developed a process model for a memory task. The subject is presented with a sequence of items followed by a test item and reports whether the test item was in the preceding list. On half the trials the test item will be equal to one of the items in the list; on the other half of the trials it will be a new item. The independent variable is the serial position of the old test item. McNabb and Massaro (1973) presented a list of 15 one-syllable words followed by a test word. The words were presented visually, employing a memory drum. Each word was exposed in the window of the memory drum at a rate of 1/sec. or 2/sec. Subjects were instructed either to repeat the words subvocally or vocally. All subjects were tested under both rates of presentation and both repetition conditions.

**Familiarity**

In this task, it is assumed that presentation of each item increases the familiarity of that item. When the subject is presented with the test item, he determines its familiarity and evaluates it against a criterion value of familiarity. If the familiarity of the test item exceeds the criterion value he responds “old”; if not, he responds “new.” Accordingly, the measure of performance corresponds to the difference in the means of the familiarity distributions for old and new items. Empirically, the difference between the means is determined from the recognition probabilities. The probability of responding “yes” given that the item was an old one in the preceding list—written \( P(\text{yes} | \text{old}) \)—is the hit rate and the probability of responding “yes” to a new item—written \( P(\text{yes} | \text{new}) \)—is the false alarm rate.

An old item can be defined with respect to serial position whereas a new item cannot. The experimenter will be able to compute a different hit rate at each serial position and the false alarm rate will be constant. We would, at first glance, expect the hit rate to be somewhat higher for items presented very early in the list. This primacy effect reflects the fact that the first items are perceived and learned better than later items. However, even though the first items have this advantage, they should be forgotten the most since they have the most intervening items between presentation and test. The critical independent variable is the number of intervening items between original presentation and test. Our quantification of this theory predicts that forgetting is a decreasing geometric function of the number of intervening items \( n \). If presentation of an item increases its familiarity to \( \alpha \) and presentation of each new item decreases the familiarity of earlier items to a proportion \( \phi \) of \( \alpha \), forgetting can be described by the equation

\[
d' = \alpha \phi^n
\] (3)
where $0 \leq \phi \leq 1$. The parameter of $\alpha$ indexes the amount of familiarity obtained during presentation and the parameter $\phi$ indexes the rate of forgetting caused by new items. Taking logarithms of Equation 3 gives

$$
\log d' = \log \alpha + n \log \phi
$$

Since $\phi$ must be less than 1 if forgetting occurs, $\log \phi$ will be negative. Accordingly, Equation 4 shows that each new item decreases the log of $d'$ by a fixed amount. Plotted, this gives a straight line on a log-linear graph of $d'$ as a function of $n$.

This model defines the basis for the theoretical analysis of the McNabb and Massaro (1973) study. The probe recognition task was carried out under two experimental conditions. In the covert repetition condition, the subjects repeated the words to themselves whereas in the overt repetition condition they repeated the words aloud. The overt repetition condition should have an advantage of synthesized auditory memory, whereas the covert repetition should not. When the subjects repeat the words aloud, they can remember

**FIGURE 4.** Memory performance measured by $d'$ values as a function of the number of intervening items for the overt and covert repetition conditions. The lines are predicted functions given by Equation 4 (after McNabb & Massaro, 1973).
not only the name of the word but, also, what the word sounded like when they repeated it. We are still interested in whether synthesized auditory memory will be constant across all serial positions or will be more prevalent at the later serial positions with few intervening items. The answer will be determined from the parameter estimates of $\alpha$ and $\phi$ in the two experimental conditions. If saying the word aloud gives the subject more information by adding the sound in SAM, $\alpha$ should be larger under the overt than under the covert conditions. If the information in SAM is interfered with by new items, more forgetting should occur in the overt than in the covert conditions.

The results obtained gave a higher parameter estimate for $\alpha$ in the overt than in the covert repetition condition, whereas the parameter value of $\phi$ did not differ in the two cases. The results in Figure 4 show that forgetting is described reasonably well by Equation 4 and that the best fitting lines are parallel, reflecting a constant rate of forgetting. The higher intercept in the overt condition shows the extra familiarity obtained by the overt repetition which places the sound of the item in SAM. These results indicate that the contribution of SAM does not necessarily have to be serial position specific, but could enhance recall of all of the items in the list.

**SPEECH PROCESSING**

In the memory-for-pitch task (see Chapter 24), the experimental situation was arranged so that subjects had to rely on the information in synthesized auditory memory to make their decision. If subjects are asked to determine whether two speech sounds are the same or different, however, two memory components can be used in their decision. Subjects could ask whether the two stimuli have the same name and/or whether the two stimuli have the same sound. In this case, information in both synthesized auditory storage (SAM) and generated abstract memory (GAM) would influence the same-different judgment.

In this section, we shall discuss the role these two memories play in tasks in which subjects are asked to either identify or compare speech sounds. Logically, a subject might forget the sound quality of a particular speech sound but still remember its name. If two stimuli have the same name but differ in sound quality, an observer can discriminate these as different as long as he maintains the relevant information in SAM. If this information is gone, he must rely on the information in GAM, which will give a high false alarm rate since the stimuli were, in fact, different although they have the same name.
SAM and GAM structures are relevant to the phenomenon of categorical perception in speech processing. Perception is said to be categorical if the subject can only make judgments about the name of a stimulus, not its particular sound quality. For example, the same speaker may repeat the same syllable a number of times. The acoustic patterns representing this syllable would differ from each other since he cannot repeat the same sound exactly. A listener who perceives the sounds categorically would not be able to discriminate any difference in the particular sound quality of each repetition of the syllable. The same listener, on the other hand, would be able to recognize a difference between any of these sounds and another syllable spoken by the same speaker. In categorical perception, the listener can recognize differences when the syllables have different names but not when they have the same name. Upon examination of the stimuli, we may find that the acoustic differences were as large when the same syllable was repeated as were the acoustic differences between two different syllables. In this case, we say that discrimination is limited by identification; the observer only discriminates that two sounds differ if he identifies them as having different names.

Subjects certainly were not limited in this way in the memory-for-pitch task. They were able to discriminate two tones as different even though they could not differentially label them. This is true for all sound dimensions: subjects can discriminate many more differences than they can identify successfully. This phenomenon, in fact, was one of the observations that convinced George Miller (1956) of the magical number 7 \pm 2. Miller observed that although we could make many discriminations along a unidimensional stimulus continuum, we can identify accurately about 7 \pm 2 of these stimuli. In this case, discrimination is not limited by identification, since subjects can discriminate differences along a stimulus continuum which they cannot identify absolutely.

How do we assess the relative roles of synthesized auditory and generated abstract memory in the discrimination of speech sounds? Going back to our hypothetical experiment in the penultimate paragraph, we could provide a set of stimuli by having a speaker repeat the syllables /ba/ and /da/ 3 times each (the vowel is pronounced /a/ as in hat). These sounds are recorded and used in our experiment. We must determine whether the subject's discrimination of every pair of sounds is limited by his identifying them as "different." Accordingly, we must determine how well he identifies the sounds and, also, how well he discriminates them.
In the first part of the experiment, we present one of the 6 stimuli on each trial and ask the observer to identify it as /ba/ or /da/. We obtain a number of repeated observations by selecting the stimuli randomly from trial to trial for a sequence of many trials. The dependent measure is the percentage of times each stimulus is identified as one of the two alternatives. After this identification task, we present pairs of the stimuli in a discrimination task. On each trial, we present one stimulus followed by a second one and ask the observer to report whether the stimuli were the same or different in sound quality. We warn the subjects to respond on the basis of how the sounds sound, not on the basis of their names. If they notice any difference whatsoever between the two sounds, they should respond “different” even if the sounds have the same name. Also, we tell the subjects that, on 50 percent of the trials, the two sounds will be different.

**Process Model**

Let us now define a process model of the two tasks in terms of our information-processing model. In the identification task, the speech stimulus initiates a preperceptual auditory storage of its sound. The primary recognition process involves a read-out of the acoustic features held there and produces a synthesized percept in synthesized auditory memory. The secondary recognition process, then, involves an analysis of the synthesized percept for its meaning, which would enter generated abstract memory. In this case, the sound quality information would be available in the synthesized percept, whereas the name information would be contained in generated abstract memory. The subject, then, would make his identification response on the basis of the name held in abstract memory.

In the same-different task, these same processes occur for each stimulus but now the subject must compare what he knows about the two sounds themselves. In this case, his memory for the sound quality of the first sound is critical, since this is what he must compare to the sound quality of the second in order to perform the task accurately. If the subject forgets the sound quality of the first sound and only remembers its name, and responds on this basis, he would show categorical perception. That is to say, he would respond “same” if he had given both sounds the same name; otherwise, he would respond “different.” In contrast, if the subject remembered the sound quality of the first sound exactly, he could discriminate it as being different from the sound quality of the second sound even though they both had the same name.

In the ba-da example, we simply recorded the sounds from natural speech and did not have specific control over the physical differences in the stimuli. Usually, in this kind of experiment, syn-
thesized speech sounds are used to control exactly the stimulus properties. Also, the stimuli differ from each other along an acoustic dimension or continuum that changes the sound gradually from one syllable into another, for example, from /ba/ to /da/. This experiment can also be carried out with nonspeech sounds, which provide a better example of how the experiment is carried out and how we can test for categorical perception.

Consider the following experiment with 7 auditory stimuli that differ along some continuum. We choose 7 pure tones from 880 to 1000 Hz. in 20-Hz. steps and randomly present one of these stimuli on each trial. The observer identifies it as either high or low. We record the percentage of times the subject responds high or low to each of the seven stimuli. The discrimination test then presents adjacent pairs of the stimuli in the same-different comparison task in which a standard stimulus is followed by a comparison stimulus. The instructions to the subject are to respond “different” if he notices any difference whatsoever in the sounds of the two stimuli. That is to say, if the two stimuli have the same name but have different sounds, the correct response is “different.” Of course, we shall include “same” trials on 50 percent of the trials to keep the subjects honest.

By comparing performance in the two tasks, we can determine to what extent the subject utilizes synthesized auditory memory in the task. If no synthesized auditory memory is employed, the subject's performance in the same-different task can be predicted exactly by his performance in the identification task. If discrimination performance is completely predicted by identification performance, then a subject should discriminate two different sounds as different only to the extent he identified them differently in the identification test. To derive the quantitative predictions, we first denote the successive stimuli used in the task as $S_1, S_2, \cdots, S_7$, respectively. The probability that the subject calls one of the stimuli “high” in the identification task is denoted $P(h|S_i)$ where $i = 1, 2, \cdots, 7$. Similarly, $P(l|S_i)$ is equal to the probability the subject called $S_i$ “low.”

Now we want to predict “same” and “different” responses in the discrimination task as a function of these probabilities. Consider the case of two adjacent stimuli, $S_1$ and $S_2$, used in the same-different task. There are three kinds of trial types: $S_1$ could be paired with itself; $S_2$ could be paired with itself; and $S_1$ could be paired with $S_2$. The probability that the subject responds “same” or “different”
on each of these trial types can be predicted from the observed probabilities, \( P(h|S_2) \) and \( P(h|S_3) \), in the identification task. The probability that the subject responds "same"—\( P(\text{same}) \)—is the probability the subject identified the standard and comparison with the same name. This could occur in two ways; he could call both the standard and comparison high or both of them low, so that

\[
P(\text{same}) = P(h|\text{standard}) P(h|\text{comparison}) \\
+ P(l|\text{standard}) P(l|\text{comparison})
\]  

(5)

The above equation states that the subject responds same if he gives both stimuli the same name. This occurs in two independent ways: he calls them both high or both low. The probability that he says "different" is the probability that he gives them different names.

\[
P(\text{different}) = P(h|\text{standard}) P(l|\text{comparison}) \\
+ P(l|\text{standard}) P(h|\text{comparison})
\]  

(6)

According to the two above equations, \( P(\text{same}) + P(\text{different}) = 1 \), as it should, since the subject makes one of these responses on every trial and there are only these 4 possible events that can occur on any trial.

Consider the case in which \( S_1 \) is followed by itself in the same-different task. The probability that the subject responds "same" given that the standard is equal to the comparison, \( P(\text{same}|S = C) \), can be derived from Equation 5 by substituting the appropriate values:

\[
P(\text{same}|S_1 = S_1) = P(h|S_1) P(h|S_1) \\
+ P(l|S_1) P(l|S_1)
\]  

(7)

Analogously,

\[
P(\text{same}|S_2 = S_2) = P(h|S_2) P(h|S_2) \\
+ P(l|S_2) P(l|S_2)
\]  

(8)

The probability that the subject calls \( S_1 \) and \( S_2 \) "different" when one follows the other in the same-different task is equal to

\[
P(\text{different}|S_1 \neq S_2) = P(h|S_1) P(l|S_2) \\
+ P(l|S_1) P(h|S_2)
\]  

(9)

These equations, therefore, predict performance in the same-different task as a function of performance in the identification
task, assuming that categorical perception occurs. It should be worthwhile to work out a concrete example utilizing the above predictions. Assume that the subject called $S_1$ and $S_2$ "high" 10 percent and 30 percent, respectively, in the identification test. If discrimination performance were predicted by identification performance, Equations 7, 8, and 9 would give

$$P(\text{same}|S_1 = S_1) = .1^2 + .9^2 = .01 + .81 = 82\%$$  \hspace{1cm} (10)

$$P(\text{same}|S_2 = S_2) = .3^2 + .7^2 = .09 + .49 = 58\%$$ \hspace{1cm} (11)

$$P(\text{different}|S_1 \neq S_2) = (.1)(.7) + (.9)(.3)$$
$$= .07 + .27 = 34\%$$ \hspace{1cm} (12)

In the discrimination task, “same” trials would be presented 50 percent of the time. If we carry out a discrimination experiment with $S_1$ and $S_2$, the predicted percentage correct, $P(C)$, in the task would be the weighted average of the percentage correct for each of the three trial types.

$$P(C) = .25(.82) + .25(.58) + .5(.34)$$
$$= .205 + .145 + .17$$
$$= 52\%$$ \hspace{1cm} (13)

If the subject consistently called both $S_1$ and $S_2$ high, predicted performance should be at chance (50 percent correct). Equations 7, 8, and 9 predict that performance should be at 100 percent, 100 percent, and 0 percent correct for the three conditions, respectively. Averaging these conditions (as we did in Equation 13) gives 50 percent, which is at chance in this task. If the subject consistently identified $S_1$ and $S_2$ differently, the equations predict that $P(C) = 100\%$.

The above predictions give performance levels when discrimination performance is limited by identification performance. In contrast, if subjects were not limited to the use of the names of the stimuli, but could reliably employ the information in synthesized auditory memory, we would expect $P(\text{different}|S_1 \neq S_2)$ to be well above that predicted by these equations. That is to say, even though subjects gave stimuli $S_1$ and $S_2$ the same name, they might discriminate the sounds as different and respond “different.”

A number of early studies have shown that some speech sounds appear to be perceived categorically. Eimas (1963) used a speech synthesizer to make 13 sounds that ranged from /ba/ to /da/ to

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Experimental Studies

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FIGURE 5. Spectrograms of the stimuli /ba/, /da/, and /ga/, with /a/ pronounced as in hat. (Note that the stimuli differ only with respect to the transition of the second formant (F₂), since the first (F₁) and third (F₃) formants are the same.) (After Eimas, 1962.) Eimas (1963) made 10 other stimuli by varying the beginning point of the second formant in equal steps within the /ba/, /da/, /ga/ range. This gave a total of 13 stimuli used in the experiment.

/ga/ with the vowel /a/ pronounced as in hat. Figure 5 shows 3 of the sounds which are always heard as /ba/, /da/, and /ga/, respectively. The figure shows that the starting point of the second formant (F₂) transition is the only acoustic difference between the 3 sounds. Therefore, it was possible to make a sound between /ba/ and /da/ by simply starting the F₂ transition at a point somewhere between the starting points of F₂ for these stimuli. Eimas, in fact, divided the range between the F₂ starting points of /ba/ and /ga/ into 11 equal steps, giving him 13 stimuli that differed only with respect to the starting frequency of the second formant. Observers first identified the stimuli as /b/, /d/, or /g/; they were then asked to discriminate them.

In Eimas' study, the subjects always heard the syllables in triads. Subjects were instructed to listen to a complete trial before making their three identification responses. For discrimination,
Eimas employed an ABX task rather than a same-different comparison task. In the ABX task, subjects are presented with a sequence of three sounds, A, B, and X, and are asked to state whether the last sound, X, is equal to sound A or to sound B. Unfortunately, the ABX paradigm may encourage the verbal encoding of the stimuli A and B since it would be very difficult to remember their auditory sound quality. Studies in the previous chapter demonstrated how a second sound interferes with the synthesized auditory memory of a previous sound. This interference is directly related to the similarity between the two sounds. In the ABX task, the B stimulus should interfere with the auditory memory of the A stimulus, leaving only its name in GAM.

Eimas' results indicated that subjects' performance in the ABX discrimination task was limited by identification. This result was not entirely due to the ABX procedure, however, because in the same kind of experiment Fry, Abramson, Eimas, & Liberman (1962) and Pisoni (1971) showed that synthetic vowels were not perceived categorically. The spectrograms of the vowels heard as /i/ as in heat, /I/ as in hit, and /e/ as in met are shown in Figure 6. Pisoni (1971) showed that subjects could discriminate differences in vowel stimuli much better than was predicted by identification performance. Accordingly, these subjects showed that vowels can be held in synthesized auditory memory and that this information can improve performance in the ABX task. Pisoni's results indicate that even though the ABX procedure may encourage verbal encoding, some synthesized memory may be used in this task. The findings seem to imply that vowels can be maintained better in synthesized auditory memory than can stop consonants.

Pisoni (1973), in a same-different comparison task, has essentially replicated the differences between consonants and vowels found by Eimas and by Fry et al. For both vowels and consonants, discrimination performance with sounds that had been given different names was better than performance with sounds that had been identified as the same. However, the differences were larger for the stop consonants than for the vowels. Pisoni also employed durations of 200 and 50 msec. for the vowel stimuli. The short vowels behaved more like consonants in that discrimination functions were more accurately predicted by the identification performance. This result is reasonable, assuming that a short vowel places less information in synthesized auditory memory than a long vowel.

Why do vowels have a better representation in synthesized auditory memory than stop consonants in CV syllables? As shown
in Figure 5, stop consonants are characterized by rapid transitions of the formants toward the steady-state vowel formants. The auditory pattern of the transition would seem to be more difficult to maintain in synthesized auditory memory than the steady-state pattern of the vowel. Note also that, whereas in Figure 5 the first and third formants do not differ for the different stop consonants, in Figure 6 all three formants differ for steady-state vowels. Steady-state vowels are more pitchlike and it is easier to maintain that sound quality than the rapid transition sound of the stop consonant.

**SAM for Consonants** Can within-category discriminations be made with stop consonants at all? Although synthesized auditory memory is limited for stop consonants, can it be employed at some level to facilitate discrimination over that predicted by identification? Two recent demonstrations have shown that subjects can discriminate the auditory differences between stop consonants that are given the same name in identification.
Categorical perception means that if subjects give different stimuli the same label, they cannot discriminate differences among these stimuli. To test this, Barclay (1970) first had subjects identify stimuli along the /ba/, /da/, and /ga/ continuum, with the vowel /a/ pronounced as in hat. As in previous experiments, subjects were given the alternatives /ba/, /da/, and /ga/. The subjects consistently labeled 3 sets of the stimuli as /ba/, /da/, and /ga/, respectively. The next day, the subjects were brought back, were given a description of the stimuli, and were told that the /da/ stimuli lay between /ba/ and /ga/. The subjects were then given another identification test with the same stimuli, but were limited to the alternatives /ba/ and /ga/. If perception of /da/ were indeed categorical, the subjects should not have been able to respond differentially to the stimuli called /da/ on the previous day. We would, therefore, expect a random assignment of the responses /ba/ and /ga/ to the /da/ stimuli. However, the results indicated that the subjects did differentiate between the different /da/ stimuli. The /da/ stimuli near the /ga/ boundary were more frequently called /ga/, and the identification response, /ba/, increased reliably as the /da/ stimuli approached the /ba/ end of the stimulus continuum.

Pisoni and Lazarus (1974) showed that special training and a sensitive discrimination test can eliminate the categorical perception of stop consonants found in ABX tasks after the regular identification task. The special training involved presenting the stimuli in sequential order across the continuum and instructing subjects to listen carefully to the differences between the successive stimuli. The discrimination test involved presentation of two pairs of stimuli; one pair was always the same and one pair was always different. Subjects reported which of the two pairs was the same. These subjects, then, were trained to utilize information in synthesized auditory memory and were given a discrimination test that made it easy to do so. The subjects given the special training showed improved discrimination performance and no categorical perception. Discriminating between sounds that are usually given different names was not significantly better than discriminating between sounds that are usually given the same name.

The foregoing studies demonstrate synthesized auditory memory for the sound quality of speech sounds. Evidence also exists that demonstrates we can preserve a memory for the characteristics of the speaker's voice. Cole, Coltheart, and Allard (1974) presented subjects with a sequence of two letters and had them report as
quickly as possible whether or not the second letter had the same name as the first. The independent variable of interest was whether the two letters were presented by same or different speakers. Since subjects would almost always be correct in this task, the reaction time (RT) of the “same” or “different” response to the second letter was the dependent variable. Certainly this task could be performed utilizing the information in abstract memory, which would simply involve a comparison of the names of the letters. In this case, it should not matter whether the letters are spoken in same or different voices. But if the sound quality of the first letter can be preserved in synthesized auditory memory, it might enhance the original recognition of the second letter and/or facilitate the comparison process.

The results indicated that subjects could respond faster on both “same” and “different” name trials when the letters were in the same voice than when spoken by different voices. Also this advantage was independent of the duration of silence separating the two letters (½ to 8 sec.). Unfortunately, these results do not locate the effect at the recognition or comparison stage of processing. It should be worthwhile to analyze a simple stage model of this task.

**FIGURE 7.** A flow diagram of the stimulus events and the processing stages in the same-different RT task.

<table>
<thead>
<tr>
<th>Stimulus Events</th>
<th>Psychological Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>present first letter (A)</td>
<td>recognize and encode letter (A)</td>
</tr>
<tr>
<td>wait interval (t_j)</td>
<td>wait</td>
</tr>
<tr>
<td>present second letter (B)</td>
<td>recognize and encode letter (B)</td>
</tr>
<tr>
<td>RT</td>
<td>compare two letters (A) and (B)</td>
</tr>
<tr>
<td>response</td>
<td>output response</td>
</tr>
</tbody>
</table>
and to ask what results would isolate the facilitating effect of speaking the two letters in the same voice. Figure 7 presents a flow diagram of the stimulus events and the processing stages in the task.

The time needed to perform the three processes of recognition, comparison, and response selection contributes to the RT to the second letter. Which stage of processing is responsible for the facilitating effect of speaking the second letter in the same voice? We can be fairly sure of eliminating the response selection stage as a causal factor (see Chapters 3 and 4). The answer is known before response selection is begun and the voice of the speaker should have no effect on this process. However, the facilitation could occur at either or both the recognition and comparison stages. If facilitation occurred at recognition, this would mean that subjects can synthesize what a speaker says, remember the characteristics of the speaker's voice in synthesized form, and use this information to enhance decoding of a second signal. This interpretation agrees with the observations of Ladefoged and Broadbent (1957) that a listener’s perception of a particular speech sound is influenced by the voice characteristics of the earlier speech input.

Facilitation could also occur at comparison if the subject utilized the sound characteristics when he compared the two letters after recognition of the second letter was completed. In this case, having the letters in the same voice would facilitate their comparison. To isolate this effect would certainly be important because it would also provide substantial information about the comparison stage of processing (discussed in Chapters 3 and 4). In point of fact, the methodology studied there is the key to isolating which process is critical in the task. The additive-factor method can be used to test whether voice quality affects the recognition or comparison stage. The experimental paradigm used is the memory search task in which subjects are presented with a test list of items followed by a probe item. The subjects respond “yes” or “no” as quickly as possible, indicating whether the probe item was in the previous list.

The significant result in this memory search paradigm is the linear increase in RT with increases in the number of items in the test list (see Chapter 4). The slope of the function provides an index of the time for the memory search and comparison of each letter. The time needed to recognize the probe item is independent of search and comparison time and contributes to the intercept value. To set up a definitive experiment would involve replicating the memory-search task with letters, while simultaneously varying the identity of the voice presenting the probe letter.
FIGURE 8. Three possible results when the number of test letters is co-varied with the identity of the voice of the probe letter. Panels A, B, and C indicate that sound quality affects recognition, comparison or both of these psychological processes, respectively.
Accordingly, we covary two independent variables: the number of letters in the test list and whether the probe is in the same or different voice as the test list. Sternberg’s classical finding is that RT increases linearly with increases in the number of items in the test list. How will the effect of same or different voice combine with this effect? The RT in the task can be described as a sum of three components: the time for recognition ($t_r$), search and comparison ($t_s$), and response selection ($t_{rs}$):

$$RT = t_r + Kt_v + t_{rs}$$  \hspace{1cm} (14)

where $K$ is the number of items in the test list. The components $t_s$ and $t_{rs}$ contribute to the intercept, and the size of $t_s$ determines the slope. Given this model, there are three possible results, each of which would be informative (see Figure 8). If having the letters in the same voice only facilitates recognition of the probe letter, the two curves will differ in intercept, but not in slope (Panel A). If the sound quality is only critical at the comparison stage, the slope of the function will be steeper for a probe letter in a different voice than in the same voice with no intercept effect (Panel B). Both slope and intercept will change if voice quality affects both the recognition and comparison stages of information processing (Panel C). This study remains to be carried out.

We have shown that information held in synthesized auditory memory can facilitate information processing in a number of experimental tasks. Bryden (1971) has presented some evidence for our central assumption of the relative independence of synthesized auditory memory (SAM) and generated abstract memory (GAM). Subjects were instructed to attend to one ear during a dichotic presentation of numbers. Subjects listened to 4 digits coming in on one ear while simultaneously 4 digits were being presented to the other ear. The pairs of numbers were presented at a rate of 2 pairs/sec. One group of observers was required to recall the items on the attended channel first and the items on the unattended channel second. Another group of observers recalled the items in reverse order.

Overall, performance was much better for recall of the attended than the unattended digits. Figure 9 shows that the serial position curves also differed for the two kinds of items. The unattended items showed a significant amount of forgetting as new items were presented during the list presentation, whereas the attended digits did not. The basic differences between the level of

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FIGURE 9. Percentage of items recalled at each serial position for the attended and unattended lists as a function of whether the list was recalled first or second. Data from those trials on which subjects reported that they followed the attention instructions (after Bryden, 1971).

performance and the serial position curves show that the unattended digits were stored differently than the attended digits. It seems likely that the names of the attended digits were transferred from synthesized auditory memory into generated abstract memory, whereas the names of the unattended digits were not. Therefore, subjects could recall the names of the attended digits directly from GAM, whereas they had to transfer the sound of the unattended items in SAM to names in GAM before they could be recalled.

Independent Memory Structures Given that the attended and unattended items were assumed to be in GAM and SAM, respectively, at the time of recall, the forgetting functions might be used to determine the respective capacities of SAM and GAM. The rapid forgetting of the unattended items sup-
posedly held in SAM shows that its capacity is under 4 items. In contrast, no forgetting was found for the attended items, supporting the idea that GAM can hold at least 4 items. Bryden’s results, therefore, reveal very nicely the differences between SAM and GAM.

It should also take more processing capacity to recall the items from SAM than from GAM. One way to measure the amount of processing capacity that is used for recall is to compare performance as a function of whether the items are recalled first or second. To the extent that recall of some items interferes with recall of the others, we can assume that recall requires processing capacity. Accordingly, we would expect the act of reporting the unattended items from SAM to interfere more with the attended items held in GAM than recall of the attended items in GAM should interfere with the unattended items held in synthesized auditory memory. Indeed, Figure 9 shows that when the unattended items were reported first, recall of the attended items was interfered with, whereas no interference was observed with recall of the unattended items when they were recalled after the attended items. These results support the idea that SAM and GAM are two relatively independent memory structures that hold information at two different levels. In agreement with the earlier results discussed in this chapter, information in SAM can supplement the limited capacity of GAM. Such storage is extremely helpful in the processing of auditory speech sounds, since the sounds arrive sequentially; they must be held in some storage until a sufficient number of sounds come in so that meaning can be derived and placed in GAM.
Synthesized visual memory

Color memory
delayed comparison task
Letter memory
  Peterson and Peterson task
  auditory vs. visual presentation
  shadowing
  phonemic similarity
Retention of visual codes
  letter matching
  interference with SVM
Faces and names
Picture memory
Independence of SVM and GAM
Preperceptual and synthesized auditory storage have their analogous counterparts in visual information processing. Preperceptual visual images have been demonstrated in recognition masking tasks by a number of investigators (see Chapters 17 and 18). Synthesized visual memory (SVM) is memory for the visual properties or dimensions of the visual stimulus read out of preperceptual storage. This is the memory that is responsible for recognizing a familiar face or visual scene that one may not have seen for years. Although many obvious examples of synthesized visual memory exist, relatively few demonstrations have taken place in the experimental laboratory.

Color memory is critically dependent upon SVM. We have some memory for the color spectrum and have (arbitrarily) defined category names for groups of colors. We have also denoted the categories to agree with those of our neighbors so that it is possible to communicate verbally about color. Even someone who is color-blind has learned that a particular shade of gray is called green when it is the color of a lawn.

Early studies of SVM for color usually employed the psychophysical method of adjustment (Burnham & Clark, 1955). In this task, the subject is given a color to memorize and then sometime later must find that color among a number of stimulus alternatives. The subject must look at a number of colors before he finds the color he thinks is correct. Accordingly, although the experimenter can systematically vary the time and events before the subject is tested, he has no control over the duration of the actual forgetting interval or the number of colors perceived and processed before the subject makes his choice. Since both time and items have been
found to be important in synthesized auditory memory for pitch (see Chapter 24), we might expect that they will also contribute to forgetting of color information. Furthermore, the measures of memory performance can be influenced by decision factors (for example, response biases) of the subject, which cannot be partitioned out in the method of adjustment task. Therefore, the early results are not adequate to measure memory for color given that the studies did not control these important variables.

**Delayed Comparison Task**

It is necessary to study color memory in a task that allows the experimenter to isolate perception, memory, and decision factors so that the forgetting of color can be accurately described. The author (unpublished) studied recognition memory for hue in a delayed comparison task. The procedure and data analysis were exactly analogous to the experiments of memory for pitch discussed in Chapter 24. The procedure, theoretical model, and data analysis discussed there can be used to work out an analogous methodology for the hue memory task.

In one experiment, a standard color was presented for .5 sec. followed by a gray color for 0, .5, or 2 sec., followed by a comparison color presented for .5 sec. The standard and comparison colors were blue-greens that differed very little in wavelength. The stimuli were Munsell color patches that are precisely specified with respect to the three visual stimulus dimensions. The value or chroma of a stimulus corresponds to its brightness, that is how much light it reflects. The saturation or purity of a stimulus provides an index of how much of the color is made up of a given wavelength and how much is contributed by white light. Light at a single wavelength is fully saturated, whereas white light has zero saturation. Finally, hue corresponds to what is usually called color and is determined by the wavelengths of the light.

As in the memory-for-pitch studies, the standard and comparison colors were very similar and could not be differentially labeled. The subject had to remember what the color looked like, not its name, on every trial. Furthermore, the standard color was randomly selected from a population of colors on every trial to prevent the subject from learning what a given standard looked like over a series of trials. These precautions insure that the experimenter is studying the storage and retention of the color that is presented on each trial.

If the subject forgot a fixed proportion of what he remembered about the standard color in each unit of time, we should be able to describe the results by our geometric forgetting equation (see Chapter 24). Plotting the $d'$ values as a function of time on semi-
logarithmic graph paper, the geometric equation describes a straight line. Figure 1 presents the results of the performance of three practiced observers in this task on such a log-linear graph. Geometrical forgetting was indicated for two of the subjects since their results are described fairly well by straight lines.

**FIGURE 1.** Memory performance for three subjects as measured by $d'$ values as a function of the duration of the forgetting interval (after Massaro, unpublished).

![](image)

The third subject's results cannot be described accurately by a straight line. The subject appears to have forgotten much more than she should have between 0 and .5 sec., than between .5 and 2 sec., if forgetting was geometric. Hopefully, the present procedure and experiment will stimulate researchers to study memory for color, given how little we can currently say about this common function.

We have assumed that SVM is a memory structure that holds information about how things look as opposed to what they sound like or their names. Analogous to SAM, SVM has a limited capacity and information in SVM can be interfered with by requiring the observer to process new information. If interference describes the forgetting in SVM, then similarity should play a role in the amount
of forgetting that occurs. We would expect that visual stimuli should interfere more than auditory stimuli with items held in SVM.

**Peterson and Peterson Task**

Two experiments have shown that letters held in SVM can decrease the interference usually found from subsequent auditory information processing. Scarborough (1972b) presented observers with a list of letters to remember in a Peterson and Peterson (1959) memory task. In this task, subjects are presented with a list of test items and are required to count aloud, backward by 3's, during the forgetting interval. They are then asked to recall the test items. The independent variable is the duration of the forgetting interval. This paradigm produces a very significant amount of forgetting in just the first 10 or 20 sec.

Scarborough presented the test letters auditorily or visually, or in both modalities simultaneously. On each trial, the subject would either see a visual display of 3 consonant letters, hear the letters transmitted over headphones, or see and hear the letters simultaneously. The presentation of the 3 consonant letters was followed after 1 sec by an auditory 3-digit number. The subject repeated the number aloud and began counting backward by 3's from that number, in time to the clicks from a metronome occurring at a rate of 1 per sec. At the end of the forgetting interval, the subject was cued to stop counting and to recall the original trigram presentation. Figure 2 presents the probability of correctly reporting the letters as a function of the duration of the interpolated counting task and the three presentation conditions.

**Auditory vs. Visual Presentation**

There are two psychological processes operating in the Peterson and Peterson task. The consonant letters must have been perceived and stored upon presentation and then remembered during the counting-backward task. Since Scarborough systematically varied the duration of the counting interval, it is possible to locate the differences between auditory and visual presentation at either or both the storage and retention stages. The figure shows that the curves intercept the Y ordinate at roughly the same point and then diverge significantly. The intercept value at zero sec. provides a measure of the original perception and storage of the stimuli, since it measures how much information the subject has immediately after the presentation of the stimuli, when no forgetting has taken place. The rate of forgetting can be determined from the slopes of the forgetting functions. According to this analysis, Figure 2 shows that the items presented auditorily are forgotten much faster than
the items presented visually. Furthermore, adding an auditory presentation to a visual one does not facilitate performance in this task. These results indicate that the items presented visually were stored differently than those presented auditorily. A good hypothesis is that the visual items were held in SVM, which would be less susceptible to interference from counting aloud than the auditory items, which would have to be held in either or both synthesized auditory (SAM) or generated abstract memory (GAM).
Another recent series of experiments also has isolated a visual storage mechanism with the properties of SVM (Kroll, Parks, Parkinson, Bieber, & Johnson, 1970; Parkinson, Parks, & Kroll, 1971; Salzberg, Parks, Kroll, & Parkinson, 1971). This memory appears to be relatively independent of SAM and GAM and is not as susceptible to interference from auditory verbal processing. The subjects in the task heard a list of letters presented in a female voice at a rate of 2/sec. The subjects were required to shadow, that is, to repeat back each letter as it occurred. Sometime during the list presentation, a test letter was inserted in the list. Besides shadowing, the subjects were also required to remember the test letter. The test letter was presented in a male voice for auditory presentations and on a photographic slide for visual presentations.

Auditory shadowing interfered more with memory for auditory presentations of the test letter than for visual presentations of the test letter. This result implies that the visual and auditory presentations of the test letter were stored in different memories, which are differentially sensitive to auditory shadowing. It appears that the visual presentation of the test letter was held in a visual form for memory which was relatively unaffected by auditory letters that had to be repeated aloud. It would be interesting to see whether subjects, trained to visually imagine the shape of auditory test letters, would show less forgetting during auditory shadowing. The experiments discussed later imply that this manipulation would be successful in the auditory shadowing task.

The investigators cited above also varied the phonemic similarity between the test letter and the letters that are shadowed during the forgetting interval. Usually two letters are defined as phonemically similar if their pronunciations share a vowel sound in common. Table 1 presents the 26 letters grouped according to their phonemic similarity.

<p>| TABLE 1 |</p>
<table>
<thead>
<tr>
<th>Letters of The Alphabet Grouped According to Their Phonemic Similarity. (Two Consonants are Phonemically Similar If They Share a Vowel Phoneme in Common)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A B C D E F G H I J K L M N O P Q U V W</td>
</tr>
</tbody>
</table>

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similarity. The results indicated that shadowing phonemically similar letters produced more interference than shadowing dissimilar letters, but only if the test letter was presented auditorily. This finding supports the hypothesis that the items presented visually were held in SVM, since we would not expect this memory to be susceptible to acoustic similarity. It remains to be seen whether the visual similarity of the letters would be a critical variable affecting storage of letter information in SVM.

Posner and his colleagues (Posner, Boies, Eichelman, & Taylor, 1969; Posner & Keele, 1967) have studied the contributions of visual codes held in SVM, using a same-different reaction time (RT) task. In this task, subjects are presented with a sequence of two letters and asked to report whether the second letter has the same name as the first. The independent variables are the temporal interval separating the two letters, and whether the second letter is physically identical to the first letter or simply has the same name. Of course, the letters have different names on half of the trials in order to keep the subject honest. The dependent variable is the time it takes the subject to make the same-different judgment.

In one experiment (Posner & Keele, 1967), a capital letter was followed by (1) a letter which had the same name but was either capital or small, or (2) a letter with a different name. The experimenters (1967) reasoned that a comparison between the RTs on the two kinds of "same" trials would provide an index of the memory code utilized by the subject. If the memory codes were identical on both kinds of "same" trials, there should be no difference in the RTs. If the memory codes were different, then the time to make the "same" judgment could differ in the two cases. Therefore, Posner and Keele looked at the RT differences between the two kinds of "same" trials. When the second letter followed the first immediately, "same" RTs were 80 msec. faster if both letters were capitals, than if a capital letter was followed by a small one. This advantage decreased with increases in the interstimulus interval. With a 1.5 sec. interval, the "same" RTs did not differ on the two kinds of trials. In another study, Posner et al. (1969) showed that the advantage of having both letters physically identical was not peculiar to matching capital letters, since small-letter physical matches facilitated "same" RTs in the same way.

These results show that presenting two letters that are both capitals or both small can facilitate the time it takes observers to
determine whether the letters have the same name. This means that the observers could have utilized the visual code of the letter held in SVM in order to facilitate their comparison task. Since this advantage disappears very quickly with increases in the interletter interval, subjects probably make their comparison on a strictly name basis at longer interletter intervals. If the second letter has the same upper or lower case as the first, does it also facilitate comparison on “different” trials? Recall that in the Cole et al. study discussed in Chapter 25, having a second letter in the same voice facilitated both “same” and “different” name matches. This result does not obtain in visual letter matches; in fact, Posner et al. (1969) found that different RTs were consistently about 20 msec. longer on trials when the first and second letters were both either capitals or small than when they were not. This result indicates that the SVM for letter case is much more letter-specific than the SAM for a speaker’s voice.

Interference with SVM

In a second experiment, Posner et al. presented two kinds of interference during the interletter interval. The first letter was presented for 1 sec. followed by a .5 sec. interval before presentation of the second letter. The forgetting interval was either empty, or with a visual noise field of black and white squares, or with an addition task in which the subject had to add a pair of digits. The RT advantage of responding “same” when the letters were physically identical as opposed to only nominally identical was 52 msec. when the letters were separated by the empty or noise intervals, but dropped to 14 msec. when the subjects had to perform the addition task. This result might indicate that the subject’s processing capacity is necessary to maintain the visual information about the shape of the letter in SVM. If the subject is required to add two numbers, this interferes with holding the information in SVM. However, the digits to be added were also presented visually and it is possible that the recognition of the digits rather than their addition produces the interference. If processing of similar visual information interferes with SVM, it is not surprising that the noise field produced no interference, since it is qualitatively different than visual information about letter names.

How necessary is it for the subject to see the first letter to facilitate physical matches? According to our model, visual information can be placed in SVM without a visual stimulus, but through the recoding process. We can all visualize the differences between upper and lowercase letters with our eyes closed. Posner et al. (1969) and Beller (1971) have shown that the subject does not have to see the first letter to operate on the basis of a visual instead of a name code in making his same-different judgment. On some trials,
the experimenters told their subjects that the second letter would definitely occur in uppercase, although it could be same or different as the first. On other trials, subjects knew it could occur in either upper or lower case. The investigators found that "same" RTs were faster in the first-mentioned kind of trials even though the first letter was presented auditorily. The result might mean that subjects generated a visual code of the uppercase form of the letter that was presented auditorily, facilitating their comparison judgment of whether the second letter was "same" or "different."

Subjects in the letter comparison task can direct their attention to either the visual form of the first letter or to its name, whichever seems to be the best strategy in the particular task. If they know that the second letter is likely to occur one way—either upper or lower case—they might concentrate on the shape of the first letter. Therefore, it will be easiest to respond "same" to the second letter when it is physically identical to the first letter. Recall that the advantage of "same" RTs on trials with same-case letters decreased with increases in the interletter interval. This result could have occurred because it is not optimal to operate solely on the basis of the visual form of the letter, since half of the same trials will be different in letter case although they have the same name.

Posner and his colleagues have shown how subjects could utilize information in SVM or generated abstract memory (GAM) for making a same-different comparison judgment. Subjects can maintain the visual quality of the form of an item as well as its name in SVM and GAM, respectively. If the subject focuses on the visual form of the item, this will decrease the time it takes to make "same" judgments when the form of the comparison stimulus agrees with the form of the item held in SVM. If the stimulus differs from the form held in SVM, the subject must base judgment on whether the two things have the same name.

An experiment by Tversky (1969) supports and clarifies our interpretation of how SVM and GAM operate in a same-different judgment task. In her experiment, subjects first became acquainted with different persons by learning to give different names to the schematic faces shown in Figure 3. After the names were learned, both the schematic faces and the names were used in a same-different RT task. Subjects were presented with a test stimulus for 1 sec., followed by a 1-sec. blank interval, followed by a second stimulus. The subjects were instructed to report whether the second stimulus was the same or different from the first with respect to the identity of the person, regardless of his physical representation. This experi-

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ment, then, is exactly analogous to the letter matching experiments. The experiment was partitioned into blocks of trials. In a given block of trials, the first stimulus was always presented in one representation, picture or name. The second stimulus could occur in either representation, but one representation was 4 times as likely to be presented as the other. Therefore, there are 4 possible blocks of trials. The first stimulus could always be a picture or could always be a name, and the second stimulus could more likely be a picture or a name. Practiced subjects were used and the 4 types of trial blocks were presented in a counterbalanced manner to eliminate any differences due to temporal order. A large number of trials was presented within each block of trials so that it was easy for the subject to learn whether the second stimulus was more likely to be a name or a picture. On half of the trials, the two stimuli had the same name; on the other half, they were different in name.

The same and different RTs were primarily a function of the likelihood that a particular representation would be presented as a second stimulus, regardless of the representation of the first stimulus. Both same and different RTs were faster when the second stimulus had the representation that was the most likely in that particular block of trials. For example, when a name always occurred as the first stimulus and a picture was most likely to occur as the second stimulus, RTs were faster for pictures than names on both same and different trials. Accordingly, although subjects were presented with the name of a person, they generated his pictorial representation, since the second stimulus was more likely to be a picture. In this case, when a picture was presented as the second stimulus, they would compare the picture with the representation in SVM; such comparison was very easily made. In contrast, if a name was presented second, they would be faced with com-
paring the name to a picture held in SVM. This would require some sort of transformation of the picture into a name or the name into a picture so that comparison could take place. The subjects took an average of 156 msec. longer when the second stimulus was presented in the unexpected than the expected representation, regardless of the representation of the first stimulus. This length of time provides an estimate of how long it took for the appropriate transformation that made a comparison possible.

Potter and Levy (1969) studied recognition memory for color pictures of typical scenes of people, animals, food, etc. Each subject viewed a sequence of 10 pictures at rates of presentation that varied from 8 pictures/sec. to 2 sec./picture. The subject was then given 32 pictures, 16 identical to those in the list and 16 new pictures. He went through this group of pictures indicating whether or not each picture was in the preceding list. The results showed a very low false alarm rate (saying a picture was in the preceding list when it was not) at all presentation rates. In contrast, the hit rate improved substantially from 15 percent at 8 items/sec. to 93 percent at 2 sec./item. The first 333 msec. of the picture appeared to be the most critical for retention; the hit rate was almost 60 percent at this rate of presentation. The last item in the list was better recognized at all presentation rates, showing that the subjects were able to continue processing this item after the slide was turned off, in agreement with the visual processing studies discussed in Chapters 17 and 18.

Potter and Levy's results show that subjects have a good memory for pictorial information even when this information is presented at relatively fast rates of presentation. With slower rates of about 5 sec./item, Nickerson (1965) and Shepard (1967) showed extremely good recognition memory for lists of hundreds of pictures. In Nickerson's task, the hit rate was .87 and the false alarm rate was .02. Shepard showed increased sensitivity by using a two-alternative forced-choice task. In this case, the subject was presented with an old and a new picture and was asked to indicate which one was in the preceding list. Subjects in this task were 97 percent correct. Haber (1970) carried Shepard's study to an extreme by asking his subjects to look at 2560 photographic slides over the course of several days. Haber's patient and courageous subjects averaged about 90 percent correct in a forced-choice recognition task. These experiments demonstrate that visual memory for complex scenes is extremely good when we are tested with a recognition procedure. This visual memory also seems to improve memory
performance substantially when subjects form images of words rather than trying to remember the words in purely linguistic form (Paivio, 1971).

INDEPENDENCE OF SVM AND GAM

In our model, we have assumed that the information in SVM is relatively independent of the information in GAM. Supporting this, Scarborough (1972a) has shown that subjects can retain a list of visually presented digits without a visual preperceptual image and without implicitly speaking them (placing them in GAM). Subjects were given a list of about 7 auditory digits presented at a rate of 2 items/sec, followed by a visual display of 6 letters or digits presented for 250 msec. The 250 msec. presentation and a letter-noise masking stimulus presented immediately after the display presentation insured that the items did not remain in preperceptual visual storage after presentation. Subjects were required to remember both the auditory and visual lists of items. Immediately after the visual display presentation, subjects were signalled by the experimenter to recall either the visual or auditory list. The cue signal was randomly varied from trial to trial so that subjects could not predict which signal would occur. Percentage of correct recall in this condition was compared to a condition in which subjects were told in advance to remember only the auditory or only the visual items.

The results showed no decrement in performance when the subjects were required to remember both lists instead of just one. Percentage of correct recall of the visual items was not lowered when the subjects were also required to remember the auditory items. Analogously, recall of the auditory items was not affected by whether or not the subjects were also required to remember the visual items. Since the auditory list was relatively long and probably exceeded the capacity of synthesized auditory memory, we can assume that it was held in GAM. Since GAM has a limited capacity, the auditory list should have decreased recall of the visual items if the visual items were also held in abstract memory. Since correct recall of visual items was not lowered, we have some evidence that the visual list was held in SVM independent of storage in GAM.

Scarborough also varied the delay of the report cue after the visual display offset. If the report cue was delayed, recall of the items in the visual display decreased significantly only when the subjects were also required to remember the auditory items. This result shows that, although information in SVM can supplement the information in GAM, SVM cannot hold a visual representation of a list of items indefinitely. With a delayed recall, the subject had
to divide his attention between the items in GAM and SVM, since either the auditory or visual list could be cued for recall. When subjects were not required to remember the auditory items, recall of the items in the visual display did not decrease with increases in the delay of the report cue. In this case, they were able to direct their attention completely to the items from the visual display held in SVM.

The studies discussed here provide some support for the existence of a storage structure that holds visual information in perceived or synthesized form for a short time. Scarborough's (1972a) study provides one method of overcoming the span of apprehension in an experimental task. His results show that a visual list of items can be held for a very short period of time in SVM, which increases the span of apprehension. However, the information in SVM can only be held in this form for a very short period of time. When the report cue was delayed, the subjects probably found it necessary to begin transferring the items held in SVM to GAM. Since GAM has a limited capacity, they would forget some of the items already held there. The storage structure SVM plays an important role in reading, since it allows the subject to hold the visual information from the last two or three eye fixations before meaning is derived and transferred in GAM. Recall from Chapter 11, also, the importance of SVM in the perception of objects rotated in depth. There we found that the subject was able to integrate the information from the last couple of eye fixations to perceive a figure in depth.
Generated abstract memory

Decay theory
Interference theory
  Broadbent and Gregory study
  Mackworth experiment
Tests of decay and interference theories
  Raitman study
  Shiffrin study
  probe recall
    Waugh and Norman study
Perceptual processing theory
  quantitative description
  experimental tests

Evaluating memory processes
In our model, synthesized visual and auditory memory can be transformed by the secondary recognition process into names held in generated abstract memory. This memory is called abstract because it is not modality-specific; it is called generated because the secondary recognition process involves an active generation of the synthesized information into abstract form. In this chapter, we attempt to analyze the way the forgetting of name information happens in generated abstract memory. Analogous to other memories, there are two primary causal contenders: decay and interference. Decay theory was first presented systematically in Broadbent's (1958) model of information processing (see Chapter 13). Interference theory has its origin in the concept of association outlined by the British Empiricists. Both of these theories will be presented, followed by experimental tests between the theories.

In Broadbent's model, incoming stimuli are held in a preperceptual form along various channels. The recognition process reads out the information along one channel at a time, so that identification can take place. However, rather than passing on this transformed information to another storage structure, it is recirculated back through the original storage. This assumption eliminates the value of the information-processing approach. Information in preperceptual form certainly differs from the name information after recognition has taken place, and the storage characteristics and forgetting
of both kinds of information should be both qualitatively and quantitatively different. Given this qualification, it is still possible to evaluate how forgetting of name information is assumed to occur in terms of Broadbent's model.

In Broadbent's formulation of decay theory, name information decays passively over time unless it is operated on; that is, unless it is rehearsed by the central processor. To cause forgetting, it is sufficient to distract the central processor away from this information so that its decay takes place. The activities of the central processor in the processing of new information do not in any way interfere with the previous information; only the neglect of the old causes forgetting. No forgetting will occur if the central processor is allowed to devote attention to the relevant information during the forgetting interval. Because the central processor is limited in capacity, some forgetting usually occurs, as the processor is incapable of processing new information and maintaining its attention on the old.

INTERFERENCE THEORY

In contrast to decay theory, interference theory assumes that no forgetting will occur unless intervening activity has a direct effect on the information in memory. The interference theory of forgetting assumes that two events occurring together in time become associated or linked together. Memory in this context functions to maintain the association between the two events. Using a stimulus-response model, interference theorists interpreted the two events as consisting of a stimulus and a response. The subject learns to associate stimulus (S₁) with response (R₁). This means that he has learned to associate certain features of that stimulus to that response. Now when he learns to respond to a second stimulus, S₂, with the response R₂, it is probably safe to assume that the second stimulus has some features in common with the first. This similarity between the two stimuli means that there are features in one stimulus that are associated with the response of the other. S₂ is like S₁ in some respect, and when S₂ is presented, the features that it has in common with S₁ will evoke not only R₂, but also R₁. Thus the similarity in the two stimuli produces competition between the two responses. In this way the learning of a new set of associations interferes with memory for an older set.

The critical difference between decay and interference theory, therefore, is in the way people forget. Decay theory says that one forgets when one is unable to rehearse, or chooses not to do so. The memory trace fades automatically over time unless it is renewed. Interference theory assumes that forgetting occurs when a stimulus-
response association is weakened by learning of another association. If no new material was learned, the subject would remember a given association permanently. This does not happen because we continuously learn new information that interferes with the old.

In 1965, Broadbent and Gregory showed how forgetting seemed to be more dependent on the attention of the central processor than on the learning of new associations. On each trial, subjects listened to 10 letters presented at a rate of 1 letter every 5 sec. Within each set of 10 letters, 1 letter occurred twice, whereas none of the other letters were given more than once. At the end of the presentation, the subject reported which letter had occurred twice. This task required the subject to recognize and remember each letter and to determine if it was presented previously. This task is analogous to the QRST task discussed in Chapter 12, since it requires the same working memory processes.

Simultaneously with this task, subjects were also required to perform a choice RT task. Subjects held the index finger of each hand on one of two buttons during the experiment. The buttons consisted of a ring, through the center of which a vibrating rod projected. The rod vibrated from time to time between the letter presentations. Under one condition, whenever one of the rods was felt to be vibrating, the subject was to press down on that same button. Under a second condition, when one rod vibrated, the subject was required to press the button under the finger of the opposite hand. The authors reasoned that the first task should be easier than the second because the response is more compatible with the stimulus. Thus, under the compatible response condition, when the left button vibrated the subject pressed it with the finger of the left hand. Under the incompatible response condition, when the left button vibrated the subject pressed the right button. If the second condition is more difficult than the first, this means that in a limited capacity system it requires more processing capacity than does the compatible response condition.

According to Broadbent's decay theory if the task of responding to the vibrating buttons reduces the processing capacity available for the letter memory task, then the second condition should reduce it more than the first. Subjects had longer RT's on the button-punching task in the incompatible response condition, showing that this condition was indeed more difficult. Performance in the memory task should, therefore, be worse when the button-pushing task is being done under the incompatible response condition. This is in fact what Broadbent and Gregory found: memory performance was 85 percent and 59 percent correct under the compatible and
incompatible response conditions, respectively. According to Broadbent’s model the subject had more time to perceive, rehearse, and update the letters in memory in the response-compatible condition. It is plausible that performance in the button-pushing task prevented rehearsal of the test items in the memory task. But it is very difficult to see how the vibration in the second task could have enough features in common with the letter stimuli to cause response competition and hence forgetting.

Mackworth Experiment Mackworth (1964) devised an experiment in which subjects were visually presented with a row of 6 letters that they read aloud from left to right. After reading the letters, they were also required to read either a row of 5 digits or 5 color patches. In both cases, the subject had to recall the letters in sequential order immediately after reading the digits or colors. It is more difficult, as measured by RT, to identify a color patch than to name a digit. According to Broadbent, given that recognition requires processing capacity, reading the colors should take more processing capacity than reading the digits. If processing capacity is limited, requiring more of it for identification of the color patches should reduce the capacity available for rehearsal of the letters. Mackworth found that memory for the letters was, indeed, better in the case in which they were followed by the naming of digits than by the naming of color patches. Identifying new items, therefore, interfered with memory for old items as a direct function of the difficulty of recognition. Again, it is easy to understand these results in the framework of the Broadbent model. Interference theory, however, which would account for forgetting as the result of similar stimuli triggering the same response, does not fit this situation.

Interference theory might explain the Broadbent and Gregory result by assuming that performance in the button-pushing task requires some subvocal rehearsal on the part of the subject. The subject may have to instruct himself continuously, “Remember, push the right button when the left hand is vibrated.” If this were the case, it seems likely that the incompatible response condition required more rehearsal than the compatible response condition. Forgetting of the letters, then, was not caused by the intervening task itself, but by the rehearsal required for the task. In this case, subvocal rehearsal, because of its similarity to letter processing, would cause interference with letter memory. Whereas in the Mackworth experiment, the similarity of the digit and color names to the letters might be proposed as the basis for interference.

Given the necessity of these post hoc explanations, the interference theorist may want to discard the assumption that similarity
is absolutely necessary for forgetting. He may simply assume that intervening activity can interfere with memory even though there is no apparent similarity between the intervening processing and the memory items. Even though this assumption makes interference theory much more similar to the decay theory, the two theories still differ and can be distinguished, at least logically. Although the interference theorist cannot offer so explicit an explanation of the nature of the interference, he does not have to concede the interference assumption itself. Interference theory attributes forgetting directly to interfering activity, whereas decay theory attributes forgetting to a lack of rehearsal.

This makes interference theory more difficult to distinguish from decay theory but, in principle, it can be done. One difference is that, according to decay theory, forgetting must occur if rehearsal is prevented whereas, according to interference theory, it should not occur if no intervening information was processed. Providing a clear test between the two theories thus depends upon demonstrating (1) that subjects either do or do not forget over time when no new material is presented, but (2) that rehearsal of the memory items does not take place. The experimenter must prevent rehearsal, so that forgetting can occur if it is a matter of passive decay, but he must not present new material, since forgetting in this situation can be explained by decay or interference. The only way to be sure one has done this is to engage the subject's attention with another task. The catch here is that the interference theorist can always say that the new task, whatever it might be, could interfere with memory for the test items. If the subject forgot the test items, the experimenter would not know whether it was because he had prevented rehearsal or because he had required new intervening activity that interfered with memory.

Reitman (1971) provided a nice experimental attempt at distinguishing between decay and interference theories. Subjects were required to remember three concrete words presented visually for 2 sec. and then were asked to recall the items at some later time. In previous applications of this task (called the Peterson and Peterson [1959] task after the investigators who first used it), the subjects counted aloud, backward by 3's, during a variable forgetting interval before recall. Results usually show about a 30 or 40 percent decrease in performance in the first 15 sec. of the forgetting interval. Both the decay and interference theories can explain this result: decay theory explains it by the amount of time that has passed while...
the subject was prevented by the backward counting task from re-
hearsal, and interference theory explains it by the interference of
the counting task itself.

The counting backward task prevented rehearsal, but in doing
so the subjects had to process new information. Reitman saw that
the problem would be solved if the experimenter could find some
means of locking the subject’s attention onto a channel clear of in-
put. That is, if the subject could be made to attend to nothing in the
period between perception of the test items and recall of them, any
forgetting that appeared in the results could only be attributed to
decay. Reitman hit upon the task of having the subject monitor an
auditory channel for a barely detectable signal. It was true that at
times there would be information coming in over that channel; there
would have to be an occasional input to hold the subject’s attention.
If the signals were properly randomized, however, there would be
some trials on which nothing would occur, yet the subject would
have no way of predicting this and would have devoted as much
attention to monitoring the auditory channel as on any other trial.
These trials, Reitman reasoned, would fulfill the condition of pre-
venting any rehearsal of the test items while at the same time avoid-
ing presentation of any new material.

Employing this logic, the Peterson and Peterson task was modi-
fied so that subjects were required to attend to the input coming in
over headphones and to hit a button whenever they detected a 100
msec. tonal signal. The intensity of signal was adjusted so that it
was just barely audible in the continuous background of white
noise. With no memory task, subjects were able to detect the tone
about 50 percent of the time. Here, 50 percent is much above chance
since the false alarm rate was negligible. Presentation of the tone
over the auditory channel was randomized in such a way that at
any point in time a signal had a constant probability of occurring
independent of when it last occurred. Under these conditions, it
was impossible for the subject to predict when a signal would come
on. The monitoring interval was 15 sec., and any number from zero
to 14 tones could occur during that interval. The probability of a
tone occurrence during any interval of time was set so that a trial
without a tonal signal would occur 14 percent of the time. On these
trials no tone would occur, but the subject should have devoted as
much attention to monitoring the auditory channel on these trials
as on the others. On each trial, at the end of the monitoring interval
the subject recalled the three test words presented before the inter-
val began.

Reitman was mainly interested in the small set of trials on
which no tone was presented during the monitoring interval. She
reasoned that here she had succeeded in engaging the subject’s at-
tention, so that rehearsal was impossible without presenting him with new material or allowing him to think of other things on his own. This situation, then, closely approximated the ideal test of decay and interference theory. Any forgetting that was observed when nothing was presented in the forgetting interval would have to be attributed to passive decay of the memory trace. Nothing had happened during the interval between perception and recall except the passage of time.

Reitman tested 18 subjects, and 13 of them showed absolutely no forgetting. At 15 sec. after perception of the display, these subjects could recall the items with 100 percent accuracy. The remaining five subjects performed between 67 and 89 percent accuracy, giving an average performance of 92 percent for the 18 subjects, much higher than performance found in the counting backwards task. A second important finding was that recall did not even decrease with increases in the number of tonal detections. Therefore, monitoring the auditory channel and tonal detection itself did not appear to interfere with memory for the test words.

It is possible that the subjects did not devote full attention to the auditory monitoring task but spent some time rehearsing the test items. To check on this, Reitman looked at performance in a control condition of the monitoring task when the subjects were not required to remember the test words. No rehearsal should have occurred here; therefore, if some rehearsal was taking place during the memory task and if rehearsal interfered with the auditory signal detection, then signal detection performance should be poorer in the recall than in the control condition. Reitman found that subjects detected the signal about 50 percent of the time in both conditions. Detection performance did not deteriorate when subjects had to recall test words at the end of the interval; therefore, Reitman reasoned, they were not rehearsing the items during this time. As a second check on rehearsal, she asked the subjects after the experiment if they were aware of being able to rehearse during the monitoring interval, and they replied that they were not.

At first glance, Reitman's study appears to provide evidence against a pure decay theory of forgetting. Subjects apparently did not rehearse and yet forgetting did not seem to occur. However, interference theory must account for the fact that detection performance does not interfere with memory for the test words. The theory could fall back on the concept of similarity but we saw that this variable is not always critical. If anything, Reitman's experiment seems to present a problem for both decay and interference theories.

A number of problems in Reitman's experiment will be quickly noticed by both decay and interference theorists. Most critical is
the incomplete experimental design, since she did not measure performance at different forgetting intervals, but only at 15 sec. after the word presentations. To show that no forgetting occurred, it is necessary to show that the subject recalled as much 15 sec. after the monitoring interval as he did immediately after presentation of the test list. Reitman believed she had done this by showing that 15 sec. after the test word presentations, performance was 100 percent correct. The problem here is that this "ceiling" effect could have hidden any forgetting that did take place. Subjects may have learned the words so well that, even though some forgetting occurred, performance was still perfectly accurate 15 sec. after presentation. The test would have been more powerful if the experimenter could have presented a larger number of words for memory so that performance would not have been perfect even if tested immediately. Then, if memory were tested after different monitoring intervals, the rate of forgetting could have been determined by looking at the slope of the forgetting function. Shiffrin's (1973) study corrects for these methodological difficulties.

**Shiffrin Study**

Shiffrin (Experiment III) made four modifications of the basic Reitman procedure. First, he presented 5 consonants for the test items for 3 sec. Second, he systematically varied the duration of the signal detection task at 1, 8, and 40 sec. Third, after the signal detection task, the subjects were also required to perform an addition task for 5 or 30 sec. Subjects saw a 3-digit number followed by a single digit every 2 sec. The subject's task was to perform a running addition of the numbers. Fourth, subjects were given monetary incentives to perform the detection and addition tasks as accurately as possible.

Given that the addition task is similar to counting backwards, we would expect it to interfere with memory, whereas the signal detection task should not interfere if Reitman's findings were valid. This expectation was obtained, as can be seen in the forgetting functions shown in Figure 1. The duration of the signal detection task had no significant effect on performance, whereas increasing the duration of an addition task lowered performance significantly. In agreement with Reitman's study, signal detection performance was also not affected by the addition of the memory task. These results support our interpretation of Reitman's findings: time without rehearsal is not sufficient for forgetting.

The ultimate acceptance of either decay or interference theory will depend on which theory best describes forgetting. In decay theory, time is the critical independent variable, whereas interfering activity is critical for interference theory. One popular test between
these two theories has been to vary the rate of presentation of a list of verbal items and to ask subjects to recall them immediately. Experimenters reasoned that faster rates should lead to less forgetting according to decay theory since there would be less time between presentation and test. However, these experimenters failed to realize that there were two important psychological processes in the task: perception and memory. The rate of presentation might affect both of these processes in different ways so that the results would not be informative with respect to the nature of the forgetting process.

A second problem with these studies is that subjects were permitted a free recall; hence their rehearsal and recall strategies were not under experimental control. This paradigm does not allow one to describe the forgetting that occurs, since the actual forgetting interval and the interference activity varies, depending upon the strategy of the subject. It is necessary to devise an experimental paradigm that can measure perception and memory directly as a function of either time or the number of interfering items. The suit-
able paradigm is a probe recognition or recall task in which the subject only responds with 1 item per trial.

**Probe Recall** Waugh and Norman (1965) employed a probe recall study in which subjects were presented with a list of items followed by a test item and had to report the item that followed the test item in the preceding list. Waugh and Norman explicitly instructed their subjects to concentrate on the current item being presented and not to rehearse earlier items in the list. This instruction was given to eliminate differences in rehearsal for the different items as a function of serial position. Accordingly, any differences in memory performance as a function of serial position could be attributed to some other variable than amount of rehearsal. The experimenters could, therefore, determine whether time or number of items is a better predictor of changes in memory, thus providing a test between interference and decay theories.

**Waugh and Norman Study** Waugh and Norman's test of interference and decay theories was to vary the rate of presentation of the list and to compare the forgetting functions under two rates. The forgetting function was determined by systematically testing the subject for different items in the preceding list. A list of 15 digits was presented at a rate of 1 or 4 digits per sec. There were 1, 2, 3, 4, 5, 6, 8, 10, or 12 digits between the tested item and its presentation in the list. Figure 2 presents the percentage of correct recall as a function of the number of interpolated digits between a digit's original presentation and its test under two rates of presentation. The results show how quickly forgetting occurs at both rates of presentation. However, the two curves drawn through the points illustrate a systematic difference between the forgetting functions under the two rates of presentation.

The function describing forgetting at a rate of presentation of 4 items/sec. starts out lower and ends up higher than the function describing forgetting when the items are presented at 1/sec. The intersection at the Y ordinate provides some measure of the original perception and storage of the digits, whereas the slope of the curves should provide an index of the rate of forgetting. According to this analysis, the items presented at 1/sec. were better stored but forgotten faster than the items presented at 4/sec. Thus, the results illustrate the importance of our stage analysis of the memory task. Every memory task contains both storage and retention stages which must be isolated in both the experimental design and theoretical description. The Waugh and Norman task allows us to see
FIGURE 2. The percentage of correct recall as a function of the number of interpolated items between presentation of the digit and its test under two rates of presentation (after Waugh & Norman, 1965). The lines are predicted functions given by Massaro (1970b).

the effects of each of these stages independently, whereas the earlier free recall experiments did not. Accordingly, it is clear that the results must be described by a theory that can account for the differences in the original storage and the differences in forgetting rates under the two rates of presentation. A simple decay or interference theory based on time or items will not suffice.
One theory that describes these results has been presented by the author (1970b). The theory is similar to the analysis presented in the previous chapters on auditory and visual memory. In describing storage and forgetting in synthesized auditory and visual memory, the concept of familiarity is used. Here, we use a similar concept called memory strength as an index of how well the subject remembers what is required in the task. In Waugh and Norman's (1965) task, the subject was given a probe item and asked to give the item that followed it in the preceding list. We assume that the probe item is associated in different degrees to a number of different items in the preceding list, because of the contiguity between their presentations. Figure 3 illustrates some possible differences in association values to a probe item. As can be seen in the figure, we expect the item following the probe item to have the highest association to the probe item. However, because of fluctuations in this value from trial to trial, the association is represented by a distribution of values rather than a fixed value. This procedure is exactly analogous to the concept of noise used in signal detection theory and in our treatment of familiarity. Other items would, on the average, have smaller associations to the probe item. The subject's decision rule would be to respond with the item that has the highest association to the probe item. Most of the time, the item following has the highest association value and the subject will recall it correctly. However, as he forgets the association between the probe item and the item following, all of the digits seem to be equally associated to the probe item. In effect, the distributions in Figure 3 are pushed closer

**FIGURE 3.** The distribution of association values to the probe item for the item that follows the probe and other items in the possible set of alternatives.
together so that the subject becomes more likely to respond with a wrong item.

The two main assumptions of the above-mentioned theory describe changes in memory strength of an item as a function of perceptual processing. Perceptual processing simply refers to the analysis of information in a sensory input used to recognize and remember the stimulus. We have seen that recognition requires an analysis of the input held in storage so that a match can be found in long-term memory. After identification of the item, further perceptual processing is necessary to remember or store the item. For example, to perform correctly in the Waugh and Norman study, the subject must remember the sequential order of the items so that he will be able to recall the item that followed the probe item in the preceding list. The first assumption of the theory is that memory for an item is directly related to the amount of perceptual processing of that item. Since an item is processed during its presentation, memory strength will increase with increases in the presentation time of the item. The second assumption is that memory for an item is inversely related to the amount of perceptual processing of other items. Accordingly, the amount of interference that a retroactive item produces will increase as the duration of the retroactive item increases.

These two assumptions qualitatively predict Waugh and Norman's results. The first assumption predicts that the items presented at 1/sec. will have more memory strength after their presentation than will items presented at 4/sec. The longer the presentation time of an item, the more time the subject rehearse it, providing a stronger memory trace at presentation. The second assumption predicts that the degree of interference with earlier items produced by a new item is directly related to the amount of processing the new item receives. Since items presented at 1/sec. receive more processing, they will interfere more with earlier items than items presented at 4/sec. We now develop a quantitative formulation of the theory to see if these assumptions can also give a quantitative description of the results.

The first assumption in quantitative form is that the perceptual processing of an item increases its memory strength according to a negatively accelerating growth function of time:

\[ s(t) = \alpha (1 - e^{-t}) \]  \hspace{1cm} [1]

where \( s(t) \) is the memory strength of the item after a presentation time of \( t \), sec. Presentation time includes both the duration of the
item and the silent interval afterwards. Equation 1 indicates that the memory strength of a single item approaches a finite asymptote \( \alpha \) at a rate \( \theta \).

Equation 1 is the same growth function used earlier in describing the recognition of visual and auditory items in Chapters 18 and 22. Memory for an item parallels its recognition. To the extent that an item is perceived clearly, it will be stored clearly in memory. Therefore, if a subject recognizes an item better, we expect him to recognize or recall it better in a later memory test. The parameter values of \( \alpha \) and \( \theta \) can also be interpreted as they were in the analysis of recognition. The parameter value \( \alpha \) provides an index of the amount of available information in the stimulus. The rate at which this information is processed for memory is reflected in the value of \( \theta \).

The second assumption is that the perceptual processing of a new item decreases the memory strength of earlier items. The amount of interference of a new item, however, is positively related to the amount of perceptual processing that a new item receives. From Equation 1, it can be seen that the total amount of processing of an item increases with increases in its presentation time. However, perceptual processing eventually reaches an asymptote \( \alpha \), so that no further information can be derived from the item. In this case, the item produces no further interference on the memory of earlier items. More specifically, Equation 1 shows that the absolute amount of processing decreases during the presentation time of the item. This means that each additional unit of presentation time adds a smaller absolute amount to the item's memory strength. Since there is a direct trade-off between processing a new item and forgetting an old, each additional unit of presentation time of a new item subtracts a smaller amount from an old item's memory strength.

To put this assumption into quantitative form, consider first the case where a test item is presented for memory followed by a single retroactive interference item. The proportion \( \phi(t_l) \) of memory strength of the test item remaining after presentation of the retroactive item for \( t_l \) sec. is given by the equation:

\[
\phi(t_l) = 1 - \lambda(1 - \gamma^l)
\]

where \( 0 \leq \lambda \leq 1 \) and \( 0 \leq \gamma \leq 1 \). Equation 2 shows that the proportion of memory strength \( \phi(t_l) \) remaining after presentation of a new item is inversely related to the duration of the new item. However, a new item's interference does not increase continually with increases in its presentation time. Equation 2 shows that the propor-
tion $\phi(t_i)$ of memory strength remaining must be at least $1 - \lambda$, regardless of the duration of the interference item. This follows from the fact that $\gamma^t$ goes to zero with large increases in $t_i$.

Equation 1 gives the memory strength $s(t)$ resulting from a presentation time of $t$, sec. The value $\phi(t_i)$, given by Equation 2 is the proportion of memory strength retained after presentation of a retroactive item lasting $t_i$ sec. Therefore, the memory strength $s(t_i, t_j)$ of an item presented for $t_i$ sec. followed by a retroactive item presented for $t_j$ sec. is equal to:

$$s(t_i, t_j) = s(t_i)\phi(t_j)$$

(3)

where $s(t_i)$ and $\phi(t_j)$ are given by Equations 1 and 2, respectively.

Next, consider the present case in which a complete list of items is presented. We assume that the items are homogeneous so that each item in the list of items has a fixed amount of information. Furthermore, subjects are instructed to process the items in the same way; therefore, $\alpha$ should be the same for all items. If the items are processed at a constant rate within a list, each new item is learned to the same degree and produces the same amount of interference with earlier items. It follows that the memory strength $s(t_i, t_n, n)$ of an item of presentation time $t_i$ after $n$ retroactive items, each lasting $t_j$ sec., is given by the equation:

$$s(t_i, t_n, n) = s(t_i)\phi(t_j)^n$$

(4)

The values of $s(t_i)$ and $\phi(t_j)$ are given by Equations 1 and 2, respectively. Equation 4 indicates that each retroactive item decreases memory of an earlier item to some constant proportion, $\phi(t_j)$, of its previous memory strength.

Equation 4 is in the same form as the quantitative theory presented in Chapter 16. We saw there that taking logarithms simplified our analysis. Taking the logarithm of Equation 4 gives:

$$\log s(t_i, t_n, n) = \log s(t_i) + n \log \phi(t_j) = \log s(t_i) + n \log [1 - \lambda(1 - \gamma^t)]$$

(5)

Consider a list of items given at a fixed rate of presentation. In Equation 5, $\log s(t_i)$ is the memory strength immediately after an item's presentation. Given that $[1 - \lambda(1 - \gamma^t)]$ will be less than 1 if either $\lambda$ or $\gamma$ are less than 1, $\log [1 - \lambda(1 - \gamma^t)]$ will be negative. Accordingly, Equation 5 can be written

$$\log s(t_i, t_n, n) = \log s(t_i) - n |\log[1 - \lambda(1 - \gamma^t)]|$$

(6)

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where the verticals represent the positive value of \( \log [1 - \lambda(1 - \gamma^n)] \). Equation 6 shows that \( \log s(t_i, i, n) \) will be equal to \( \log s(t_i) \) immediately after its presentation, that is, when \( n = 0 \). When \( n = 1 \) with 1 intervening item, \( \log s(t_i) \) is reduced by the positive value of \( \log [1 - \lambda(1 - \gamma^n)] \). With each intervening item, \( \log s(t_i) \) is decreased by this same fixed amount. Thus, \( \log s(t_i, t_i, n) \) should be a linearly decreasing function of \( n \) with a \( Y \) intercept of \( \log s(t_i) \) at \( n = 0 \).

**Experimental Tests**

The independent variable—rate of presentation—will affect the \( Y \) intercept and the slope of the linear function in the following way. Since \( \log s(t_i) \) increases with increases in the presentation time of an item, the intercept of the function should increase with decreases in the presentation rate. Since the amount forgotten due to another item's presentation is directly related to \( t_i \), the slope of the forgetting function should be steeper as the presentation time \( (t_i) \) increases. That is, subjects should forget at faster rates as we decrease the rate of presentation.

The quantitative predictions of the theory were tested against Waugh and Norman's results. The observed data are in terms of percentage of correct recall as a function of serial position and rate of presentation. The theory describes changes in memory strength values—the distance between the means of the two memory strength distributions in Figure 3. The subjects had 10 possible response alternatives in the task and were forced to recall a digit on each trial. Therefore, the proportions correct can be translated into strength values using a method analogous to the calculation of \( d' \).

The strength values were taken from a set of tables given by Elliot (1964), who has computed strength values as a function of percentage correct and the number of alternatives in the response set. The predictions of the theory (Equation 4) were determined by finding the parameter values for \( \alpha \), \( \theta \), \( \lambda \), and \( \gamma \) that minimized the squared deviations between the predicted and observed \( d' \) values. The computer search routine described in Chapter 10 was also used here. This routine searches a parameter space defined by the experimenter for the optimal parameter values.

Predicted \( d' \) values can then be translated back into percentages for comparison with the observed percentages of recall (see Figure 2). The predicted and observed \( d' \) values of the Waugh and Norman study are shown in Figure 4. The memory strength values are plotted against the number of interpolated items as a function of the rate of presentation. As predicted by Equation 5, the figure indicates that log memory strength is a simple linear function of the number of interpolated items (\( n \)). Furthermore, the forgetting function is steeper for the slower than for the faster rate of presentation.
FIGURE 4. The predicted and observed memory strength values for the Waugh and Norman (1965) study as a function of the number of interpolated items and the rate of presentation.

This result indicates that, as predicted, the rate of forgetting as a function of the number of items increases as the rate of presentation is decreased.

The analysis of the Waugh and Norman (1965) study supports the idea that perceptual processing of new items interferes with retention of old items in memory. Norman and Waugh (1968) presented a list of 16 memory words followed by a test list of 10 words. The subject's task was to indicate whether each test word had occurred in the preceding list. With this procedure the experimenters were able to evaluate the interference effect of both inter-
polated memory items and test words. The results showed that each additional test word decreased retention of the memory words in the same way as did interpolated memory words. The perceptual processing necessary to categorize test words as old or new interferes with items already held in memory. Waugh and Norman (1968) also showed that a recently presented and redundant (predictable) item does not decrease the memory of earlier items, although new and unpredictable items do interfere with memory. When subjects are able to predict the occurrence of an item, presentation of the item requires little, if any, processing for memory. Thus, the lack of processing of predictable items preserves the integrity of earlier items in memory.

A simple decay or interference theory will not describe the forgetting rule in generated abstract memory. Forgetting is a function of the processing of new information during the forgetting interval. The more time the subject spends preparing a new item for memory, the more interference with memory for previous items. This limited capacity rule is somewhat similar to Broadbent's original decay theory but describes perception and memory as a function of what the observer is doing, rather than of passage of time alone. This theory explains why Mackworth (1964) found more interference when subjects read color patches than digits, since naming colors takes more perceptual processing. It can also explain Reitman's and Shiffrin's findings by assuming that the detection task requires very little processing capacity relative to counting backward or to an addition task in the retention interval. Some evidence for such an assumption was found in Chapters 15 and 16. Although the theory provides a good forgetting rule, much is still to be learned about the processes of storage and retention in generated abstract memory.
Evaluating Memory Processes

In our study of memory, we have relied on experimental procedures that control exactly the events between presentation of a memory item and its later test. There are critical design problems with other procedures, such as a free recall test in which the subject recalls all of the words in whichever way he chooses. Faced with the free recall protocol of a subject, the experimenter cannot isolate the psychological processes responsible for performance. Memory for an item is a joint function of perceptual, mnemonic, and decision processes and each of these must be evaluated exactly to make sense of the results.

As an example, consider the problem confronting the experimenter when he varies the rate of presentation in a free recall task. Subjects might be presented with a list of 24 words at a rate of 1 or 2 sec. per item. We know that the additional study time should enhance the storage of each of the items in memory. This same additional time, however, will probably produce additional interference with the retention of other items in the list. The helpless experimenter has no way of determining the operations of each of these processes; hence, he cannot develop an understanding of how each of these processes operates.
Long-term memory

Forgetting
Tip of the tongue
Perceptual and conceptual codes
Dissimilarity ratings
animal space
Analogy
Memory search and comparison
Word recognition
lexical decisions
associations
semantic features
discrete nodes
features of nodes
temporal course of association
If an object did not appear similar to itself, if
recurrences of an event did not seem the same, if
members of a class bore no resemblances to one another,
if relations could never be seen as alike, in short, if
every event was new and unfamiliar, the commonplace
stability of the perceptual universe could never be
constructed out of the raw material of our experience
and the world would necessarily remain a blooming,
buzzing confusion.
—George A. Miller (1956)

Our study of the early stages of information processing is heavily
dependent upon certain implicit assumptions about long-term mem-
ory. The psychological processing of a stimulus event is continually
interpreted in terms of the knowledge the observer brings to the
given task. For example, we saw how subjects could utilize the
spelling rules of English orthography to facilitate the perception of
letter strings. Language users also utilize phonological, syntactic,
and semantic rules in the processing of language. All of this infor-
mation must be stored in long-term memory, making its capacity
much larger than the other storage structures studied earlier.

How do we go about studying long-term memory? One method is to
present subjects with material to be learned, and then wait a suffi-
ciently long period of time before testing to ensure that whatever
information is recalled must be recalled from long-term memory.
Analogous to our short-term memories, this approach should allow
us to determine how forgetting occurs in long-term memory, the
nature of memory search strategies in long-term memory, and pos-
sibly the form of the structure of long-term memory. Wickelgren
(1972) has traced out long-term memory forgetting over a time span
up to 2 years. These studies utilize the same methodological and
procedural techniques that we analyzed in studies of short-term
memory. The interested reader is referred to the original paper for
the methodological details and results. This chapter concentrates
on experimental paradigms that have not yet been discussed for our studies of long-term memory.

**TIP OF THE TONGUE**

One unique approach to the study of long-term memory is to ask subjects what they already know, rather than to have them learn something new. Brown and McNeill (1966) capitalized on a phenomenon that we all have experienced: a “tip of the tongue” (TOT) state. In this state, an individual is unable to remember a word that he is sure he knows. The experience that he knows this particular word is usually accurate, because he may eventually recall the word days later, be able to recognize it correctly, or be able to give partial information about the word. Brown and McNeill successfully induced the TOT state in some subjects some of the time by presenting them with a definition of an uncommon English word and asking for the word. Subjects, given the definition of a word, sometimes entered the TOT state. In this state, subjects were in mild torment trying to recall the correct word. Brown and McNeil encouraged their subjects to give all of the words that came to their mind; the subjects were also asked the first letter and the number of syllables of the word they were trying to remember.

Given the definition of *sextant*, “a navigational instrument used in measuring angular distance, especially the altitude of the sun, moon, and stars at sea,” the TOT state was induced in 9 out of 58 subjects. Some of the words subjects gave were *astrolabe*, *compass*, *dividers*, *protractor*, *secent*, *sextet*, and *sexton*. The first four words are similar in meaning to the target word, whereas the last three are similar in sound and spelling. Some of the words similar in meaning could be traced directly to certain parts of the definition. For example, *protractor* is used in measuring angular distance but, of course, not of the stars at sea. The semantic confusions show that words with similar meanings can be thought of as being stored and/or retrieved together or substituted for each other.

The similar sounding items show that the perceptual description of words must be stored along with their meaning. We can assume that some subjects were able to retrieve the correct concept given the meaning, but had only partial information about the perceptual properties of the word corresponding to that concept. Analyses of the physical similarity between the correct word and the words recalled that were similar in sound indicated that the number of syllables of the word, the primary stress of the word, and its first and possibly its last letter were the most prevalent features. This result shows that subjects can have partial information about the sound of a word corresponding to a concept, with certain attributes
more prevalent than others. The final interesting result of the Brown and McNeill (1966) study is that subjects knew how much they knew. That is, subjects knew that similar sounding words were not correct but that they were, in fact, similar sounding.

Brown and McNeill’s results can be used to develop a model of the way the meanings of words are stored in long-term memory. This model is compatible with the model we developed earlier for visual and auditory recognition. We assume that long-term memory contains the equivalent of a dictionary or a lexicon with two distinct dimensions. These dimensions are perceptual and conceptual representations. The perceptual representation describes the sound of the word and the sight of the word. Brown and McNeill’s results reveal that the number of syllables, the primary accent, and first and last letters are important attributes of this perceptual representation. The conceptual representation contains, in some abstract form, the meaning of the word. Each perceptual code is associated with one or more conceptual codes and each conceptual code is associated with one or more perceptual codes. A perceptual code can be associated with more than one conceptual code because the English language contains homophones (seen, scene); the same conceptual code can be associated with different perceptual codes because of synonyms. Figure 1 illustrates our model of the secondary recognition process.

In the processing of language, we have postulated that subjects attempt to find perceptual codes in long-term memory that match the information held in synthesized auditory or visual memory. This is the process of secondary recognition, the outcome of which is the location of a perceptual and, therefore, a conceptual code in long-term memory. Location of the perceptual code is usually sufficient to take us directly to meaning, since the perceptual and conceptual codes are stored together. Brown and McNeill reversed the process by presenting subjects with information that should be contained in the conceptual code and then asking them for the associated perceptual code.

How can this model explain Brown and McNeill’s results? We must explain both the semantically related and perceptually related confusions. For the perceptually related confusions, we can assume that the subject was able to locate the correct conceptual and, thus, the perceptual code in long-term memory, but that the attributes of the perceptual code were not completely available. Therefore, the subjects simply generated whatever words they could bring to mind, based on this partial information. Subjects were not sure of
FIGURE 1. A model of the secondary recognition process. The process attempts to achieve a match between synthesized visual and/or auditory information with a representation in long-term memory.

their responses because they knew all of the attributes were not available. Conceptual confusions show that the correct conceptual code was not always located given the definition. If the correct conceptual code corresponding to a definition was only partially defined, a subject might find a better match of the definition with another "incorrect" conceptual code. In this case, the meaning of the word would be semantically similar to the correct word even though it was incorrect.

Henley (1969) provided another important technique that can be used to study the structure of long-term memory. She was interested in the relationship between animal names. A dog has certain properties or features that distinguish it from a horse and so on. Henley asked, What dimensions are important in the meaning of animal names? For example, how does a mouse differ from an elephant? Most people would agree that size is the most distinguishing factor between these two animals. In contrast, a deer and a gorilla seem to be about the same size, but differ in ferocity. To get subjects
to compare animals in this way, Henley asked them to rate the amount of dissimilarity between two animals on a scale from 0 (no difference) to 10. She used 30 animals and presented subjects with all possible pairs, one pair at a time.

The dependent measure in this experiment is a matrix of dissimilarity ratings. The dissimilarity of each animal to every other animal would be represented by a number between 0 and 10. The investigator faced with a dissimilarity rating for all possible pairs of 30 animals is unable to determine how many dimensions were important in the subject's ratings. There is a mathematical procedure called multidimensional scaling which aims to represent the animals in an n-dimensional Euclidean space so that the distance between two animals would be directly related to the rated amount of dissimilarity. In addition, the analysis provides the representation with the smallest number of dimensions possible. In our earlier examples, we said that subjects might judge the dissimilarity of the animals on the basis of only size and ferocity. In this case, the multidimensional scaling routine would indicate that the animals can best be represented in a two-dimensional space. The multidimensional routine cannot label the dimensions but simply places animals in the space. The experimenter must use his ingenuity in finding dimensional names or concepts that describe the placement of the animals. The experimenter would be justified in labeling the two dimensions size and ferocity if the animals were arranged from small to large and gentle to fierce, respectively, on the two dimensions. The relationship between the animals could then be seen directly on a simple two-dimensional plot. Animals judged to be very dissimilar would be very distant spatially, whereas animals judged to be similar would be represented very close together.

Henley found that three dimensions were necessary to describe the dissimilarity ratings of the animals. Three dimensions or attributes seemed to be important to the subjects in rating dissimilarity. Figure 2 plots the spatial relationship between her selected set of animals in a way that best describes the dissimilarity ratings. The three dimensions seem to correspond to the attributes of size, ferocity, and humanness although it may not be possible to describe each dimension in terms of a single word. The dimensions may be more complex and difficult to specify exactly. This spatial structure was also found when other methods, such as a method of association
FIGURE 2. Spatial relationship between the animals along the dimensions that best describe the dissimilarity ratings (after Henley, 1969).
were used. In this case subjects were required to respond with the animal word that came to mind upon presentation of a test word. The test words were the 30 animals’ names. In this instance, animals were considered to be similar to the extent they were given as responses to each other. The multidimensional scaling routine revealed the same structure for these responses as for the dissimilarity ratings.

In terms of our model, subjects performed the dissimilarity rating task by comparing the conceptual codes corresponding to the animal names. Subjects could evaluate the overlap in the definitions and respond accordingly. In the association task, their response rule might be to respond with the word whose conceptual code overlaps the most with the test word. Since, in both cases, three dimensions seemed to be important, the organization of the conceptual codes might be said to be structured along only these three dimensions. Henley’s results reveal that it is reasonable to represent the conceptual codes of animals in a multidimensional space with roughly three dimensions. Given this structure, investigators have devised experimental studies to determine how we operate on the stored information in order to carry out certain cognitive tasks.

In the first task we shall study (Rumelhart & Abrahamson, 1973), subjects were required to complete analogies of the form A:B as C:—-. For example, a subject might be given the problem:

fox:horse as chipmunk:———.  
Answer with one of these alternatives:  
  a. antelope  
  b. donkey  
  c. elephant  
  d. wolf

Rumelhart and Abrahamson formulated a model that predicts the solution to the analogy is an animal that has the same relationship to chipmunk as horse has to fox. Therefore, the subjects’ solutions to these animal analogies would be described in the framework of the semantic space given by Henley’s analysis. Consider the relationship between fox and horse in the above analogy. According to Henley’s multidimensional analysis, a fox can be considered to be about 60 units smaller, 65 units fiercer, and about 10 units less humanlike than a horse. A chipmunk can also be represented along these three dimensions, and the ideal solution would be an animal that is 60 units larger, 65 units less fierce, and 10 units more human-
like than a chipmunk. Of the four alternatives the best solution to this problem is antelope. Wolf is a particularly bad choice since it is much less humanlike than a chipmunk. Elephant is too large. Donkey is the next poorest choice because it is significantly less humanlike than the chipmunk. The best solution is antelope, although it need not be considered an ideal one. The ideal solution would be a nonexistent animal with the properties described above. The results of the experiment generally supported Rumelhart and Abrahamson’s model of analogical reasoning.

MEMORY SEARCH AND COMPARISON

Homa (1973) has shown how memory search and retrieval can be influenced by semantic properties. Semantic similarity was manipulated by defining items as semantically similar if they belong to the same superset category and semantically dissimilar if they belong to different superset categories. The categories used were taken from the Battig and Montague (1969) norms, constructed by presenting subjects with names of semantic categories and asking them to generate all of the instances that came to mind. Some examples of semantic categories used were four-footed animals, fruits, trees, items of furniture, and family relations. Homa took the popular instances that were given to the category names and used them as target and test items in the Sternberg memory search task (see Chapter 4).

Homa varied the size and the number of categories in the target list by covarying the two independent variables: the number of categories in the target list and the number of words per category. This factorial design is shown in Figure 3. The list could contain either 2, 3, or 5 categories of either 2, 3, or 5 words per category.

**FIGURE 3.** The factorial design used by Homa (1973) in generating target lists in the Sternberg task. The entries give the number of items in each target list.

<table>
<thead>
<tr>
<th>Number of Categories</th>
<th>2</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>
Consider two different target lists of size 15. In one condition, the target members would be drawn from 3 categories of 5 members each. In the other, the target members would be drawn from 5 categories of 3 members each. Any differences in RT between these two conditions would reveal some influence of category membership in the search task.

Homa (1973) also specifically varied the semantic relationship of the test item to the target list. One of three types of test items could be presented. The positive item would be a test item that was contained in the target list. The negative item could either belong or not belong to one of the categories defined by the target list. For example, the target list might contain the items dog, cat, pig, chair, stool, and couch defining the categories animal and furniture, respectively. The negative item lion would belong to the same semantic category as some of the target items but would not be a specific member of the target set. Therefore, the correct response would be “no.” The negative item doctor would be semantically unrelated to the target set, since its members define the categories animals and furniture, respectively. Accordingly, Homa’s subjects were tested on positive (P), negative but same (NS) category, and negative but different (ND) category items. Homa’s experiment allowed him to test a number of specific models of the search process.

In Chapter 4, we said that the serial exhaustive search model described the results of experiments using digits as target and test items. This simple model predicts that the critical variable in Homa’s experiment is the absolute number of items in the target set. The number of categories and the number of words per category should not be critical over and above their effect on the absolute size of the target list. Furthermore, the type of negative item should have no effect on the functions relating RT to the number of items in the target set.

Alternative models can be developed which assume that category membership can affect the memory search and comparison process. Figure 4 shows the target list as an organized hierarchical structure that the subjects could store. Homa’s subjects were given the positive target set a day before the experiment so that they had sufficient time to organize it optimally. Subjects could define the categories in the target set and store all of the instances under the appropriate category name. This organization could facilitate the memory search and comparison process with the use of the following search algorithm: Upon presentation of a test item, determine its superset category. Then search the category names in the target set. If the category of the test item does not match any of the categories of the target items, respond “no.” If the category of the test item does agree with one of the target categories, search
FIGURE 4. A hierarchical organization for storing the target items in Homa's (1973) experiment.

The instances of that target category. If the test item matches one of the target items under the positive category, respond "yes." Otherwise, respond "no." This search strategy is presented graphically in Figure 5. The reader might try to write a computer algorithm (analogous to those written in Chapter 4) for storing and searching the target list.

FIGURE 5. A search algorithm of the memory search task based on the hierarchical organization given in Figure 4.
The organization of the target items allows subjects to respond faster to ND items as opposed to NS items. Subjects presented with a test item could first compare the category membership of that item with the categories represented in the target list. If the test item did not belong to the same category as any of the target items, the subject could select a "no" response. But if the test item was a member of the same category as some of the target items, a "no" response would be premature at the end of the search through category names. The subject would have to examine the members of the category of the test item represented in the target list. This strategy predicts that responses to ND items should be faster than responses to NS items. Figure 6 plots the RT as a function of the number of categories for ND and NS items when category size was equal to 5. The figure shows that category membership influenced the search.

**FIGURE 6.** Mean RT as a function of the number of categories for negative test items of (1) the same superset category as some of the target items (NS), and (2) a different superset category (ND). Size of each category was 5 items (after Homa, 1973).
strategy in the predicted direction. Subjects were able to reject ND items faster than NS items presumably because they were able to reject ND items on a search through the category names, whereas they could not reject NS items until they also searched the members of the category given by the negative item.

Figure 7 presents another plot of the Homa data when there were two categories in the target list. The figure plots RT as a function of the number of items in each category for each of the three test items. If subjects search category names, as was described in the organized search strategy, then the number of target items in each category should have no effect on the RT for ND items. Subjects can terminate their search (as shown in the search algorithm) after they exhaust the search of the category names, since the cate-

FIGURE 7. Mean RTs as a function of the number of items per category for negative but same (NS), positive (P), and negative but different (ND) test items. The target list was made up of two categories (after Homa, 1973).
gory of an ND item will not match any of the category names of the items in the target set. Given that the RT for ND test items increases with the number of items per category, it appears that subjects do not always perform an organized search through the category names, especially with small target lists (Atkinson, Herrmann, & Wescourt, 1974). Although Homa's data show a significant role for semantic similarity in memory search and comparison, his quantitative data are not easily described by the organized search strategy.

Much of the information we have stored in long-term memory can be discovered in very simple demonstrations. For example, consider what we know about the lexical rules of English, that is, the relationship between letter strings and meaning. Consider the following letter strings: dampness, dempster, demgster. Do these letter strings spell words? A typical answer might be "yes," "maybe," and "no," in that order for the three respective words. We are sure that dampness is a word since we use it and know its meaning. Most of us might not know the meaning of dempster but we realize that it could be a word. In contrast, demgster is difficult to pronounce and, therefore, it is difficult to believe that it would be a word. This example demonstrates that we know which words we can define and also, at some level, which letter sequences are valid in English. We have a rule in English which says that a nasal phoneme m, n, or ñ as in me, no, or sing, followed by a stop consonant p, b, t, d, k, or g must share the same point of articulation where the mouth is closed, or occluded. Therefore, demp can be a word, since both m and p are articulated by occluding the mouth at the lips. On the other hand, demg is an invalid syllable since the consonant g is articulated by occluding the mouth towards the back. Therefore, demg cannot be easily pronounced.

This demonstration shows that two decisions can be made about a string of letters; (1), whether the letter sequence obeys the rules of English orthography, and (2), the meaning of a valid sequence of letters. Subjects might know that a sequence of letters could spell a word but not know the meaning of the word.

Meyer and Schvaneveldt (1971) showed how the semantic meaning of words could affect the time required to determine whether or not a string of letters spelled a word. They presented 2 strings of letters; 1 string of letters was centered above the other. Each string of letters spelled or did not spell an English word, so that the subject might see 2 words, 2 nonwords, or a word and a
nonword. The subject's task was to respond "yes," as quickly as possible if both strings spelled words, and "no," otherwise. The major independent variable of interest was the relationship of the two words on "yes" trials. Half of the word pairs were commonly associated words such as bread-butter and doctor-nurse. The other half of the word pairs were associatively unrelated, such as bread-doctor and butter-nurse. The second independent variable was the position of the nonword (top or bottom) when it occurred with a word string. Table 1 gives possible trial types in the experiment and the probability of occurrence of each type. Of course, each trial type was presented randomly from trial to trial so that subjects could not predict their responses in advance.

The first interesting result was the large effect of the position of the nonword when it occurred with a word string. The RT of the "no" response was 183 msec. faster when the nonword occurred in the top than in the bottom string (see Table 1). This result indicated that subjects performed a serial self-terminating search of the 2 letter strings, beginning with the top letter string. Since subjects could respond "no" as soon as they found 1 nonword, performance was faster when the nonword occurred in the top position, which

<table>
<thead>
<tr>
<th>Type of stimulus pair</th>
<th>Correct response</th>
<th>Proportion of trials</th>
<th>Mean RT (msec.)</th>
<th>Mean % errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top string</td>
<td>Bottom string</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>word</td>
<td>associated word</td>
<td>yes</td>
<td>.25</td>
<td>855</td>
</tr>
<tr>
<td>word</td>
<td>unassociated word</td>
<td>yes</td>
<td>.25</td>
<td>940</td>
</tr>
<tr>
<td>word</td>
<td>nonword</td>
<td>no</td>
<td>.167</td>
<td>1,067</td>
</tr>
<tr>
<td>nonword</td>
<td>word</td>
<td>no</td>
<td>.167</td>
<td>904</td>
</tr>
<tr>
<td>nonword</td>
<td>nonword</td>
<td>no</td>
<td>.167</td>
<td>884</td>
</tr>
</tbody>
</table>

was searched first. When the top string was a word, it was necessary to determine the status of the bottom string before a decision could be made. Figure 8 presents a diagram of the operations in this task. The self-terminating search is also supported by the finding that 2 nonwords were not responded to significantly faster than were a nonword and a word, when the nonword occurred in the top row. The lexical status of the bottom row should not matter when the top string is a nonword.

Table 1.
The Possible Trial Types, their Probability of Occurrence, and the Observed Results in the "Yes-No" Meyer and Schvaneveldt (1971) Task.
The significant variable on "yes" trials is the associative relationship between the two words. Given that the top string is a word, the bottom string must be processed before a response is executed. The question is whether the meaning of the top word influences processing of the bottom word. Meyer and Schvaneveldt (1971) found that RTs were 85 msec. faster when the words were associatively related than when they were unrelated. This result indicates that the semantic meaning of the first word string can facilitate recognition of the second string. That is to say, the subject can determine more quickly that the sequence of letters doctor is a word if he has just read nurse, than if he has just read butter.

Meyer and Schvaneveldt (1971) carried out another type of experiment to show that this phenomenon was not unique to a particular experimental task. The psychological processes discussed in this book have made themselves visible in a number of experimental tasks and can be considered reliable phenomena.
psychologically meaningful, a phenomenon must be robust, so that we can conclude it plays a role in normal everyday processing. In the second experiment subjects saw the same letter strings, but now they responded “same” if both strings of letters were words or if both strings were nonwords, and “different,” otherwise. Table 2 presents the design of this study. In the same-different task, the subjects must determine the status of both letter strings regardless of the outcome of the decision about the top string. Figure 9 presents a flow diagram of the necessary operations involved in the same-different task. As an exercise, interpret the results in Table 2 in relation to the processing operations delineated in Figure 9.

In terms of our model, recognizing that a letter string spells a word requires a sequence of psychological processes. First, the primary recognition process transforms the preperceptual visual image into a synthesized percept in synthesized visual memory. The secondary recognition process must now analyze the synthesized percept for meaning. If it spells a word, the conceptual code must be found that gives the word meaning. The association effect seems to facilitate the secondary recognition process, that is to say, the location of the conceptual code in long-term memory.

<table>
<thead>
<tr>
<th>Type of stimulus pair</th>
<th>Correct response</th>
<th>Proportion of trials</th>
<th>Mean RT (msec.)</th>
<th>Mean % errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top string</td>
<td>Bottom string</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>word</td>
<td>associated word</td>
<td>same</td>
<td>.125</td>
<td>1,055</td>
</tr>
<tr>
<td>word</td>
<td>unassociated word</td>
<td>same</td>
<td>.125</td>
<td>1,172</td>
</tr>
<tr>
<td>nonword</td>
<td>nonword</td>
<td>same</td>
<td>.25</td>
<td>1,357</td>
</tr>
<tr>
<td>word</td>
<td>nonword</td>
<td>different</td>
<td>.25</td>
<td>1,318</td>
</tr>
<tr>
<td>nonword</td>
<td>word</td>
<td>different</td>
<td>.25</td>
<td>1,386</td>
</tr>
</tbody>
</table>

Schaneveldt and Meyer (1973) propose two explanations of how the association can facilitate the secondary recognition process. The first model assumes that the conceptual codes of words are made up of a number of semantic features. According to this conceptual priming model, retrieval of a word in memory facilitates retrieval of associated words because the conceptual codes of the words share a number of semantic features or have them in common. That the concept of a word can be represented by an inter-
section list of semantic features is illustrated by the following example. When asked to think of something bubbly, no definite answer comes to mind. When asked, independently, to think of something pink, again no unique answer comes to mind. However, when asked to think of something bubbly and pink, many people respond with champagne. The concepts of doctor and nurse share
certain semantic features such as medical profession, white uniforms, hospital, pain, etc. If the secondary recognition of the letter sequence doctor activates all of the semantic features which define doctor, this activation would facilitate retrieval of the conceptual codes of semantically related words such as nurse. Doctor and butter do not share many semantic features and, therefore, recognition of one of these words does not facilitate retrieval of the conceptual code of the other.

**Discrete Nodes**

A second hypothesis is based on the assumption that the conceptual code of each word is stored at a discrete location or node. In this case, the conceptual code of a word has a single representation rather than a whole bundle of semantic features. In this model, the association between words determines the distance between the representations of their conceptual codes. Secondary recognition occurs in this model when the process locates the correct conceptual code in memory. The process can only read out one location at a time and the time needed to shift from one conceptual code to another increases with the distance between conceptual codes. This model predicts the effects of association in the Meyer and Schvaneveldt study by assuming that the conceptual codes of associated words are stored closer together in long-term memory than are the conceptual codes of unassociated words. Since secondary recognition must shift from the conceptual code of the first letter string to the second, recognition time of the second word is a direct function of distance of their conceptual codes. Hence, location shifting time and RT will be shorter for associated words than for unassociated words. Figure 10 presents a graphic representation of these two models.

**Features or Nodes**

Both the semantic-features and the discrete-node models predict the positive results of association in the previous studies. To discriminate between these two models, Schvaneveldt and Meyer (1973) carried out an ingenious experiment. They presented 3 horizontal strings of letters in a vertical array and manipulated the locations of the 2 associated words. The letter strings could either spell 3 words or any combination of words and nonwords. Subjects were requested to respond “yes” if all of the letter strings spelled words, and “no,” otherwise.

The central assumption of this experiment is that subjects will process the letter strings in a top-down order. This assumption can be tested by observing the RTs for “no” responses as a function of the position (top, middle, or bottom) of the first nonword. If subjects self-terminate the search as soon as they find a nonword, the
responses should be systematically ordered as a function of the position of the nonword. Letting W and N represent words and nonwords, respectively, the three possible sequences (NWW), (WNW), and (WWN) gave large and orderly differences in RT, 846, 1020, and 1187, respectively. This result supports the assumption that the subject read the strings in a top-to-bottom order and that reading time for each additional string averaged about 170 msec. Therefore, we can assume the subjects read the strings in a top-to-bottom order in our test of the two models of the association effect.
The RTs to the four kinds of "yes" trials can be used to differentiate the two models. These trial types are presented in Table 3. Letting A and U stand for associated and unassociated words, respectively, consider the two trials AAU and AUA. Examples of these trials might be doctor-nurse-butter and doctor-butter-nurse, respectively. The discrete-node model predicts a positive effect of association in the first case but not in the second. In the first case,

**TABLE 3.**
Average RTs of a "Yes" Response as a Function of the Different Kinds of "Yes" Trials in the Schwaneveldt and Meyer (1973) Study.

<table>
<thead>
<tr>
<th>Trial type</th>
<th>RT (msec.)</th>
<th>Mean % errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAU</td>
<td>1093</td>
<td>3.4</td>
</tr>
<tr>
<td>AUA</td>
<td>1090</td>
<td>4.4</td>
</tr>
<tr>
<td>UAA</td>
<td>1073</td>
<td>3.1</td>
</tr>
<tr>
<td>UUU</td>
<td>1175</td>
<td>3.8</td>
</tr>
</tbody>
</table>

the associated words will be processed in immediate succession, so that the time to recognize the second word should be shortened because of the close distance between the conceptual codes of the words. In contrast, given the string AUA, there should be no effect of association since the secondary recognition process must travel to the conceptual code of an unrelated word before it gets back to the conceptual code of an associated word. Therefore, the short distance between the conceptual codes of the two A words should play no role in an AUA sequence and should not shorten reaction time. In contrast to the predictions of the discrete-node model, the semantic-features model predicts that the secondary recognition of the second A word in the sequence AUA could still be facilitated if the semantic features of the first A word remain present during the readout of the third letter string. We would expect the features to be still available since secondary recognition of the middle word requires only another 170 msec. The results supported the semantic-features model. The "yes" RTs were about 90 msec. faster when 2 of the 3 words were associated than when all 3 words were unrelated. However, the position of the two A words had no significant effect, contradicting the prediction of the discrete-node model.

**Temporal Course of Association** Meyer, Schwaneveldt, and Ruddy (1972) have substantiated the above results by tracing out the temporal course of the association effect. They also modified the experimental paradigm to assure that
the subjects processed the letter strings in sequential order. In this paradigm, subjects were presented a sequence of letter strings, one at a time, and responded "yes" or "no" to each string individually, with respect to whether or not the letter string spelled a word. Subjects responded to each word individually and a following word was presented 250 msec. after the subject's response. Again, we can test the semantic-features model and the discrete-node model by comparing "yes" RTs to unassociated words, separated associates, and adjacent associates by comparing performance on the trials UUU, AUA, and UAA. In this paradigm, the dependent variable is the RT to the third word, depending on its relationship to the previous two words. Examples of UUU, AUA, and UAA trials might be nurse-star-butter, bread-star-butter, and star-bread-butter. The results show that the association effect is attenuated with an intervening word but not eliminated completely, supporting the results of the Schvaneveldt and Meyer (1973) study.

In another experiment, the investigators varied the time between 2 words in the sequential task. In this task, the subject saw a sequence of 2 letter strings on each trial and responded "yes" or "no" to each letter string, depending upon whether or not it spelled a word. The independent variable was the delay interval between the first response and second letter string. The dependent variable is the RT to the second word. The measure of the association effect is the difference in RTs to the same word when it follows an associated and nonassociated word. This difference at each of the delay intervals measures the temporal course of the association effect. The results showed that the association effect decreased with increases in the delay between the two words, but a significant effect remained even after 4 sec. The reason for the positive result at a long delay is probably that the subject was not required to process any new information during the delay interval and could continue thinking about the first word. This study should be repeated when the subject is required to perform an interfering task during the delay interval.

Long-term memory remains one of the least explored areas using the techniques of information-processing methodology. We have seen a number of techniques that appear to be successful in discovering the structural properties and processing rules of long-term memory. In contrast to the paucity of experimental work, there has been a large increase in theoretical work, influenced by recent studies in linguistics. Perhaps the methods developed here will begin to bring together the theoretical and empirical approaches to the investigation of long-term memory.
Learning

Interaction of processes
Learning concepts
Prototype learning
  insofar as can see
dot patterns
Temporal course of learning
  learning curves
  auditory melodies
  testing theories
What is learned?
  ants and jelly
  turtles and logs
... and it is no wonder that she [the soul] should be able to call to remembrance all that she ever knew about virtue, and about everything; for as all nature is akin, and the soul has learned all things, there is no difficulty in her eliciting, or, as men say, learning, out of a single recollection all the rest.

—Plato's Meno.

Implicit throughout the book is the assumption that man is continually learning, and this learning process plays a factor in normal perceptual and cognitive functioning, as well as in experimental tasks. In our experiments subjects usually show a remarkable improvement in performance during the first few or even the first few hundred trials. In a pitch discrimination experiment subjects' identifications improve remarkably during the first 20- or 30-minute session, leveling off thereafter. In our studies we have eliminated the contribution of learning as a possible confounding by (1) practicing the subjects before the experiment proper so that performance is asymptotic during the trials of interest, or (2) randomizing all conditions within experimental sessions and among subjects so that, on the average, all experimental conditions are tested equally at all levels of learning. As a result, our studies are informative with respect to the study of perceptual and cognitive functioning for a relatively fixed learning level.

Learning itself is, of course, an interest to the experimental psychologist. However, learning, as traditionally studied, appears to be a result of the interaction of a number of psychological processes rather than a distinct process itself, analogous to recognition or decision. In fact, learning typically results when we recombine many of the processes discussed throughout this book. Hence, we actually know more about learning and how to study learning than might be inferred from our disuse of the term. The verbal short-term memory studies provide a good case in point. If a subject correctly recognizes that an item was presented earlier in a previous list of items, we can say he has learned that it was presented earlier.
Accordingly, a description of the learning process will be exactly the same as our descriptions of perception and storage, retention and retrieval, and decision that were necessary to describe performance in the short-term memory task.

**LEARNING CONCEPTS**

The concept of learning has been discussed here without defining it explicitly; we have relied on the fact that our interpretations of this word are sufficiently similar to make this dialogue worthwhile. In fact, the use of a word or concept in this way presents a significant challenge to the learning psychologist or the philosopher of knowledge. For example, how do we come to know “learning”—an abstract concept—having had contact with nothing more than a series of relatively unrelated concrete instances of the learning process? This problem was posed by Plato in the *Meno* and has yet to be explained adequately. His explanation was that the soul or mind has already been acquainted with abstract concepts from a previous reality, so that all present signs of learning are actually signs of anamnesis (recollections). Plato solved the problem of learning by redefining it so that no explanation was necessary. Since we know everything there is to know, there is no need to describe how we come to know.

Aristotle rejected his mentor’s solution and proposed, instead, that learning and knowledge are derived from experience with concrete particulars. Aristotle reformulated the problem so that the question to be answered was: How does experience with a sequence of learning acts lead us to the generic concept of learning? His solution was one of abstraction; we isolate out common elements of learning scenarios to derive what is critical to the learning process. Aristotle’s common elements will not enable us to abstract enough information to define learning, mainly because perception is not a passive process but an active, constructive one. For example, we have discussed how the rules of English orthography are utilized to help make unambiguous a sequence of written letters. By constructing the relevant dimensions, we seem to be able to derive concepts from particulars. In philosophical terms, we arrive at universals on the basis of experience with particulars. This chapter will concern the rules by which one comes to learn a concept or schema as a function of his experience with concrete particulars.

**LEARNING PROTOTYPE**

Plato was concerned with the acquisition of the concept of virtue. Since virtue is difficult to bring into the laboratory, however, recent...
experimenters have studied the learning of visual and auditory concepts that can be specified precisely. The task is to have subjects classify instances of prototypical patterns while varying the similarity between the prototype and the instance to be classified. Consider two prototype patterns, A and B; these patterns can be distorted to various degrees and presented to subjects for classification. The experimenter seeks to determine which stimulus attributes are critical for classification and, more importantly, how the subject comes to know these stimulus attributes.

How does learning fit into our general information processing model? Learning occurs when the subject imposes a transformation in the processing sequence that leads to more accurate performance on subsequent trials. Consider insofarasiconsee, the sequence of letters presented one at a time to a subject who is to learn them in sequential order. This task could be relatively difficult, since the number of letters exceeds the span of immediate memory. If the observer learns, however, that the letter sequences spell a common and simple phrase, his learning rate should increase dramatically. In this case, calling on his lexical memory structures the task so that learning is facilitated. Whether or not the subject applies this rule, the sequence of processes is easily understood in terms of our information-processing model. In one case, the transfer from synthesized visual memory to generated abstract memory is in terms of letters; in the other, the transfer is in terms of words. However, the question here is how the subject comes to know that the letters spell words; and when he does, how does he recognize the correct words?

One way to ensure that the reader will interpret the sequence of letters as words is to put blank spaces in the appropriate places. Here we have changed a structural aspect of the stimulus to obtain this effect. By varying the number of blank spaces in the sequence of letters, we should be able to systematically influence the probability that the subject will read the letters as words. Even with no blank spaces, however, he will have some probability of interpreting the letters as words. This probability could also be influenced by context variables; for example, the subject could be given the appropriate set by first presenting other letter sequences that spell words. However, the best index of performance the experimenter can get is a probability; he cannot predict exactly whether a particular person will see words or unrelated letters on a particular trial. This is no different from our probabilistic interpretations of detection, recognition, and retention discussed in detail throughout this book.
Dot Patterns

The discussion above implies that learning is critically dependent upon perception, which is critically dependent upon the structural aspects of the stimulus situation. One demonstration of this has been a series of experiments carried out by Posner and his colleagues in which they distorted dot patterns that were then categorized by college students. In the Posner, Goldsmith, and Welton (1967) study, subjects were required to classify visual dot patterns as an instance of either a triangle, the letter M, the letter F, or a random pattern. The instances presented to the subjects were distorted from their prototypical pattern (shown in Figure 1), so that classification was not easy. Four levels of distortion were employed in generating instances from the prototypical patterns. The instances corresponding to these four levels of distortion of the triangle are shown in Figure 2.

Each prototypical dot pattern was represented on graph paper divided into squares. The dot would essentially fill one complete square. Each dot of the prototype would be moved according to a probabilistic schedule that differed for the different levels of distortion. The space was partitioned into five areas by defining a series of rings around the prototypical cell. The cell containing the prototypical dot was called zero, the eight surrounding cells called 1, and the next sixteen cells surrounding these eight were called 2, and so on until five such areas were defined. For each level of distortion, the dot could move into any of these five areas with a certain proba-

FIGURE 1. The four prototypical patterns used in the Posner, Goldsmith, & Welton (1967) study.
FIGURE 2. Four examples of distortion of the prototypical triangle. The numbers define the average number of squares each dot was moved for that level of distortion (after Posner, Goldsmith, & Welton, 1967).

bility. Once it entered an area, it was equally likely to enter any of the cells defined by this area. By varying the probabilities that a given dot can enter any of the five areas, the experimenter has direct control over the average distance each dot in the pattern will move. In one experiment (Experiment III, replication) Posner et al. (1967) chose 3 levels of distortion. Table 1 gives the average number of squares moved for each of the 3 levels of distortion.

In the experiment subjects were assigned to 1 of the 3 levels of distortion and presented instances of the 4 prototypes shown in
TABLE 1
Three Levels of Distortion Defined by the Average Distance (number of squares) Each Dot was Moved and the Mean Number of Classification Errors to a Criterion of Learning (after Psiner, Goldsmith, & Welton, 1967).

<table>
<thead>
<tr>
<th>Average distance</th>
<th>Mean number of errors to criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.23</td>
<td>4.6</td>
</tr>
<tr>
<td>1.91</td>
<td>12.2</td>
</tr>
<tr>
<td>4.56</td>
<td>71.1</td>
</tr>
</tbody>
</table>

Figure 1 generated from the appropriate distortion rule. The subject’s task was to respond to each pattern by pushing 1 of 4 buttons in front of him. The task involved learning to hit the correct button to each pattern. After the response the subjects were given feedback on each trial, indicating the appropriate response for each pattern. Three different instances of each of the 4 prototypes were presented in a random order until the subject made 24 correct classifications in a row or completed 240 trials. The mean number of errors to criterion at each of the 3 levels of distortion is presented in Table 1. As can be seen, the difficulty of the classification task is a direct function of the level of distortion employed to generate the instances. To the extent a dot was moved from its prototypical location, performance was disrupted. This result is not surprising and can be located in the recognition stage of information processing. If an instance of a triangle is distorted so that it no longer looks like a triangle, it cannot be classified correctly on this basis. Subjects given instances which were highly distorted had to learn the appropriate response to each of the 12 instances individually, since they were not able to see them as members of a prototypical pattern class.

TEMPORAL COURSE OF LEARNING

Although these experiments tell us that structural aspects of the stimulus are critical in prototype learning, we still do not know how the observers come to know the concept. Throughout the history of psychology there have been two major theories of the learning process. One theory assumes that learning occurs in a gradual incremental fashion; the subject slowly builds up the relevant information required for the task. The incremental learning theory can be viewed as a multistate process in which the subject goes through many successive learning states. In each learning state the probability of a correct response is slightly higher than it was in the
preceding learning state. The other theory is that the subject learns, or comes to know, in an all-or-none fashion. He tests out certain rules describing the situation and operates according to these rules or hypotheses until he settles on one that leads to accurate performance. The all-or-none learning theory is a two-state process. In the first state the subject knows very little and the probability of a correct response is near chance. In the second state the subject has solved the problem and the probability of a correct response is as high as is possible in the learning task. (The asymptotic probability may not be 1, since problems might not be capable of a perfect solution.)

How do we test between these two theories of learning? The task seems easy enough. We devise an experimental task and plot out a learning curve—performance across successive learning trials. The incremental learning theory predicts that percentage of correct responses should increase gradually across learning trials, whereas the all-or-none theory predicts that learning should occur in a single step at some point in the training session. However, when we look at the responses of a subject across trials, it is difficult to tell which theory gives a better description of performance. On each trial, performance is either correct or incorrect, and a trend in the data is

**Learning Curves**

**FIGURE 3.** A group learning curve demonstrating gradual learning, but based on the all-or-none results in Table 2.
not directly apparent. For this reason investigators have pooled the results over a number of subjects and have plotted group learning curves as shown in Figure 3. Here the curves plot the probability of a correct response on each trial derived from dividing the number of correct responses on each trial by the total number of subjects. These results invariably show incremental learning, rather than all-or-none learning curves.

Unfortunately, the group learning curves say nothing about the learning of individual subjects. As pointed out by a number of investigators (e.g., Estes, 1956), the individual subjects may actually have learned the problem in an all-or-none fashion, but by pooling the results this effect is washed out, giving a gradual learning curve. That is to say, pooling the results could give the incremental data shown in Figure 3, even if subjects learn in all-or-none fashion on different trials. Table 2 is an example of the individual results of ten subjects who learned the problem in an all-or-none fashion but gave

<table>
<thead>
<tr>
<th>Subject</th>
<th>Trial number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
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<tr>
<td>4</td>
<td>I</td>
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<td>5</td>
<td>I</td>
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<tr>
<td>6</td>
<td>I</td>
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<tr>
<td>7</td>
<td>I</td>
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<tr>
<td>8</td>
<td>I</td>
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<tr>
<td>9</td>
<td>I</td>
</tr>
<tr>
<td>10</td>
<td>I</td>
</tr>
<tr>
<td>Group average P(C)</td>
<td>0</td>
</tr>
</tbody>
</table>

the pooled results of Figure 3. This demonstration convinces most investigators that individual subject analysis is necessary to distinguish between the all-or-none and incremental learning theories. Unfortunately, even when an individual subject analysis is employed, it is very difficult to distinguish between the theories.

TABLE 2
When Pooled, Individual Protocols which Show All-or-None Learning Give the Gradual Incremental Curve Shown in Figure 3. The Letters I and C Refer to Incorrect and Correct Responses, Respectively.

Auditory Melodies Massaro (unpublished) asked whether prototype learning occurs in an all-or-none or incremental fashion. Auditory melodies were employed as stimuli. Each melodic pattern had 6 notes that lasted 50
msec. each, with 250 msec. of silence separating each note. Figure 4 presents the prototypes for the two patterns A and B. On each trial the stimulus pattern was determined by randomly choosing the pattern A or B. Then each successive note of the pattern was determined by choosing the prototypical note with a probability of 10/16; a tone one note higher or lower than the prototypical tone with probability of 2/16 each; and a tone two notes higher or lower than the prototypical tone with probability of 1/16 each. As can be seen in the figure, the first and last notes are the same for the prototypes of both patterns. Accordingly, these notes cannot provide reliable information for identification, and recognition must be based on the middle four tones.

Listeners were instructed to classify the auditory pattern on each trial as A or B by pushing the appropriate button on a panel in front of them. Subjects were informed that the melody would be a variation of either A or B, and they were to classify it as an instance of A or B. They were told that they could learn the patterns, since feedback would be given after they made their response on
each trial. Each trial began with the presentation of an auditory pattern followed by a 3 sec. response interval. The subject responded by pushing one of two buttons labeled A and B, respectively. Feedback was given at the end of the response interval by presenting the letters A or B for .5 sec. on a visual display. The intertrial interval was 1.5 sec.

**Testing Theories**  It is necessary to analyze individual subject data in order to test between the two learning theories. The all-or-none theory says that

**FIGURE 5.** A graphic representation of a hypothetical response sequence. This analysis can be utilized to display the temporal course of learning for an individual subject.
performance will begin at chance accuracy (.5 in this case) and then jump to some asymptotic level (not necessarily 1.0). By contrast, the incremental learning theory says that performance will gradually improve over the course of learning. The experimenter can process the data to give a sequence of Zeros and Ones, respectively. In this case, Zeros refer to correct responses and Ones refer to errors. The subject’s response protocol will, therefore, represent a sequence of Zeros and Ones. The incremental learning theory says that the probability of a Zero occurring should increase gradually over trials, whereas the all-or-none theory says that the probability of a Zero occurring should remain fixed for some number of trials and then jump to some higher value when learning occurs.

Viewing the sequence of Zeros and Ones, the experimenter will find it difficult to tell which theory describes the response protocol best. One graphic method involves plotting the sequence of Zeros and Ones on linear graph paper as shown in Figure 5. The X and Y axes are marked off in unit steps. The experimenter starts in the lower left-hand corner and goes up one unit for each correct response and to the right one unit for each incorrect response. If the subject is performing at chance accuracy (.5), then the steps traced out should follow a straight line with a slope of 1. As accuracy improves beyond .5, the slope of the line through the steps should become steeper and steeper. If the improvement in performance occurs in an all-or-none manner, the change in slope should be a sudden one.

The graphic analysis of the learning of an actual subject presented in Figure 6 shows that the change in slope might be interpreted as sudden rather than gradual. For this typical subject there appears to be a change in slope at Trial 36. The interpretation of the graphic representation is based on a mathematical analysis of the data developed by Theios (1968). The analysis indicated that the best description of the learning of this subject can be given by the two-state process predicted by the all-or-none learning theory. In the first state the subject’s correct response probability is fixed at some value, g, across trials. Then, on some trial, the subject learns or transits into a second state where his correct response probability is fixed at some value k, where k > g. The correct response probability then remains constant for the rest of the experimental session. For this subject the probability of a correct response was .61 during the first 36 trials and .89 thereafter.

Can we conclude with some confidence that this subject learned to identify the patterns in an all-or-none as opposed to an incremental manner? One way to check on our conclusion is to generate some hypothetical data according to incremental learning theory and to compare this data to the observed data, employing
FIGURE 6. Response protocols for a typical subject tested in Massaro's prototype learning study and a simulated subject behaving according to an incremental model.
both our graphic and mathematical analyses. We would expect and hope that the response sequences generated by the incremental model could not be described by the all-or-none model. Thus, there would be no sharp change in slopes in the graphic analysis and the response sequences could not be described with two probabilities (g and k) of being correct before and after a given trial.

A large number of incremental learning models could be generated since incremental learning might occur in a number of ways. For example, the subject could learn a small fixed amount on each trial. In this case, the probability of being correct should also increase by a fixed amount on each trial. Accordingly, performance could be described by the equation

\[ p_n = p_{n-1} + \alpha \]  

(1)

where \( p_n \) is the probability of being correct on Trial \( n \) and \( \alpha \) would represent the increment in correct performance. In our prototype experiment \( p_1 \) would be .5, since the subject will be correct half the time even if he knows nothing and \( p_n \) must asymptote below 1, since the subject cannot master the task completely. If we assume that maximum performance is about 85 percent and \( \alpha = .01 \), the task would be learned in 35 trials. This would correspond roughly to the time it took the actual subject in Figure 6 to learn. We can generate hypothetical or simulated response protocols according to this model by randomly drawing a Zero (success) or One (error) with \( p_n \) representing the probability of a success. In this case, \( p_1 = .5 \), \( p_2 = .51 \), \( \cdots \), \( p_{35} = .85 \), \( p_{36} = .80 \) = .85.

Using a random number table, we can look at a new two-digit number for every trial. If the number is less than \( p_n \times 100 \), we give the subject a success (Zero) on that trial. If it is larger, he gets an error (One). Also graphed in Figure 6 is a hypothetical response protocol according to this learning model. As can be seen in the simulated subject's slope, this data can also be interpreted as all-or-none learning, even though it was actually generated by an incremental learning theory. The mathematical analysis interpreted the learning sequences as arising from a two-state process with the probabilities of \( g \) and \( h \) equal to .61 and .77, respectively, with learning occurring after Trial 37.

Our short exploration into all-or-none vs. incremental learning indicates how difficult it is to distinguish between these two theories in actual experimental situations. Research in learning in the 1960s was focused on this controversy, and it has remained unresolved. According to the thesis developed in this book, our knowledge about learning will increase as we find out more about the
component processes that make it up. After we define the operations of these processes, it will then remain to be seen if a description of learning is possible.

**WHAT IS LEARNED?** What do subjects learn, remember, and utilize in normal cognitive functioning? The prototype learning experiments have shown that subjects learn to utilize certain dimensions or attributes of the stimulus for their categorization response. Bransford and Franks (1971, 1972) have carried out a series of interesting experiments to study what is learned and remembered when subjects are presented with a series of sentences. More specifically, they asked whether we retain specific sentences or whether we integrate these into a more holistic concept, forgetting details of sentence type.

**Ants and Jelly** Bransford and Franks had to develop an experimental paradigm to test their ideas. They presented subjects with a list of sentences. These sentences were not unrelated, but consisted of subsets of sentences each of which made up part of an arbitrarily chosen complete idea. The investigators asked whether the subjects would remember the sentences separately or whether they would integrate related sentences into a more holistic representation of the complete idea.

Consider this sentence: *The ants in the kitchen ate the sweet jelly which was on the table.* This sentence could be broken into basic propositions, each representing one fact, two facts, and so on as shown in Table 3. In a series of experiments, subjects were given

---

**TABLE 3**


<table>
<thead>
<tr>
<th>Sample Sentence</th>
<th>Component Sentences</th>
</tr>
</thead>
</table>
| The ants in the kitchen ate the sweet jelly which was on the table. | The jelly was sweet.  
The ants were in the kitchen. |
| **Type One:** 1 fact: |  
Type Two: 2 facts: | The ants in the kitchen ate the jelly.  
The sweet jelly was on the table. |
| Type Three: 3 facts: | The ants ate the sweet jelly which was on the table.  
The ants in the kitchen ate the sweet jelly. |

---
sentences from 4 different complete ideas. During the acquisition phase of the experiment, subjects were given sentence types One, Two, or Three from each of the 4 ideas. The sentences were randomly intermixed before presentation so that the relatedness of the sentences would not be completely obvious. Bransford and Franks also chose to use an incidental learning task. That is to say, subjects were not told that their memory for the sentences would be tested later or that the experimenters were interested in how they remembered the sentence. Subjects were merely asked a simple question about each sentence immediately after it was presented. For example, given the sentence The jelly was sweet, the experimenters might ask how the jelly tasted. In all, 24 sentences were presented.

Following the acquisition phase of the experiment, subjects were given a recognition test. They were presented sentences one at a time and told to indicate whether the sentence was old or new, that is, whether it had been presented earlier. They also rated the confidence in their decision on a five-point scale. Besides old sentences, two kinds of new sentences were presented during the test. Some of the new sentences were not presented during acquisition, but their meaning was part of one of the complete ideas generated by the old sentences. The meaning of other new sentences could not be derived from one of the complete ideas. The results indicated that the subjects seem to remember the overall meanings of the complete ideas rather than the specific sentences that were presented. Subjects easily mistook new sentences, with the same meaning as one of the complete ideas, as having been presented before. By contrast, new sentences that had a different meaning were correctly recognized as new most of the time. These results are especially convincing given the fact that many of the new sentences with different meanings were subtle distortions of the complete ideas. For example, subjects incorrectly answered "old" for the new sentence The scared cat running from the barking dog jumped on the table when it agreed with the complete idea, and correctly answered "new" for the sentence The scared cat was running from the barking dog which jumped on the table when it disagreed with the complete idea. These results show that subjects easily forget sentence length and complexity but remember an integrated meaning derived from a number of sentences.

The Bransford and Franks experiments show that the individual sentences are not treated separately if they are semantically related. The information from different sentences is integrated to form an interrelated structure which is remembered and used in
later processing. Bransford and Franks also show that subjects use what they know, to add to whatever linguistic information is given. They distinguish between the following two sentences:

(1) Three turtles rested beside a floating log and a fish swam beneath them.

(2) Three turtles rested on a floating log and a fish swam beneath them.

Even though the two sentences are very similar linguistically, they express different things about the state of the world of turtles, a fish, and a log. Sentence (2) specifies that the fish must have swum beneath the log since it swam beneath the turtles which were on the log. Sentence (1) does not imply or deny this possibility. Using what they know about spatial relations, then, subjects could infer that the fish swam under the log given Sentence 2, but not given Sentence 1.

Subjects were given sentences of either type in acquisition and tested for recognition memory using old and new sentences. New sentences corresponding to (1) and (2) above would be: Three turtles rested beside a floating log and a fish swam beneath it and Three turtles rested on a floating log and a fish swam beneath it, respectively. The results indicate that new sentences corresponding to (2) were recognized as old as often as actual old sentences. By contrast, new sentences corresponding to (1) were recognized as old significantly less often than the actual old sentences. These results show that subjects used what they knew to encode the sentences and were later interpreting a new sentence as old since it agreed with what they actually inferred and remembered. For example, if the subjects used visual imagery to remember the sentences, different visual images would be constructed for sentences (1) and (2), respectively. The visual image constructed given sentence (2) would have the fish swimming under the log; this would not necessarily be the case for sentence (1). Given the new test sentence, subjects reviewing their visual images would err in one case but not the other. The Bransford and Franks paradigm should prove to be highly useful for studying learning and remembering in a situation that closely approximates the way information is usually processed.

While the information-processing approach has not contributed many techniques to the study of the temporal course of learning itself, many of the studies throughout this book actually illuminate the learning function or its parts. Learning has maintained its behavioristic influence longer than other areas of experimental psychology and has lagged in its application of the information-processing approach. Indices taken from recent research in learning suggest a reversal of this trend.
By itself, a study of motion can tell us almost nothing about that which, in any given instance, is being moved. Similarly a study of behavior can, by itself, tell us almost nothing about the individual mind-body that, in any particular instance, is exhibiting the behavior.

—Aldous Huxley (Brave New World Revisited)

We have traveled a long, laborious road utilizing the information-processing approach to experimental psychology. What have we learned and what remains to be learned? Here we summarize our experimental approach and our information-processing model; and then we speculate about what remains ahead.

We have continually stressed that the experimenter must account for each of the processing stages in his psychological task. The information-processing analysis demands that the experimenter make explicit the implicit assumptions inherent in any experimental situation. Failure to do so severely limits what can be learned from the results. Such a fine-grain analysis is more than an exercise in esoteric argument. Rather, the information-processing methodology can be thought of as a microscope: it allows us to see what is not directly observable.

In this book, man is conceptualized as an information-processing system. The psychological phenomena we study begin with some stimulus and end with some observable response. One goal is to understand the stimulus-response relationship. A stimulus has potential information and in order to understand the response to the stimulus it is necessary to account for the operations initiated by the stimulus. The central assumption of our information-processing model is that a number of processing stages occur between stimulus and response. These processing stages are assumed to be successive and each stage operates on the information available to it. The operations of a particular stage take time and trans-
form the information, making it available to the next stage of processing. Two theoretical constructs are important in this approach. First, the structural construct describes or defines the nature of the information at a particular stage of processing. Second, the functional construct describes the operations of a stage of information processing.

This book utilizes a specific processing model as a theoretical and experimental guide for experimental psychology. The model is structured around experiments employing a particular experimental methodology. It is also used as a heuristic to incorporate data in some coherent manner from a number of different studies. In this way the model also functions as an organizational structure for the state of the art in experimental psychology. The main advantage of the theoretical framework is that it forces consistency in methodology, interpretations, and conclusions.

Figure 1 presents a flow diagram of the temporal course of visual and auditory information processing. The sound and light wave patterns are transformed by the auditory and visual receptor systems, respectively. We call this process feature detection, and this operation transduces the physical signal into a neurological code in preperceptual storage in the form of features. The features are described as acoustic or visual, since we assume that there is a direct relationship between the nature of the auditory or visual signal and the information in preperceptual storage. This one-to-one relationship between the signal and the information in preperceptual storage distinguishes the feature detection process from the succeeding stages of information processing. There is no one-to-one relationship between the input and output of the processing stages that follow, since these later stages actively utilize information stored in long-term memory in the sequence of transformations. For this reason the passive transduction of feature detection contrasts with the active construction of the later processing stages.

The outcome of the feature detection process is the information of whether or not a particular feature is present. We assume that the feature detection process sets up a list of features in preperceptual storage. These features are held there for a very short time—on the order of 250 msec. The primary recognition process involves a readout of the features in preperceptual storage and a transformation of these features into a synthesized percept in synthesized memory. Three sources of information are available to the primary recognition process: (1) the features in preperceptual storage, (2) knowledge in long-term memory, and (3) other contextual or situational knowledge. Perception requires an analysis and synthesis of the information made available by the detection of features in the sound or light pattern.
The minimal sound or light patterns that can be recognized are referred to as perceptual units of information. Perceptual units correspond to those patterns that are uniquely represented by signs in long-term memory. Each sign contains a list of features that describe the perceptual unit. The primary recognition process finds the sign with the best description in long-term memory that matches the features held in preperceptual storage and the current contextual information. The location of this sign initiates a synthesis program for seeing or hearing this particular sign, that is, for transforming the information into synthesized memory.

The secondary recognition process transforms the synthesized memory into meaningful units in generated abstract memory. This process also involves recognition in the sense that the observer chooses which of several alternatives is presented; it is called secondary recognition (conception) to distinguish it from the primary recognition process. Although conception is an uncommon term for this stage of processing, it seems to be an appropriate description, since it involves an analysis of synthesized memory for...
meaning. This conceptual stage of processing involves finding a match between the synthesized percept and information held in long-term memory.

We assume that the knowledge responsible for secondary recognition is stored in long-term memory in the form of codes with perceptual and conceptual attributes. The representation of every concept has a code with both perceptual and conceptual attributes. For example, the perceptual code of wind might contain some representation of the sound of the word wind, the look of the letters that spell wind, the sound of the wind blowing, and the pictorial representation of a windy scene. The conceptual code of wind would be the variety of properties that constitute the meaning of wind, such as air movement. The secondary recognition process looks for a match between the percept of the sound pattern held in synthesized memory and a perceptual representation of that code in long-term memory. The location of the perceptual representation also locates the conceptual code, since the perceptual and conceptual codes are stored together. The secondary recognition process transforms the synthesized perceptual pattern into a conceptual meaningful form in generated abstract memory, so called because the transformation is an active generation rather than a passive derivation and because meaning is abstract rather than modality-specific.

The recoding process operates on the concepts in generated abstract memory to derive further meaning from the entire sequence. This transformation of the string of meanings into a more specific and abstract form does not change the specific nature of the information. Hence, this information is recirculated back through generated abstract memory. The recoding process has access to whatever knowledge of rules the system has available in long-term memory—for example, the semantic and syntactic rules of a language. The recoding process can also operate in reverse. Given an abstract idea, it can transform this concept into a sequence of words in generated abstract memory or a perceptual representation in synthesized auditory or visual memory. Finally, the processing at this stage may be a simple regeneration or repetition of the information in generated abstract memory, in which case the operation is called rehearsal.

This general model serves as a heuristic to study each information-processing stage and how the stages work together. The utilization of this model has met with preliminary success in the study of speech perception and reading (Massaro; in press). We believe that the information-processing approach can bring the psychologist from experimental research to a greater understanding of difficult, meaningful, and important psychological phenomena.
Hopefully, the reader has been able to impose a structure on this journey, making our trip a worthwhile experience. One can consider a good book to be analogous to a good symphony. It must have a prelude which first attracts the observer's attention. Then its movements—light and heavy—occur at the appropriate times to keep the participant engaged. Finally, the work should have a grand finale. Having here completed the prelude and many light and heavy movements, what about the finale? To reach the finale, the information-processing approach to experimental psychology must still complete its long-term test of increasing our knowledge of ourselves.
Many of the questions raised in the two monumental volumes of William James (1890) remain central to experimental psychology. Almost a century after they were written the volumes make particularly good reading. The mind-body problem has recently become the object of renewed interest by psychologists. Sperry (1969), known for his fascinating work among patients with surgical separation of the two hemispheres, has argued against the epiphenomenalism currently fashionable in the neurosciences. His solution to the mind-body problem is very similar to the monistic theory developed here. A recent analysis of consciousness is provided by Mandel (in press), and reviews of the work in biofeedback training can be found in Miller, Barber, DiCara, Kamiya, Shapiro, and SToyva (1973).

Hadamard's (1954) eclectic treatment of the nature of discovery was influential in developing the stage analysis of discovery. Albert Einstein's reflections on the thought processes involved in the creation of the theory of relativity were the source for a chapter in Wertheimer's classic study (1945, reissued in 1959). McCormick (1959) provides an introduction to digital computers, and Wooldridge (1963) gives an exciting treatment of the machinery of consciousness and its similarities to the operations of inanimate information-processing systems.

Some relevant sources for the history of experimental psychology can be found in Boring (1950), Bruno (1972), and Ranorello (1968). Radford (1974) contains a recent reflection on introspection and Norman (1970, 1973) analyzes questions such as the one we discuss, "in the house you lived in two houses ago . . . ."

The time it takes to decide "What day is today?" is the subject of a study by Koriak and Fischoff (1974). McCain and Segal (1973) introduce the student to the psychology of the scientist and his game of science, while Kuhn (1970), in an important work, covers the nature of scientific discovery.
Chapter 3  Donders' original paper has been translated and republished (1969) in the same volume as Sternberg's (1969b) presentation of the additive-factor method. A good introduction for the beginning student is Sternberg (1969a), and a review of the applications of the additive-factor method to a number of psychological problems is provided in Sternberg (1971). Woodworth (1938) devotes a chapter to the early work on reaction times. Murray (1970) and Grice (1968) have studied how stimulus intensity influences reaction time.

Chapter 4  The memory search task has developed into one of the most popular paradigms of current psychological research (e.g., Atkinson & Juola, 1974), and the serial-exhaustive search model has not gone unchallenged (J. A. Anderson, 1973; Murdock, 1971; Theios, 1973). A comprehensive review of many of the recent studies utilizing reaction times is contained in Nickerson (1972). Kristofferson (1972a,b,c) and her colleagues (Kristofferson, Groen, & Kristofferson, 1973) have explored the effects of practice and error rates in both the Sternberg and Neisser search tasks and show that differences in these variables are responsible for many of the differences originally found in the two tasks. A visual search task that eliminates the necessity of eye movements has been developed by Sperling, Budiansky, Spivak, and Johnson (1971).

Chapters 5, 6, and 7  Krantz (1969) has developed a threshold theory with three sensory states and Stevens (1972) argued for a neural quantum model of sensory discrimination. The question of whether or not confidence judgments could be used as a test between two-state and multistate theories can be followed in a series of papers by Watson, Rilling, & Bourbon (1964), Larkin (1965), Watson & Bourbon (1965), Broadbent (1966), Wickelgren (1968), and Massaro (1969). Massaro provides an experiment that uses the dice game to analyze the operations of the decision system.

Chapter 8  The treatment of the Hecht et al. (1942) experiment is similar to that provided by Cornsweet (1970), who presents an excellent treatment of brightness and color vision. The Hecht et al. study is reprinted in Cain and Marks (1971) along with other historical papers on sensation.

Chapter 9  Most of the relevant readings or, more appropriately, viewings can be found in the picture credits. Also, your local art museum is a great resource center. For op (optical) art Barrett's (1970) book provides a nice introduction. Kanizsa (1974) provides an intriguing treatment of illusory contours, and Coren (1972) makes the case that these contours are seen because of depth cues such as inter-

A particularly fine treatment of visual illusions by Luckiesh in 1922 has been reprinted (Luckiesh, 1965). Gardener (1970) devotes one of his sections on mathematical games in Scientific American to optical illusions, and a variety of illusions are explained by Day (1972), who utilizes so-called perceptual constancies such as size constancy. Robinson (1972) gives the most complete and exhaustive coverage of research and theory in illusion. The influence of psychological research on M. C. Escher's creative work is discussed in Teuber (1974). A fun exhibition called Illusion in Science, Nature, and Art, which opened in London in 1973 and is scheduled for an international tour, was the basis for a book of related essays edited by Gregory and Gombrich (1973).

The phenomena of size and shape constancy are reviewed by Epstein, Park, and Casey (1961) and Epstein and Park (1963), respectively. Helmholtz's treatise of the last century has been reissued, as has Hering's work, allowing the reader to follow their disagreements (Helmholtz, 1962; Hering, 1964; Warren & Warren, 1968). Presentations of high excellence are provided by Hochberg (1971) on the invariance hypothesis of size and shape perception, and by Cornsweet's (1970) treatment of brightness and hue constancy. A good historical and theoretical account of the horopter is given by Shipley and Rawlings (1970), and, for further reading on binocular vision, Ogle's (1964) book is recommended, as are Sperling's (1970) and Julesz's (1971) advanced treatments. Gibson (1950, 1966) focuses on the structural information defining our visual world.

Sperling's (1960) partial report task has been replicated and extended by a number of investigators (Turvey & Kravetz, 1970; von Wright, 1968, 1970, 1972). In contrast, Dick (1969, 1971) has demonstrated how short-term memory processes may play the significant role in the partial report task. Our analysis of the Averbuch and Coriell (1961) experiments in Chapters 17 and 18, however, substantiates our interpretation of Sperling's results and is not open to Dick's criticisms. Nonetheless, his point of view is well taken and is particularly applicable to utilization of the partial report task in audition (see Chapter 21). One of the most influential memory models is that of Atkinson and Shiffrin (1968). A number of recent experiments have focused on immediate and delayed tests of memory as a way of investigating the fate of memorized items (e.g.,
Bartz, Lewis, & Swinton, 1972; CRAIK, 1970; Darley & Murdock, 1971; Light, 1974). The readings given for Chapters 24–28, which provide a more extensive treatment of memory, are also relevant.

**Chapters 13, 14, 15, and 16**

In the recent literature, attention has received a great deal of exactly that. The latest are the books by Kahneman (1973) and KEELE (1973), and Broadbent (1971) has an excellent review and treatment of the attention literature. Hochberg (1970), Norman (1968), Swets and Kristofferson (1970), and Treisman (1969) are recommended for further reading.

**Chapters 17, 18, and 19**

Experimental psychologists have lately shown renewed interest in the reading process. Woodworth (1938) still remains one of the best treatments of psychological processes fundamental to reading. Smith (1971) is a good introduction to reading, while Huey's book (1906; reissued in 1968) provides a refreshing, insightful treatment focusing on many of the problems still current today. Turvey's (1973) article is a trenchant empirical and theoretical analysis of visual masking. Some recent studies in letter and word recognition are found in Estes (in press). Massaro and Schmuller (in press), present a review of the visual features utilized in letter and word recognition. In the same volume, Massaro (c) presents a summary and evaluation of current theories of reading and Shebilske analyzes the implications of reading eye movements from an information-processing point of view.

**Chapters 20, 21, 22, and 23**

Denes and Pinson's (1963) introduction to sound and speech can be profitably followed by Wilder's (in press) review of the characteristics of speech production and the physical properties of speech sounds. The processing model developed here has been extended to account for many aspects of speech processing. Massaro (in press, a) provides an analysis of the acoustic features that are functional in speech perception and (b) analyzes the temporal course of processing speech. Paap, in the same volume, sets forth a detailed analysis of the current theories of speech perception and an evaluation of these theories against empirical data. In another approach Cole and Scott (1974) tackle the same questions. Thurlow (1971) and Lindsay and Norman (1972) cover some aspects of auditory perception—such as spatial localization—that are not discussed in this book.

**Chapters 24, 25, and 26**

The delayed comparison task has been used by Siegel (1974) to study persons with absolute pitch. Synthesized auditory memory has been the focus of a number of recent experiments (Crowder & Morton, 1969; Darwin & Baddeley, 1974) and investigators have
also shown renewed interest in categorical perception (Pisoni, 1973). Paap (in press) reviews these studies with special emphasis on the role of synthesized auditory memory in processing speech and Freund (in press) covers recent research on prosodic information—intonation and stress—that is presumably held in synthesized auditory memory for processing. Highly relevant to the concept of synthesized visual memory is the recent empirical and theoretical work on visual imagery by Bower (1970) and Palvio (1971).

The structures and the processes operating in short- and long-term memory are central to much of current research. The greatest impact has come from the influence of artificial intelligence and linguistics (Shank, 1972; Fodor, Bever, & Garrett, 1974; Anderson & Bower, 1973). Smith, Shoben, and Rips (1974) have utilized semantic features to describe reaction times to analytic statements. The development in linguistics in terms of an information-processing approach is reviewed in Solberg (in press). Bower, Garner, Mandler, and Tulving have contributed to our knowledge of organization factors in memory and learning (e.g., Bower, 1972; Garner, 1974; Mandler, 1972; Tulving & Thomson, 1973). A comprehensive coverage of theory and data in human memory is presented in Murdock (1974), and Kausler (1974) has a refreshing treatment of verbal learning and memory. Hellige (in press) analyzes the role played by generated abstract and long-term memory in sentence processing. Recent work in learning (Estes, 1973; Grant, 1972, 1973) has taken on an information-processing outlook.

Journals provide the most current coverage of experimental psychology. Articles relevant to the philosophy of science and such topics as the mind-body problem can sometimes be found in American Psychologist, Psychological Review, Psychological Bulletin, and Cognition.

Behavioral Research Methods and Instrumentation presents papers dealing with methodology and instrumentation. The scientist in the twentieth century is critically dependent on the most technologically advanced equipment. This journal gives the reader a good idea of the state of the art in the relevant technology. Research in psychophysics and perception can be found in Journal of the Acoustical Society of America, Vision Research, Perception and Psychophysics, Journal of Experimental Psychology: Human Perception and Performance, Perception, and American Journal of Psychology.

Articles on attention, auditory and visual information processing, memory, learning, and decision making are published in the same journals recommended for psychophysics and perception and...


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