower bounds. For many purposes, this amount of discrepancy would be unsatisfactory, but it probably is all right in this case since we were only concerned to see whether the pattern of results in Humphreys' study would appear again.

Table 8 gives the estimated parameter values for the four experimental groups. Since different simplifying restrictions applied in the different groups, the parameters are not comparable in simple ways. In order to obtain summaries that are comparable, the mean numbers of trials in each stage were calculated using Eq. 4. These figures are also given in Table 8. Note that the mean number of trials in the first stage seems to have been influenced by both the stimulus and response variables, as was true in Humphreys' data. In this study, however, the effect of the stimulus variable seems to have been somewhat stronger than the effect of the response variable. The number of trials required to complete the second stage seems to have been determined mainly by the stimulus variable, as was true in Humphreys' experiment. Thus, the main conclusions that were made on the basis of Humphreys' data seem to have been corroborated in our replication.

Table 8

Parameter Estimates and Theoretical Mean Numbers of Trials in Each Stage in Replication of Humphreys' Experiment

Group	a	b	d	e	q	r	s	t	$E(Z_1)$	$E(Z_2)$
EE	.11	.33*	.33	.73*	.73	.83	.06	.24	1.49	3.00
EH	.17	.30*	.30	.75*	.75	.85	.27	.14	2.55	3.34
HE	.26	.13	.14	.35	.68	.35*	.74*	.03*	3.90	9.75
HH	.13	.06	.17	.34	.69	.34*	.82*	.01*	5.51	8.51

*Note -- these parameters were determined by simplifying restrictions.

It should be remembered that the conclusion of the analysis may depend on accepting the validity of the measurements based on the Markov model, including the assumption of discrete stages. The analyses reported here were carried out using the only two-stage model for which statistical methods have been worked out. It is possible that use of other models might lead to different conclusions. However, if the present analysis is accepted, the conclusion based on these experiments with varying stimulus and response difficulty is that the first stage of paired-associate memorizing is affected by characteristics of both stimuli and responses, but the difficulty of the second stage seems to depend almost entirely on the stimuli. This supports the storage-retrieval theory, since it is consistent with the idea that subjects store the stimulus-response pair as a unit, and then have to develop strategies to retrieve the stored items from memory when they see the stimulus terms.

Analysis of Negative Transfer

The data to be presented in this section were obtained in experiments conducted by Carlton James where prior training produced negative transfer in paired-associate memorizing. The experiments involve comparisons between two conditions. One group learned two lists with the same responses but different stimuli. This is called the A-B, C-B paradigm, and will be referred to here as the C-B condition. The other group learned two lists with the same stimuli and responses, but each stimulus was paired with a different response in the second list than it was in the first list. This is called the A-B, A-B_r paradigm, and will be referred to here as the A-B_r condition.

In these studies, the storage-retrieval theory cannot be compared with

the response-hookup theory The reason is that in both the A-B_r and the C-B conditions, the responses used in the second list are the same as those used in the first list, so there should be no effect due to response strengthening However, the theory of association learning includes a different factor which should differ between the two conditions of these experiments In a theory that dates from Melton and Irwin's (1940) study of retroactive interference, negative transfer is explained by the effect of associations that are learned in the first list and must be unlearned before the new associations can dominate performance In an A-B_r condition, where the stimuli are the same as those learned in the first list, the effect of first-list associations should be quite strong and retard learning by a large amount In a C-B condition, new stimuli are used in the second list and the first-list associations should have a much smaller effect

We can construct a version of the unlearning theory that would fit with the two-stage Markov model Keep in mind that in these experiments the subject knows the responses from the beginning of training on the second list, since they are the same as those used earlier This means that any reasonable two-stage theory should assert that both stages of learning involve learning the associations in the second list Suppose that in State O, the association for a stimulus from List 1 is retained and dominates the subject's performance on that item The item goes from State O to either State E or State C when the first-list association is unlearned The transition to State L occurs when the second-list association is learned According to this conceptualization, the main difference between A-B_r and C-B conditions should be a difference in the difficulty in accomplishing the first, unlearning stage of the memorizing process

The storage-retrieval theory suggests a different expectation. The task given to an A-B_r group is to learn to use each stimulus from the first list to retrieve a response that is different from the one paired with it originally. In the C-B group, new stimulus cues are used. This leads to the expectation that the main difficulty in A-B_r, relative to C-B, should be in learning to retrieve the new pairs from memory, and the theory says that this occurs in the second stage of paired-associate learning.

Data were obtained from a variety of conditions. In one experiment each list contained ten pairs of two-syllable adjectives, with two groups (an A-B_r and a C-B group) learning the first list to a criterion of one perfect trial (No OT) and the other two groups learning the first list to the one-trial criterion and then receiving 15 additional trials of overtraining (OT). In another experiment, each list contained six pairs of two-syllable adjectives. There were eight groups in a 2 x 2 x 2 factorial design. One factor was the main variable--the difference between A-B_r and C-B conditions. A second factor was the presence or absence of a series of pretraining lists (PT or No PT) each with the same responses as those used in the last two lists but with different stimuli, and each studied for six trials. And the third factor was the presence or absence of 18 trials of overtraining on the next-to-last list following a criterion of one perfect trial (OT or No OT).

These experiments were carried out using a memory drum with the anticipation procedure. Stimuli were presented for 2 sec during which the subject tried to give the correct response. Then the response was shown along with the stimulus for 2 sec. There was a 4 sec pause between each cycle in which all the items were presented.

In all, there were 12 experimental groups for this analysis The simplifying assumption involving the initial vector of the model (Eq 2) was acceptable in all the groups Although other simplifications were acceptable in some groups, they were not used in testing goodness of fit or estimating the parameters of the model The same five tests for goodness of fit were used here as in the analyses described earlier With 12 groups, there were 60 tests Three tests were significant using upper bounds of the degrees of freedom, and 15 tests were significant using lower bounds Thus, the model seems to have fit these data reasonably well

The theoretical measures of difficulty for the first and second stages of learning are given in Table 9 The values of $E(Z_1)$ for comparable C-B and A-B_r groups seem to show small and inconsistent differences, except for the condition with ten items and overtraining However, the measures of difficulty in the second stage show large and consistent differences, with A-B_r having greater difficulty in the second stage in every case

Table 9

Theoretical Quantities for A-B_r and C-B Conditions

Condition	Mean Trials in First Stage		Mean Trials in Second Stage	
	C-B	A-B_r	C-B	A-B_r
Ten Items, No OT	3.94	4 54	2 76	4 12
Ten Items, OT	3 50	6 49	2 95	10 05
Six Items, No PT, No OT	2 99	2 58	1 28	5 08
Six Items, No PT, OT	2 58	3.19	2 70	4 35
Six Items, PT, No OT	1 87	1 74	1 55	3 80
Six Items, PT, OT	2 48	2 92	1 22	3 59

Statistical tests were carried out to compare the difficulty of learning in the A-B_r and C-B conditions, using separate likelihood ratio tests for the two stages. The results are in Table 10. Note that in every case, the difference in the second stage was significant, but the difference in the first stage was significant only in one of the six comparisons. These results seem to justify the conclusion that the main difference between learning A-B_r and C-B lists occurs in the second stage of memorizing.

The results of this analysis provide additional support for the hypothesis that paired-associate memorizing involves storage and learning to retrieve. The hypothesis of unlearning and replacement of associative connections leads us to expect most of the difference between A-B_r and C-B to occur in the first stage. However, in five of six conditions we failed to find a significant difference in the first stage. In the hypothesis of storage and retrieval learning, it is reasonable to expect the main difficulty in A-B_r to involve retrieval learning, and this expectation is consistent with the finding that most of the difference between A-B_r and C-B was in the second stage of learning.

Table 10

Tests of Invariance between A-B_r and C-B

Condition	First Stage	Second Stage	Both Stages
Ten Items, No OT	1.4	20.4***	21.4***
Ten Items, OT	29.8***	59.5***	88.1***
Six Items, No PT, No OT	1.1	19.7***	20.7***
Six Items, No PT, OT	1.6	9.4***	9.6***
Six Items, PT, No OT	0.1	16.3***	29.9***
Six Items, PT, OT	1.9	11.0***	32.2***

Note -- ***denotes $p < .01$.

Summary and Conclusion

I began this article by stating a theoretical question--whether associations are memorized by a process of forming connections between stimuli and responses or by a process of storing stimulus-response units and learning to retrieve then. The preceding two sections have presented evidence that the storage-retrieval theory is a more reasonable hypothesis about the memorizing process. The evidence consists of results obtained by measuring difficulty of two learning stages in various experimental conditions, using a Markov model with the assumption that learning occurs in two discrete stages.

First, it seems that the similarity among stimuli is quite a strong variable in determining the difficulty of the first stage of learning The difficulty of the first stage is also affected by response variables. Differences were obtained by varying the pronouncibility of trigram responses and by varying the frequency of use of word responses. The first stage of memorizing was not affected in one important case -- five of six comparisons between A-B_r and C-B negative transfer conditions failed to show a reliable difference in the first stage of learning.

The second stage of learning was strongly influenced in these experiments by the similarity among stimuli, and large differences in difficulty of the second stage were obtained in comparisons between A-B_r and A-C negative transfer conditions. These experiments have consistently failed to show effects on the second stage of memorizing due to response variables. Pronouncibility of trigrams and frequency of words both failed to produce reliable second stage differences in these data.

If the measurements presented here are accepted, the findings seem

very hard to explain using the theory of stimulus-response connections. Regarding the first stage of learning, sizable effects were found where the theory of connections predicts little or no effect, and effects were not found where the theory leads us to expect them. Specifically, the version of association theory that says the first stage is mainly a process of increasing response availability leads us to expect little or no effect of stimulus variables in the first stage. Yet, the stimulus variables manipulated in these studies influenced the first stage of learning significantly. On the other hand, the version of association theory that says old associations have to be unlearned before new associations can dominate performance leads us to expect a substantial first-stage difference between $A\text{-}B_r$ and C-B negative transfer conditions. But all except one of our experimental conditions failed to show this effect.

Regarding the second stage of learning, connection theorists often suggest (and sometimes state outright) that the formation of connections probably comes after other processes like response strengthening or unlearning have taken place. And the formation of connections is often treated as a relatively symmetrical process, which would be expected to be influenced about as much by response variables as by stimulus variables. However, in the data reported here the second stage of learning was affected almost exclusively by stimulus variables. Stimulus similarity had strong effects on the second stage of learning and the difference between $A\text{-}B_r$ and C-B conditions was mainly a second-stage effect. Response pronouncibility and frequency of word use failed to show significant effects.

On the other hand, the theory of storage and retrieval learning has

features that seem to be quite consistent with the pattern of results obtained in these studies. First, the fact that both stimulus and response variables affect the first stage of learning seems to support the idea that the first stage is just the storage of the stimulus-response pair as a unit. The fact that $A\text{-}B_r$ and C-B conditions usually did not differ in the first stage does not seem so surprising if the first stage is storage in memory -- after all, both groups of subjects had the same material to store. And the failure of response variables to have important effects on the second stage of learning seems consistent with the idea that the second stage is a process of learning to retrieve. The subject must learn to retrieve each item using the stimulus as a cue. Therefore, similarity among the stimuli and previous use of the stimuli to retrieve different pairs probably should make the process of learning to retrieve more difficult.

The main conclusion of this paper is that basic concepts in a theory of paired-associate memorizing should be storage and retrieval, rather than the concepts of traditional association theory. The present data are certainly insufficient to support a firm conclusion on a fundamental theoretical question. However, to the extent that a conclusion is supported, the conclusion seems to be that the theory of memory has no need for a concept describing a process of association in the sense of connection between mental elements. The processes of information storage and retrieval which seem most adequate for handling recall and recognition memory also seem to be favored for the theory of memory for associations.

Relationship with Other Theories

I have gone to considerable effort to emphasize differences between the storage-retrieval theory and the traditional theory of associative

connections. I want to conclude by pointing to some consistencies between the theory used here and others that have been developed recently.

Perhaps the clearest relationship exists between the present two-stage theory and the all-or-none model of memorizing (Bower, 1961; Estes, 1960; Rock, 1957). While the all-or-none hypothesis postulates a single discrete step in learning, the present analysis assumes two such steps. And the statistical machinery used in the present analyses is a direct extension of that used in the all-or-none analyses (especially by Bower, 1961).

The two-stage model of Eq. 1 can be viewed as a generalization of the all-or-none model. Suppose in Eq. 1 that b = 1. In the interpretation of this article, this would mean that once an item is stored in memory, it can be retrieved reliably enough to meet the experimental criterion of learning. On this interpretation, learning should be *approximately* all-or-none in cases where retrieval is easy. And this seems to fit with the facts. Typically, experiments showing all-or-none results use short lists of items and two or three response alternatives that were known by the subjects at the beginning of the experiment. The experimental task then is very close to a sorting task, where there are two or three categories and the subject must learn which category each stimulus belongs in. As the number of categories or the number of items in each category increases, retrieval should become more difficult, and we should expect data to depart from the all-or-none model. And data often seem to be consistent with this expectation.

A two-stage Markov model similar to Eq. 1 was analyzed by Bower and Theios (1964), and they demonstrated that the idea of two discrete learning steps was consistent with data from several experiments. These studies included experiments by Theios where subjects memorized associations and had to adjust to changes in the correct responses for individual items. Kintsch (1963) applied the two-stage model successfully to the results of a paired-associate experiment, but he interpreted the stages as response learning and association-forming, an interpretation that seems to be questionable in the light of results reported here. Another application by Kintsch and Morris (1965) involved recognition and free recall learning, but was consistent conceptually with the present argument. Kintsch and Morris' data supported the idea that when subjects memorize a list of words, the first stage of learning an item permits the subjects to recognize the item and the second stage permits him to recall the item. Storage and retrieval seem like acceptable alternative names for these two subprocesses.

Restle (1964) also proposed a two-stage Markov model as an extension of the all-or-none theory. Restle proposed a trace theory in which learning consisted of acquiring strategies enabling the subject to recall traces. In the first stage of learning, a subject becomes able to recall the response for an item, and in the second stage he discriminates that item from other items similar to it in the list. Restle's theory is like the present theory in that mnemonic records are assumed to represent experiences, rather than connections. And Restle's hypothesis about the second stage of learning as discrimination seems indistinguishable from the present view of learning to retrieve. Restle was not entirely clear about the nature of the first

stage of learning--he called it "learning to recall a response," but other aspects of his theory make it seem as though stimulus variables probably would influence the process.

The hypothesis presented here bears an interesting relationship to a recent theory by Martin (1968). In Martin's theory, a major factor in memorizing an association is variability in encoding the stimulus. An hypothesis consistent with Martin's view is that some trials may be required to establish a reliable association between some encoding of the stimulus and the response, and then some further trials may be required to stabilize the encoding. This interpretation of Martin's hypothesis is very similar to the hypothesis proposed in the present article. As nearly as I can tell, the evidence that is presented here does not differentiate between Martin's idea and mine, and the two ideas may be different expressions of the same hypothesis.

The present hypothesis of storage and learning to retrieve also closely resembles Feigenbaum's (1963) model of memorizing incorporated in the program EPAM, and Hintzman's (1968) extension of this work in the progran SAL. In EPAM and SAL the early phase of learning is called image building, and its effect is to store a partial representation of the stimulus and a representation of the response in memory. The later phase of learning permits the subject to discriminate among the stimuli in the list, and therefore to permit reliable retrieval. Thus, I see no important difference between the hypothesis offered here and Feigenbaum's and Hintzman's hypotheses for new learning. On the other hand, EPAM and SAL might lead to predictions about $A\text{-}B_r$ transfer that differ from the hypothesis about storage and retrieval that was developed based on James' experimental results

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13. ABSTRACT

It is observed that performance in tasks involving recall or recognition of items seems to be explained best with concepts of storage and retrieval, rather than formation of associative connections. Evidence is presented that this is also true of paired-associate memorizing, and it is proposed that the stages of memorizing are storage and learning to retrieve. Statistical methods are presented for obtaining measurements of difficulty in each of two stages of learning, using a Markov model. In experiments with varying response difficulty and stimulus similarity, the difficulty of the first stage depended on both stimuli and responses, but the second stage depended only on the stimuli. This favors the storage-retrieval theory over the hypothesis that the first stage is response learning and the second is hookup learning. In negative transfer experiments where responses in the transfer list were the same as in the first list, groups with new pairings with old stimuli (A-B) had more difficulty in the second stage of learning than groups with new stimuli (C-B) but in five of six conditions A-B and C-B groups did not differ in the first stage. This favors the storage-retrieval theory over the hypothesis that the first stage is unlearning of an interfering connection and the second stage is replacement with the new association.

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