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Memory Storage Dynamics

Wayne A. Wickelgren

University of Oregon

Memory has three operationally-distinct temporal phases: acquisition (learning), storage (retention), and retrieval (usage). It is reasonable to suppose that these operational phases also correspond to theoretical phases. Of course, there may be a number of interesting theoretical interactions between acquisition, storage, and retrieval processes. For example, the rate of forgetting for one event might be slower than the rate of forgetting for another because of differences in the extent or nature of the acquisition process in the two cases. Another frequently cited interaction is that the nature of the retrieval process, particularly for recall and possibly also for recognition, is such as to underestimate the level of memory, perhaps to a different extent at different retention intervals.

Another way in which the phases may not be so sharply distinguishable concerns the time of onset and offset of acquisition, storage, and retrieval. It could be that the acquisition phase terminates precisely when the storage phase begins, and the output of the acquisition process at that terminal point is the input to the storage phase. But this need not be so. It could be that the storage phase begins for all or a portion of the trace while the acquisition phase is continuing for the same or other portions of the trace. The latter possibility is reasonable on the assumption that the portion of the memory trace that has already been acquired begins to undergo decay and interference while the trace is being further strengthened during acquisition. It seems very likely that recall of a memory trace constitutes an opportunity for acquisition when recall is correct and also for interference when recall is incorrect. Finally, the conscious process of acquisition may be supplemented by an unconscious consolidation process.

necessary in some way for the establishment of a viable long-term memory trace. Consolidation may occur in part during acquisition, but it is frequently supposed to occur largely or completely during storage, while other events are being processed.

Despite all these complications, the distinction between acquisition, storage, and retrieval is essential to a clear understanding of the dynamics of memory. Developing a good theory of memory dynamics is a complex problem. No progress can be made in such a problem without analyzing it into parts. However, the nature of this analysis is critical to the success of the endeavor. One analysis into subproblems is superior to another analysis to the extent that solutions to the subproblems in one analysis are more independent of each other than in the other analysis. Although almost all memory researchers accept the acquisition, storage, and retrieval analysis, they differ concerning the usefulness of other concepts and subproblem analyses. In some cases I will present arguments in support of my positions, but for much of my general subproblem analysis of memory, I can only hope to present the concepts and analyses clearly, so that the purposes of this chapter are understood.

The present chapter is concerned with memory dynamics. Memory dynamics refers to time changes in the level (strength, probability of correct recall or recognition, etc.) of the memory trace being acquired, stored, or retrieved. Memory dynamics is concerned with quantitative properties of the trace and how these change over time. By contrast, coding is concerned with qualitative properties of memory such as the modalities of memory, representation by attributes, features, chunks, concepts, propositions, and images, etc. Although there is probably some interaction between coding and dynamics, it is perfectly reasonable to suppose, for example, that the encoding properties of a trace can be handled by estimating one or two parameters within a theory of memory dynamics, without the need to assume any particular coding theory. Thus, the present chapter is concerned with memory dynamics, with the nature of coding being presumed to affect this in a very limited way.

In addition, the present chapter is primarily concerned with storage dynamics as opposed to acquisition or retrieval dynamics. That is to say, the primary concern is with what happens to the memory trace during the retention interval. Consolidation in storage will be discussed, as will the degradative processes of decay and interference that may occur during the retention interval. In addition, other causes of retention failure that are primarily localized during acquisition or retrieval will be discussed for two reasons: First, such causes of retention failure are sometimes difficult to distinguish from causes that originate during storage. Second, there are interesting possible interactions between the acquisition or retrieval phases on the one hand and the storage phase on the other.

The term "memory trace" should be considered to be theoretically neutral, implying nothing concerning the nature of this trace or the way in which it is represented in theory. However, as is typical of those who use the term "memory trace," I will discuss memory within the continuous strength conception, rather than the all-or-none (discrete, finite-state) conception of memory. That is to say, I shall assume that memory varies continuously on a dimension called strength. Prior to acquisition, memory strength is zero. After acquisition, it rises to some positive value, from which it generally declines during the storage interval. At the time of retrieval, the remaining strength of the memory trace (or some portion of it) is used to determine recall and recognition, with higher strength producing higher probability of recall and recognition.

By contrast, an all-or-none theory (Bower, 1961; Estes, 1960) assumes that the memory trace for any particular association (for example, for an *A-B* word pair) has only two values: learned (1) or unlearned (0). In a learning trial there is some probability that an association will go from the unlearned state (0) to the learned state (1). In some period of time during the retention interval there is also some probability of making the reverse transition from the learned to the unlearned state. Many other finite-state theories have been formulated. For example, Atkinson and Crothers (1964) developed a model in which a memory trace can be in one of four states: in long-term memory (L), in short-term memory (S), forgotten (F), and unencoded (U). With respect to performance on a memory test, being in states L or S produces an equivalently high probability of correct performance, while being in states F or U produces an equivalently low probability of correct performance. However, states L and S differ in forgetting probabilities, and states F and U differ in acquisition probabilities (probabilities of entering the L state on a learning trial).

Despite numerous attempts to devise a critical experiment distinguishing between the continuous strength and the finite-state conceptions of memory, it has proven to be impossible so far to decide this issue on the basis of any simple series of experiments or theoretical argument. Most theoretical assumptions one may wish to make about memory can be formulated in either framework, and only time will tell which framework is most useful.

Finally, in this chapter I will assume that there is only a single dynamic type of associative (nonsensory, nonactivity, postattentional) memory trace, with no need to distinguish short-term and long-term memory. Dual-trace theories assume the existence of two types of traces with different laws of acquisition, storage, and/or retrieval. The most commonly assumed difference has been in forgetting rate, with short-term traces being destroyed in a matter of seconds or tens of seconds in the absence of rehearsal and long-term traces lasting for perhaps hours, days, weeks,

or years. More qualitative differences in storage dynamics have sometimes also been postulated (for example, Wickelgren, 1974a) such as that short and long traces differ in susceptibility to interference from subsequent experience and the mathematical form of the forgetting function (memory strength as a function of retention interval).

All of the evidence that for so many years was interpreted in support of a dual-trace theory now appears to be more adequately explained by a single-trace theory (Craik & Lockhart, 1972; Wickelgren, 1973, 1974b, 1975a). Hence, in this chapter the single-trace theory will usually be assumed, with only occasional references to a few interesting logical possibilities that are obtained with a dual-trace theory that are not present in the single-trace theory. In the sections of this chapter concerned with consolidation and decay I also present arguments in support of a particular single-trace theory.

I. CONSOLIDATION

The idea that memory traces become more firmly fixated over a period of time following the termination of formal practice has been around at least since the classical preservation-consolidation theory of Müller and Pilzecker (1900). From a psychological standpoint, there appear to be two basic classes of consolidation theories: In one, the strength or availability of the long-term component of the trace actually increases for a period of time following formal practice. In the other, some other property of the trace changes in such a way as to make the trace less susceptible to forgetting or other sources of trace degradation.

Since an absolute increase in the strength of the memory trace (remembrance) is only rarely observed, the first class of theories typically depends upon the assumption of two (or more) traces. The rapid decay of a short-term trace occurs simultaneously with a gradual increase in the strength or availability of the long-term trace. This produces net forgetting under most circumstances, but perhaps occasionally could produce remembrance. Within the dual-trace conception there are two classes of hypothesis regarding the relationship between short-term and long-term memory in consolidation: the independence hypothesis and the conversion hypothesis.

A. Increase in Strength

The independence hypothesis has been advocated by only a few researchers (for example, Shallice & Warrington, 1970; Wickelgren & Berian, 1971). According to this hypothesis, short-term memory and long-term memory are established by independent mechanisms, with long-term memory taking more time to be established than short-term memory, but also decaying more slowly thereafter.

The conversion hypothesis is much more popular (for example, Atkinson & Shiffrin, 1968; Norman & Rumelhart, 1970; Waugh & Norman, 1965). According to this hypothesis, the consolidation process consists of a transfer of information from short-term to long-term memory. In conversion hypotheses, there has frequently been some ambiguity regarding whether the conversion process was conscious rehearsal or an unconscious conversion from short-term to long-term memory. Amusingly or appropriately enough (depending on how you look at it), this theoretical ambiguity has often been paralleled by experimental ambiguity regarding the degree to which rehearsal was adequately controlled during the retention interval. If traces get stronger because human (or animal) subjects can continue thinking about the learning experience during the early portion of the retention interval, then it would seem that no separate consolidation phase need be assumed. One just has to admit that frequently acquisition is prolonged past the experimentally defined practice period.

Essentially, all animal behavioral and physiological studies of consolidation are subject to the criticism that the organism may go on actively "thinking" about the learning experience during the retention interval. We do not even have a beginning idea concerning how to control this type of thinking (rehearsal?) in animals. With human beings, there is some intuitive plausibility to the notion that difficult information-processing tasks eliminate most or all rehearsal, but there is no proof that various tasks which are supposed to eliminate rehearsal do not allow different degrees of rehearsal (or conscious thinking of some other type) regarding the learning experience.

In any event, whatever the experimental and theoretical difficulties in distinguishing acquisition and consolidation, it appears that rehearsal and the time per se for which an item is thought about plays a much less important role in the formation of a long-lasting memory trace than does the encoding of the material to be remembered in the form of an integrated visual image or proposition (for example, Anderson & Bower, 1973; Bower, 1972; Craik & Lockhart, 1972).

An increase in the probability of correct recall or recognition over some retention interval (reminiscence) has occasionally been used as evidence for the existence of a consolidation process (for example, Peterson, 1966). However, reminiscence is a very infrequent phenomenon and a variety of more plausible explanations can be given for this effect in the few cases in which it has been observed. At all retention intervals, forgetting is overwhelmingly more frequently observed than reminiscence. Many published findings of reminiscence are undoubtedly Type-I errors. Furthermore, all the systematic work which has been done to determine conditions that reliably produce reminiscence has been done with recall rather than recognition. Since recall is subject to a variety of retrieval interference effects, one can hardly argue for an increase in strength during

storage using a recall measure. Although there are a few scattered reports of reminiscence in the literature using a recognition measure, these few reports are overwhelmingly outweighed by recognition studies that show forgetting over the same period of time. In my own research, I have obtained hundreds of retention functions for a wide variety of verbal and pictorial material at hundreds of different retention intervals from fractions of a second to over two years under a variety of conditions using a variety of paradigms, and I have never obtained any systematic evidence for reminiscence at any retention intervals under any conditions for any type of material.

Finally, arguments favoring a single-trace theory over a dual-trace theory also argue against the hypothesis of consolidation as an increase in the strength or availability of the long-term memory trace (Wickelgren, 1973, 1974b, 1975a).

B. Decrease in Fragility

The second class of consolidation theories is compatible with a single-trace theory of postattentional memory, since it asserts, not an increase in trace strength, but rather a decrease in the susceptibility of that trace to decay, interference, and/or other sources of trace degradation (Wickelgren, 1972, 1974a, b).

According to the latest version of this theory (Wickelgren, 1974b) there is only one memory trace, but it has two important dynamic properties: strength and fragility. Greater strength implies a greater probability of recognition and recall, while greater fragility produces greater susceptibility to time decay, but not to interference. As a memory trace ages, it undergoes forgetting due to both time decay and interference, but the fragility of the trace is also decreasing with increasing trace age, producing a progressively slower and slower rate of time decay. Fragility decreases throughout the lifetime of a memory trace. Thus, consolidation is assumed to go on potentially for years, though the principal decrease in fragility occurs within minutes or hours following learning. Proportionately more consolidation occurs in the first second than in the next second than in the next second, etc. There is a substantial degree of support for this theory of consolidation from several different sources.

1. Form of Retention Functions

First, the formulation of this theory (Wickelgren, 1974b) predicts that the form of the retention function should be as follows:

$$d = \lambda(1 + \beta t)^{-\psi} e^{-\pi t} \quad (1)$$

In the above equation d is the strength of the memory trace t sec following learning, λ is the degree of original learning, β and ψ are rate parameters for the time decay process (ψ is inversely proportional to the rate of consolidation), π is the rate parameter for the interference process (representing the similarity of interpolated learning to original learning), and t is the retention interval. This equation provides a remarkably good fit to the retention data over a wide variety of retention intervals ranging from seconds to over two years. Furthermore, although the interference parameter (π) varies substantially for different types of material, the time decay rate (ψ) does not appear to vary systematically with the retention interval from seconds to years.

However, irrespective of exactly what equation is eventually shown to provide the best fit to retention functions, the data are clearly in accordance with Jost's Second Law, that the rate of forgetting continually decreases with increasing time since learning. For example, consider the retention functions illustrated in Figure 1. These retention functions come from a continuous recognition memory experiment reported in Wickelgren (1972b). In various conditions, either words or consonant triple and digit triple (CCCDDD) items were presented for either 3.5 or 7.0 sec,

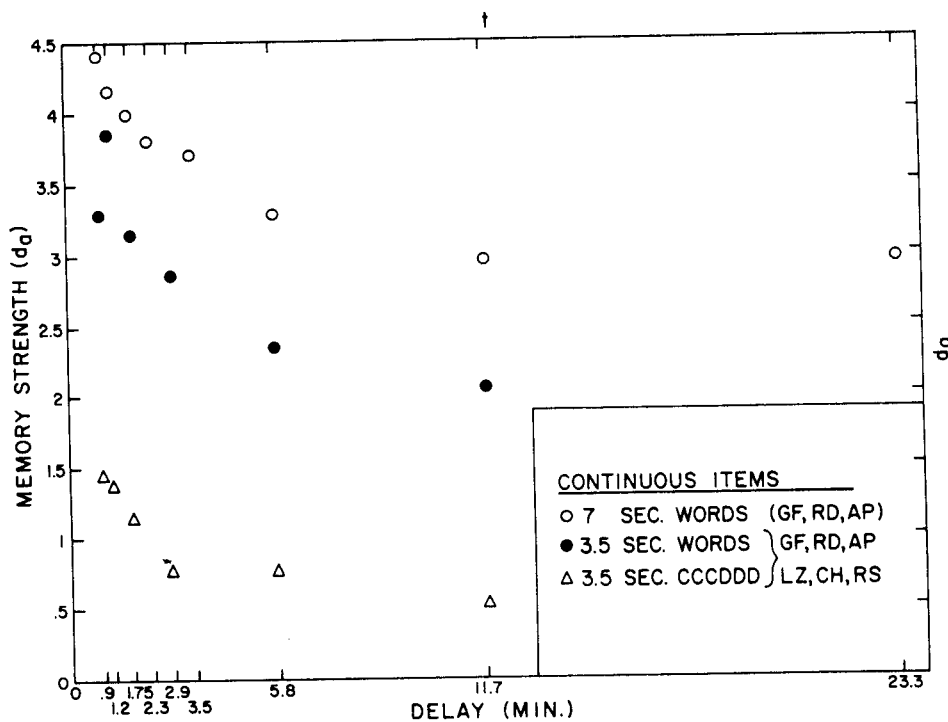


FIGURE 1 Retention functions for continuous recognition memory from Wickelgren (1972b).

one after another without a break (continuously). The items were a mixture of new items and old items (repeats at various retention intervals of items presented earlier). Subjects decided "yes" or "no" as to whether each item had been presented earlier and rated their confidence in this decision on a four-point scale. From the recognition accuracy at each retention interval, a measure of strength (d_a similar to d') was computed using the methods of statistical decision theory. As can be seen in Figure 1, the forgetting rate slows down drastically as the delay since learning increases. Furthermore, the same conclusion holds if log strength is plotted against time, to eliminate any necessary slowdown in forgetting as performance approaches chance.

This gradual reduction in forgetting rate is in accord with the theory of consolidation as a gradual decrease in susceptibility to trace degradation. This sort of property does not appear to be derivable from a theory in which short-term memory is gradually converted into long-term memory over a period of years. The problem is that the short-term trace must be assumed to have relatively rapid decay to distinguish it from the long-term trace. This being the case, the short-term trace would be gone long before it could be converted to long-term memory, assuming that the conversion process takes years to complete (as it must in order to fit long-term retention functions). Perhaps there is a way out of this dilemma, but numerous attempts on my part to make a conversion hypothesis fit have failed completely. I have never been able to make an independence hypothesis of the transformation of potential long-term memory into retrievable long-term memory fit the long-term retention data either, but I am not quite so sure that it is impossible as I am with the conversion hypothesis.

2. *Retrograde Amnesia*

Second, the decreasing fragility theory of consolidation accounts for the dependence of retrograde amnesia on the age of the memory trace. Following severe concussion-type head injuries, patients frequently suffer from retrograde amnesia extending for periods ranging from seconds to minutes, hours, days, weeks, or even years prior to the accident (Russell, 1959). The temporally selective character of the law seems to require the assumption of a second property of the memory trace besides strength, since it is not the strongest or the weakest traces that are lost, but the most recent traces, irrespective of strength. In agreement with the hypothesis that the consolidation process continues over a period of years, the data indicate that retrograde amnesia may extend over a variable period of time up to as long as many years. Thus, precisely the same type of extended consolidation process is necessary to explain both the form of retention functions and retrograde amnesia.

It should be mentioned that the losses seen in retrograde amnesia are rarely permanent. Usually the patient recovers most of the lost memories. The temporary or permanent nature of this loss is completely outside the scope of the present consolidation theory and is not relevant at present to its validity. However, the recovery shows the same temporal specificity shown by the initial loss, namely, when memories are recovered, the oldest are recovered first. Hence, the decreasing fragility theory of consolidation explains the systematic character of both retrograde amnesia and the recovery therefrom.

3. *Recency Judgments*

Third, assuming that the fragility of the memory trace is a retrievable attribute, it could serve to a limited degree as a kind of biological clock measuring the age of a memory trace. Thus, fragility might serve to mediate recency discrimination under conditions where subjects have no access to external clocks of any kind. This implication has been tested, and both the qualitative and quantitative results concerning recency discriminability over a period of a minute to two hours are in accord with the predictions of the theory (Wickelgren, 1974b).

4. *Spacing Effects*

Fourth, this theory of consolidation may provide an explanation for the effects of spaced learning on retention (Wickelgren, 1972b). The longer the interval between two learning trials, the less fragile the trace contributed by the first trial and therefore the less rapid the forgetting of that component of the trace. Of course, the greater the spacing between trials, the more forgetting of the first trace and presumably the smaller its contribution to the total memory trace. No satisfactory quantitative formulation of this general idea has been developed.

5. *Physiological Studies*

Some mention should be made of the extensive animal physiological studies on consolidation, such as studies of effects of electroconvulsive shock or drugs such as protein synthesis inhibitors (see Deutsch, 1969, and Weiskrantz, 1966, for review). Virtually all of these studies were interpreted to support the hypothesis that consolidation is an increase in the strength or availability of a long-term trace. However, these physiological investigations are at least as consistent, if not more so, with the hypothesis of consolidation as a reduction in trace fragility in a single-trace theory.

A consistent methodological problem in this area concerns the failure to adequately distinguish between learning and performance. Of course

there are the usual motivational and attentional issues and their interactions with physiological manipulations. However, one of the most widespread problems concerns ceiling effects at short retention intervals. When a study reports that a physiological manipulation, such as the administration of a protein synthesis inhibitor, produces no deficit at short retention intervals, but a substantial deficit at longer retention intervals, it is not justifiable to conclude that this evidence supports a two-trace theory in conjunction with consolidation as an increase in the strength of the long-term trace over time. Such results could equally well be interpreted as indicating that the treatment increased the rate of decay of a single memory trace. Such an increase in decay rate might well have no observable effect at short retention intervals, since relatively little time has been allowed for the decay process to occur.

The physiological manipulation might also simply produce an immediate reduction in trace strength (or lower initial degree of learning). If performance is near ceiling, even a substantial drop in strength might have little or no effect on performance at a short retention interval. Such an effect would show up only later after some forgetting had taken place. The use of one-trial learning tasks in the study of consolidation has a number of advantages, but it also has the disadvantage of producing an unknown degree of overlearning.

Furthermore, the time period of consolidation across a variety of physiological studies varies substantially: from seconds to hours or days depending upon the conditions and the nature and strength of the amnesic agent. Such variability seems more consistent with the hypothesis of a reduction in trace fragility. Certainly a strong case can be made (for example, Weiskrantz, 1966) that the physiological studies support some hypothesis in which consolidation takes place at a decreasing rate over the entire lifetime of a memory trace (rather than being completed in a short period of time on the order of seconds, minutes, or hours).

Finally, a study of hemispheric conflict and the forgetting of lateralized traces by Goldowitz, Buresova, and Bures (1973) also supports the hypothesis of consolidation as decreasing fragility of traces (see Wickelgren, 1974a, for a more detailed discussion).

II. INTERFERENCE

The hypothesis that a considerable portion of forgetting is due to interference between different learning or other information processing activities is about as old as the scientific study of human learning and memory. Sometimes, it is implied that there is "an" interference theory. Actually, there are a large variety of different interference theories. The best way to

describe all the possible interference theories available at present is to list the six different interference mechanisms that have been suggested. Any combination of these mechanisms constitutes a different theory of interference though not all combinations have been advocated. Of course, there are also a variety of different ways to formulate each of these six interference mechanisms, leading to an enormous variety of different possible interference theories. The six different interference mechanisms can be given the mnemonic labels: competition, unlearning, blocking, response suppression, associative suppression, and acid bath. Each of these interference mechanisms will be defined, along with the evidence for or against each one as a contributor to retention failure.

A. Competition

In a conventional paired-associates recall experiment, a subject is forced to give a single response to each stimulus. If the subject learns an $A-B$ list followed by an $A-C$ list ($A-B$, $A-C$ paradigm) and then is given a recall test for the first list, a subject might well recall both the B and C associates to the A stimulus, but not recall which associate occurred on the first list and which occurred on the second list. That is to say, even if the subject had perfect memory for the $A-B$ association, he might fail to answer correctly because he had imperfect memory for list membership. Experiments on list differentiation indicate that subjects forget list membership over time just as they forget anything else. Furthermore, it is possible in some instances that subjects did not learn to differentiate the lists to any very high degree at the time of initial acquisition. Whenever list differentiation is imperfect, competition is a *logically necessary* source of interference in a conventional recall test. Although list identification of B and C responses in an $A-B$, $A-C$ paradigm is rather good, it is usually less than perfect even at short retention intervals, and declines progressively with increasing delay. For example, Koppenaal (1963) found list identification to decline from 96 to 88% correct over a period from one minute to one week following $A-C$ learning, and Birnbaum (1965) found a decline from 99 to 78% over a period from 3 min to 1 week following $A-C$ learning.

The method developed by Barnes and Underwood (1959) in which subjects give two responses to each A stimulus logically avoids interference due to competition arising from imperfect list differentiation. This method, which has come to be known as modified modified-free recall (MMFR) almost invariably demonstrates more accurate recall of first list associates (B responses) in an $A-B$, $A-C$ paradigm than does conventional recall (for example, Houston, 1966; Howe, 1967; Postman, 1962;

Postman, Stark, & Fraser, 1968). However, the difference between conventional recall and MMFR is not too great, especially at short retention intervals, reflecting the high level of list differentiation. Also, the magnitude of the proactive and retroactive interference that is seen with MMFR is approximately as great as that obtained using conventional recall (for example, Houston, 1967a; Postman, Stark, & Fraser, 1968), though it should be noted that there are uncertainties regarding such comparisons of differences when performance is at different levels.

Nevertheless, it certainly seems clear that competition, while present in conventional recall, is not a large source of interference except at long retention intervals. Furthermore, some of the differences between conventional recall and MMFR arise because of the fact that MMFR tests have been unpaced (a large amount of time for recall, largely subject determined), whereas conventional recall has typically been paced at a relatively rapid 2- to 4-sec rate. At slower rates of pacing, the level of conventional recall for first list associates approaches the level obtained in MMFR (Houston, 1968).

B. Unlearning

Melton and Irwin (1940) proposed that, in addition to competition, the interpolated learning of an *A-C* pair produces unlearning of the originally learned *A-B* pair. For many years the unlearning hypothesis lacked substantial empirical support, since memory was largely tested by recall. Recall is subject to many retrieval interference factors. Hence, it was difficult to derive unambiguous support for a storage interference factor such as unlearning. In particular, it does not seem safe at present to assume that MMFR tests provide pure tests of the strength of a memory association in storage, simply because they avoid competition effects by permitting a subject to make both *B* and *C* responses. This statement of caution should not be taken to imply that we know for certain that MMFR is sensitive to other types of interference besides unlearning. It is possible that MMFR directly measures unlearning, independently of other factors. But we cannot be sure, because of the possibility of blocking to be discussed in a subsequent section.

However, there is extremely strong face validity for the assumption that a "yes-*no*" or associative matching recognition test of *A-B* pairs provides a relatively pure measure of loss in storage under many (though not all) experimental conditions. The validity of the assumption that recognition tests can be used to assess storage losses is sometimes questioned, and this will be discussed in the retrieval section of the present chapter. For the moment, it will be assumed that recognition tests (including associative matching tests) provide pure measures of losses in memory storage.

Making this assumption, there is now not a shadow of a doubt that unlearning occurs under the $A-B$, $A-C$; $A-B$, $C-B$; and $A-B$, $A-B_r$ (same stimuli and responses with the pairings rearranged) paradigms compared to $A-B$, Rest or $A-B$, $C-D$ (control) paradigms. For example, McGovern (1964) had subjects learn an $A-B$ list of paired associates followed by learning either an $A-C$, $C-B$, $A-B_r$, or $C-D$ list. Second list learning was followed by a recognition memory test of the strengths of associations between the stimulus and response items from the first list: subjects were given the list of A stimuli and the list of B responses and instructed to match them. Because all the A and B items were supplied, no retrieval interference factors concerned with list differentiation or availability of items could affect the results. Nevertheless, ability to correctly recognize (match) the $A-B$ pairs across the different conditions varied significantly, being poorest after interpolated $A-B_r$ learning, next poorest after $A-C$ or $C-B$ learning, and best after dissimilar $C-D$ learning. These results support the hypothesis that $A-C$ interpolated learning produces unlearning of the forward association from A to B , while $C-B$ learning produces unlearning of the backward association from B to A , and $A-B_r$ learning produces unlearning of both forward and backward associations. To my knowledge, there are no less than 21 other studies that support this same conclusion: Abra (1968), Bahrck (1970), Birnbaum (1973), Ceraso and Henderson (1966), Delprato and Garskof (1968, 1969), Garskof (1968), Garskof and Bryan (1966), Garskof and Sandak (1964), Goggin (1968, 1969), Goulet and Bone (1968), Houston and Johnson (1967), Keppel and Zavortink (1969), Merryman (1971), Postman (1965), Postman and Stark (1969, 1972), Postman, Stark, and Fraser (1968), Weaver, Rose, and Campbell (1971), and Wickelgren (1974b).

As against this massive total in support of the unlearning hypothesis there are exactly two studies that have failed to find the unlearning effect (Bower and Bostrom, 1968; and Wickelgren, 1967) in $A-B$, $A-C$ versus $A-B$, $C-D$ paradigms. These studies were very likely tapping a very short-lasting type of memory with a predominance of phonetic encoding. This leads to the likely supposition that even the $C-D$ interpolated learning was highly similar (phonetically) to the original $A-B$ learning, drastically attenuating any differences in unlearning as a function of the similarity of interpolated learning. Furthermore, these conditions are extremely conducive to uncontrolled rehearsal of the $A-B$ pair during presentation of an $A-C$ pair. Thus, a plausible error analysis can be given for these two negative findings, in addition to the overpowering evidence of 22 studies supporting similarity-dependent unlearning.

Although most of the supporting evidence for unlearning has come from paired-associate learning studies with verbal materials, Bahrck

(1970) has obtained evidence for unlearning in paired-associate recognition memory for pictures of objects or Chinese characters. Also, Wickelgren (1974b) in a continuous recognition memory study found a lower level of recognition memory for an $A-B$ pair when the retention interval contained just one $A-C$ pair along with many $C-D$ pairs compared to cases where the retention interval contained only $C-D$ pairs.

Furthermore, unlearning has also been demonstrated using a mixed-list comparison of $A-B$, $A-C$ and $A-B$, $C-D$ paradigms in which some of the A stimuli are paired with new responses ($A-C$ pairs) during interpolated learning and others are omitted and replaced with $C-D$ pairs. Using both matching tests (Birnbbaum, 1973; Weaver, Rose, & Campbell, 1971) and MMFR tests (Birnbbaum, 1972, 1973; Delprato, 1972; Weaver, Rose, & Campbell, 1971; Wichawat & Martin, 1971), poorer retention was found for the $A-B$ pairs which had $A-C$ pairs in the interpolated list learning than the $A-B$ pairs which did not. There was one previous failure to find this effect by Birnbbaum (1970), which Birnbbaum has since disavowed. Thus, what has been called "cue-specific retroactive interference" can be regarded as well established.

Although the vast majority of the studies on unlearning using recognition matching tests have assessed unlearning at retention intervals within 5 min of interpolated learning and approximately 10–20 min following original learning, there are some demonstrations that at least a portion of the unlearning effect is "permanent," persisting to periods of approximately an hour following interpolated learning (Wickelgren, 1974b) or one day (Abra, 1968; Ceraso & Henderson, 1966). In the light of the possibility that there might be some spontaneous recovery from unlearning (as will be discussed later), there is obviously a need for a greater number of studies of the long term persistence of unlearning effects.

Finally, comparison of $A-B$, $C-D$ with $A-B$, Rest conditions has generally indicated little if any unlearning under the $A-B$, $C-D$ condition, and the unlearning that has sometimes been obtained in this paradigm (principally, Houston, 1967c) has been plausibly attributed to a certain degree of residual similarity between the A and C stimuli in the $A-B$, $C-D$ condition (Abra, 1968).

C. Blocking

One possible retrieval interference mechanism that has received little if any discussion is the possibility that when two associations have been learned to the same stimulus ($A-B$ and $A-C$), recall of one associate might partially block (inhibit) recall of the other associate, even on an MMFR test where the subject is allowed to give both responses. Both competition

and blocking are interference factors that operate at the time of retrieval. They differ in that blocking is an inability to recall the identity of one of the responses whereas competition implies recall of both responses, but an inability to recall which response was on which list (in which context). Thus, while MMFR tests eliminate competition as a source of retrieval interference, MMFR tests may still be subject to blocking. Recognition tests of the strength of association between pairs eliminate blocking by presenting both the stimulus item and the response item(s). Recognition tests can also eliminate competition between *B* and *C* responses by presenting only the *B* items (or only the *C* items) to be matched to the *A* items.

MMFR tests appear to show a larger retroactive interference effect from *A-C* interpolated learning than do recognition tests (Postman and Stark, 1969). The susceptibility of MMFR (but not of recognition) to blocking might be partly responsible for this. However, the possibility that recognition tests make greater use of the backward (*B-A*) association than do recall tests can also account for this finding (Merryman, 1971).

More direct evidence in support of blocking as a source of interference comes from Postman, Stark, and Fraser (1968). In this study a comparison was made between ordinary MMFR and a special MMFR in which the second list (*C*) responses were supplied and subjects were required to recall only the first-list (*B*) responses to the *A* stimulus in an *A-B*, *A-C* paradigm. Despite the fact that subjects had to recall fewer items when second-list responses were supplied, this condition was actually significantly inferior in recall of first-list responses compared to ordinary MMFR, where both *B* and *C* responses had to be recalled. The blocking hypothesis predicts this and also explains why a number of studies have found that free recall of a subset is inhibited by explicit presentation of the remainder of the items in the set as compared to complete recall of the entire set (Brown, 1968; Karchmer & Winograd, 1971; Roediger, 1973; Rundus, 1973; Slamecka, 1968).

Houston (1967b) also found that supplying second-list associates depressed recall of first-list associates even at retention intervals as long as one week after both original and interpolated learning, but the effect, while reasonably large, fell short of statistical significance.

Unfortunately, the free recall results can be given an extremely plausible alternative interpretation in terms of the supplied list members breaking up the subjective organization of the list, which is known to be extremely important in free recall. Furthermore, the Postman, Stark, and Fraser result was obtained only at the short retention interval of approximately 2 min after interpolated learning, and the difference between the two MMFR procedures completely disappeared 18 min after interpolated learning. The depressant affect of priming *A-C* associations at the time of retrieval appears to be a transient phenomenon closely dependent upon proximity

to $A-C$ learning. Thus, as Postman, Stark, and Fraser concluded, the effect may be a transient suppression of B responses (or $A-B$ associations) that was produced by the $A-C$ learning and more effectively maintained during the MMFR test by explicitly supplying the $A-C$ pairs. As blocking is defined here, the inhibition in recalling B (or C) response to a common A stimulus should be produced any time one thinks of the $A-C$ (or $A-B$) association at the time of recall. Blocking in recall of a B response should not depend on close proximity of the recall test to $A-C$ learning, provided the $A-C$ association is strong.

Finally, blocking appears to require a negative correlation between the recall of B and the recall of C in response to any given A stimulus. This negative correlation has not been obtained; rather the recall of B and C appear to be independent (Delprato, 1972; Martin, 1971; & Greeno, 1972; Wichawut & Martin, 1971). However, this result, which Martin and Greeno call the "DaPolito independent retrieval phenomenon," is subject to a large number of possible confounding effects (Hintzman, 1972; Postman & Underwood, 1973), and the most careful analyses of the independent retrieval phenomenon to date by Martin and Greeno (1972) do show slight trends in the direction predicted by the blocking hypothesis. Furthermore, the magnitude of blocking as indicated by Postman, Stark, and Fraser is sufficiently small that it would be difficult to detect by an independence test of $A-B$ and $A-C$ associations, especially if there are small confounding factors working in the opposite direction.

Nevertheless, the evidence in support of blocking is practically nil, and while the evidence against it cannot be considered to be definitive, this interference mechanism must be considered as an unlikely possibility at present. Further studies are needed comparing ordinary MMFR with recall of the first-list responses in the presence of second-list responses, as performed by Postman, Stark, and Fraser (1968), at a variety of retention intervals. If the difference between these two procedures truly does disappear with increasing delay following interpolated learning, then the blocking hypothesis will be definitively disproved.

It is worth noting that Martin (1971) has interpreted the independent retrieval phenomenon as evidence against unlearning, on the grounds that if $A-C$ interpolated learning produces unlearning of $A-B$, then the more learning of $A-C$, the greater the unlearning of $A-B$. According to Martin, this should induce a negative correlation between the recall of B and C in response to A . While this is admittedly one possible version of unlearning theory, it is by no means the only version. Should the independent retrieval phenomenon be shown to hold with all confounding factors controlled, it would still not be evidence against unlearning. All it would be evidence for is that there is no correlation between the degree of $A-C$ learning produced by a given amount of time spent in $A-C$ learning and the

amount of unlearning of $A-B$ so produced. Such a theory is perfectly reasonable in that it may be the activity of $A-C$ learning that produces the $A-B$ unlearning, independent of the strength of the $A-C$ trace this activity produces.

D. Response Suppression

In the 1960s, Postman and some of his colleagues (for example, Postman, Stark, & Fraser, 1968) proposed a theory that during $A-C$ interpolated learning, second-list C responses are primed by a selector mechanism while first-line B responses are suppressed (made less available). Following interpolated learning, the first-list responses spontaneously recover from suppression over a period on the order of 20 min or so. Response suppression explains a number of phenomena.

Of primary importance, response suppression explains the so called spontaneous recovery phenomenon for first-list associates on MMFR tests. This spontaneous recovery is sometimes only *relative* to the control list (or second list) as in Koppenaal (1963) and Slamecka (1966). That is to say, there is relatively less retention loss for the original $A-B$ pairs than for control (single-list) pairs or for interpolated $A-C$ pairs on an MMFR test. However, sometimes there is an actual increase in first-list correct responses with increasing retention interval (reminiscence) as in Ceraso and Henderson (1965), Kammann and Melton (1967), Postman, Stark, and Fraser (1968), Shulman and Martin (1970), and Silverstein (1967). Spontaneous recovery, whether relative or absolute, is now well established on MMFR tests. Furthermore, the explanation given by Postman, Stark, and Fraser (1968) for the instances where it is either not obtained or was not significant is quite plausible. Thus, we must regard spontaneous recovery on recall tests and possibly even associative recognition matching tests (see Postman, Stark, & Fraser, 1968) to be a well established phenomenon in need of some explanation.

Second, response suppression explains the previously discussed relationship between the two types of MMFR tests (second-list responses supplied or not), making the assumption that supplying second-list responses helps to maintain suppression of first-list responses. Third, it explains why MMFR tests show a greater sensitivity to retroactive interference than do associative matching tests. However, as noted, this phenomenon could result from unlearning alone.

Fourth, significant retroactive interference is found in an $A-B$, $C-D$ paradigm compared to a control condition, with an MMFR test (for example, McGovern, 1964; Postman & Stark, 1969; Postman, Stark, & Henschel, 1969). However, no significant retroactive interference is obtained in the $A-B$, $C-D$ paradigm with recognition matching tests when care

is taken to make the *A* and *C* stimuli extremely dissimilar (Delprato & Garskof, 1969; Postman & Stark, 1969). The recognition matching tests show no unlearning of *A-B* associations occurring during *C-D* learning. Blocking is logically ruled out by the *A-B, C-D* paradigm. Competition is logically ruled out by the MMFR test. Hence, some additional interference mechanism such as response suppression is needed to explain the interference obtained with MMFR in the *A-B, C-D* paradigm.

Fifth, on an MMFR test approximately equal spontaneous recovery of first-list responses is observed over a twenty-minute period for both *A-B, A-C* and *A-B, C-D* paradigms (Postman, Stark & Henschel, 1969). This fits if it is assumed that response suppression and spontaneous recovery are independent of the similarity between original and interpolated stimuli. The opposite has sometimes been assumed by response suppression theorists.

Sixth, with retention intervals on the order of a few tens of minutes, the point of interpolation of the interfering list in either the *A-B, A-C* or *A-B, C-D* paradigms appears to have a systematic effect in the direction predicted by the response suppression and spontaneous recovery hypothesis (Postman, Stark, & Henschel, 1969; Postman & Warren, 1972). A related study by Howe (1969) also supports this effect. The result is that interpolated learning close to the retention test produces greater retroactive interference than interpolated learning close to original learning. As will be discussed later, the evidence indicates that unlearning as assessed by recognition tests is independent of the delay between original and interpolated learning. Hence, there must be some other interference mechanism responsible for this effect in MMFR.

The response suppression hypothesis does not eliminate the need to assume unlearning of *A-B* associations during *A-C, C-B*, or *A-B_r* interpolated learning. For one thing, response suppression provides no explanation for the significant retroactive interference obtained with these paradigms using recognition tests. For another, response suppression cannot explain the substantial retroactive interference obtained on MMFR tests in the *A-B, A-B_r* paradigm (Birnbaum, 1973; McGovern 1964; Postman & Stark, 1969; Shulman & Martin, 1970). Since subjects have to learn new second-list associations, but the set of responses is identical for both lists, it is difficult to see how the subjects could be simultaneously priming and suppressing the *B* responses during *A-B_r* interpolating learning.

The fact that the *A-B, A-B_r* paradigm produces approximately an equivalent amount of retroactive interference as the *A-B, A-C* paradigm on MMFR while *A-B, A-B_r* produces markedly greater retroactive interference than *A-B, A-C* on an associative matching test argues in favor of the hypothesis put forward by Merryman (1971), Wickelgren (1972a, 1974a), and others that recall tests primarily tap unidirectional association while recognition tests tap bidirectional associations (though this is not the

only difference between recall and recognition tests). $A-B$, $A-B_r$ produces unlearning of both forward and backward associations and hence greater retroactive interference on an associative matching test than an $A-B$, $A-C$ paradigm, where only the forward associations are unlearned, but the two paradigms produce approximately equal interference in a recall test which is less affected by the strength of the backward association.

Presumably, if response suppression is operating in $A-B$, $A-C$, but not in $A-B$, $A-B_r$, then the $A-B$, $A-B_r$ paradigm should actually produce less retroactive interference on an MMFR test than the $A-B$, $A-C$ paradigm. This was found in the McGovern (1964) and Postman and Stark (1969) studies, but a small reverse effect was found by Birnbaum (1973) and a large reverse effect by Shulman and Martin (1970). Some of this variation may be explained by the availability of the response sets, as Shulman and Martin took all of their B responses from a single class (names of professions), and all the other studies used a mixed set of adjectives. It should be much easier to reinstate the first-list response set when the responses are from a common class. Also, the backward association is more likely to play a role in the MMFR test in this case. Both factors would tend to make $A-B$, $A-B_r$ worse than $A-B$, $A-C$.

E. Associative Suppression

All but one of the six phenomena accounted for by response suppression can also be accounted for by assuming that unlearning of associations contains a transient component, which can be termed "associative suppression." Postman opted in favor of response suppression, rather than unlearning (transient or permanent), partly because he concluded that the high performance on associative matching tests indicated little or no unlearning. As we have seen, this conclusion is falsified by the results of some 22 studies, including several by Postman and his colleagues. A somewhat similar point has been made by Merryman (1971) that recognition matching tests may simply be somewhat less sensitive than MMFR tests to the unlearning of forward associations produced by $A-C$ interpolated list, since associative matching can use both the forward and backward associations, while most recall tests (including MMFR) probably rely primarily on the strength of the forward association. Since $A-B$, $A-B_r$ always produces substantial unlearning, and 22 of 24 studies obtained unlearning in $A-B$, $A-C$ with an associative matching test, there can be little doubt that unlearning is occurring. Hence, this reason for preferring response suppression to associative suppression is invalid.

The only phenomenon that currently argues strongly for response suppression is the fact that retroactive interference is found in the $A-B$, $C-D$

paradigm for MMFR, while recognition tests indicate no unlearning (transient or permanent) in this paradigm.

Further studies need to be done to distinguish between response suppression and associative suppression. For one thing, Postman, Stark, and Fraser (1968) found some spontaneous recovery in an associative matching test over a 20-min interval, but it was not statistically significant. If spontaneous recovery can be shown not to occur with recognition tests, then there is no transient component to unlearning. If spontaneous recovery is obtained with recognition tests, then some transient associative suppression must be assumed. However, note that a few studies have demonstrated unlearning with retention intervals as long as an hour, a day, or a week, arguing that only a portion of the unlearning effect is transient, though this could stand some replication as well.

There is an experimental design that will allow one to make a relatively definitive decision between response suppression and associative suppression as shown below:

Learn	Recall
<i>EB AB AD</i>	<i>AB & AD</i> (MMFR)
<i>EB AB CD</i>	<i>AB & AD</i> (MMFR)
<i>EB AB Rest</i>	<i>AB & AD</i> (MMFR)
<i>EB AB AD</i>	<i>EB</i>
<i>EB AB CD</i>	<i>EB</i>
<i>EB AB Rest</i>	<i>EB</i>

If response suppression is occurring during *A-D* learning, then the recall of *E-B* should be suppressed in the *E-B*, *A-B*, *A-D* paradigm compared to the *E-B*, *A-B*, *C-D* and *E-B*, *A-B*, Rest conditions, just as the recall of *A-B* should be poorer in *E-B*, *A-B*, *A-D* as compared to *E-B*, *A-B*, *C-D* and *E-B*, *A-B*, Rest. On the other hand, if what is occurring during *A-D* learning is suppression of the *A-B* association, then there will be no difference in the recall of *E-B* between *E-B*, *A-B*, *A-D* and *E-B*, *A-B*, *C-D* or *E-B*, *A-B*, Rest.

F. Acid Bath

A clever new interference mechanism was proposed by Posner and Konick (1966) to the effect that the strength of a memory trace decreases more rapidly the greater the number of similar traces in storage. The greater number of similar traces increases the "acidity" of the local environment for the trace in a manner that produces more rapid decay. The most straightforward test of the acid bath interference mechanism is to assess rate of forgetting as a function of the presence or absence of similar proactive interference. This has been done in short-term retention by Hawkins,

Pardo, and Cox (1972) using the presence or absence of a phonetically similar prior list, with results entirely negative for the acid bath theory. There was no difference in forgetting rate as a function of the presence or absence of the proactive interference list. In long-term retention, the ubiquitous Postman, Stark, and Fraser (1968) experiment demonstrated no difference in forgetting rate over retention intervals from 20 min to 48 hr for an *A-C* list as a function of the presence or absence of a prior *A-B* list. Finally, Wickelgren (1974b) in a one-trial-learning, continuous recognition paradigm demonstrated that the presence or absence of an *A-B* pair had no effect on the form of retention function or rate of forgetting for a subsequent *A-C* pair. Thus, there appears to be no support for the acid bath interference mechanism.

G. Conclusions about Interference

Competition is a logical necessity in conventional recall when list differentiation is imperfect, which it almost always is, to some extent or another. Existing evidence appears to provide overwhelming support for unlearning and some form of transient suppression. Response suppression appears to be well established. Associative suppression is still a possibility. Blocking probably does not occur, and acid bath has no empirical support.

III. DECAY

With the exception of the attempt in the 1950s by a few English psychologists (for example, Broadbent, 1956, 1957; Brown, 1958; Conrad, 1957) to revive the decay theory for a hypothetical short-term memory trace, it is fair to say that the decay theory of memory has been in disuse since the classic paper by McGeoch (1932). However, at this time, four different lines of evidence support the importance of a temporal decay process which is independent of the nature of the material processed during the retention interval. Since, as discussed in the preceding section, there is also evidence for storage interference (unlearning), it will be argued that a two-factor theory of storage loss is required.

A. Retention Functions

One argument favoring a temporal decay factor contributing to forgetting is the good fit to retention functions provided by the two-factor fragility theory which assumes temporal decay as a major factor producing forgetting, especially at retention intervals from a minute to a few weeks (Wickelgren, 1974b, 1975b). According to the theory, the form of the retention

function is the product of the acquisition parameter (degree of learning) times a power function decay factor (characteristic of the time decay process) times an exponential decay factor (characteristic of the interference process).

The rate parameter for the time decay process appears to vary somewhat over different studies, and I do not yet understand the reason for this variation. However, the range of the variation is quite modest: less than a factor of ten. This is small in comparison to the variation in how long different memories last: greater than a factor of 10^7 . By contrast, the interference parameter varies enormously, apparently as much as a factor of 10^6 . This is as expected, since interference depends upon the similarity of the encoding of interpolated material to originally learned material.

It is amusing to note that fragility theory attributes the rapid forgetting found in certain short-term memory tasks (for example, Norman, 1966; Waugh & Norman, 1965; Wickelgren, 1969, 1970; Wickelgren & Berian, 1971; Wickelgren & Norman, 1966) primarily to the interference process, with much of the forgetting in long-term retention being attributed to the time decay process. This is just the opposite assumption from that made by Broadbent, Brown, and Conrad, in their revival of decay theory, who attributed the forgetting in short-term memory primarily to decay, with forgetting in long-term memory being due to interference.

The logic of my theory is that the studies in which rapid exponential decay have been observed are precisely those in which there is a great deal of attribute-level (usually phonetic) encoding rather than high-level semantic (conceptual and propositional) encoding. With attribute encoding, subsequent materials will share many of the attributes of the originally learned material, leading to a high value for the similarity parameter and substantial interference. This type of unlearning is considered to be the same as that which occurs in a longer-term paired-associate experiment by the interpolation of *A-C* learning following original *A-B* learning.

Studies which varied the rate of presentation in a short-term probe design to decide whether forgetting is primarily determined by the amount of interference (number of interpolated items) or time delay have found a very large contribution from the number of interpolated items (for example, Norman, 1966; Waugh & Norman, 1965; Wickelgren, 1970). However, these studies also found evidence for a contribution from time as well (Wickelgren, 1970).

Furthermore, nonverbal interpolated material produces vastly less forgetting than verbal interpolated material in verbal short-term retention (Reitman, 1971; Shiffrin, 1973; Watkins, Watkins, Craik, & Mazuryk, 1973), while interpolated tones produce greater forgetting than interpolated verbal material in short-term memory for tones (Deutsch, 1970).

This also supports the hypothesis that the rapid loss characteristically found in many short-term retention tasks is largely produced by interference.

In summary, one line of support for the two-factor theory comes from its ability to fit both short-term and long-term retention functions using a single trace.

B. Delay of Interference

The apparent lack of effect on unlearning of the time interval between *A-B* and *A-C* learning is a strong indirect argument in favor of a time decay factor in forgetting. The argument is as follows: The susceptibility of a memory trace to storage loss (forgetting) appears to be continually decreasing as it gets older. If the only mechanism producing loss in storage were interference from other learning, then there must be less interference the longer the delay between original and similar interfering learning, to account for the slowing down of the forgetting rate. Both the pure interference theory of Wickelgren (1972b) and the inhibition of consolidation theory of retroactive interference of Landauer (1974) predict just such an effect, that short delays between original and similar interpolated learning will produce maximum storage interference (unlearning). Given that proactive interference has been ruled out as a factor in producing storage loss on recognition tests (Postman, Stark, & Fraser, 1968; Wickelgren, 1974b), it would appear that any pure interference theory of storage loss must predict greater susceptibility of a trace to retroactive interference at short delays of interfering learning to account for the faster rate of forgetting at short delays.

With the exception of Landauer (1974), previous studies employing conventional recall and MMFR tests provide no support for this prediction (for example, Archer & Underwood, 1951; Houston, 1967b; Lazar & Weiss, 1970; Newton & Wickens, 1956; Postman, Stark, & Henschel, 1969; Postman & Warren, 1972). In fact, as discussed previously, "point of interpolation" studies using recall frequently find the reverse effect: Having the interpolated material occur close to the recall test produces greater interference than having it occur immediately after original learning, when the total retention interval is held constant (Howe, 1969; Newton & Wickens, 1956, Expts. 2 and 3; Postman, Stark & Henschel, 1969; Postman & Warren, 1972). This finding was used in support of the response suppression and spontaneous recovery hypothesis.

The conventional point of interpolation study confounds the delay between original and interpolated learning with the delay between interpolated learning and the test of original learning. Thus, it could well be that the

greater response suppression obtained with a shorter delay between interpolated learning and test masks a greater unlearning effect produced by a shorter delay between original and interfering learning on recall tests. Conventional recall is subject to competition effects which also might mask an unlearning effect. For these reasons, a recognition test is far preferable to either conventional recall or MMFR in assessing whether unlearning varies with the delay of interference. Furthermore, it is desirable for the delay between interfering learning and test to be long in relation to any of the various delays between original and interfering learning, to allow time for any possible transient associative suppression to dissipate as well. Ideally, a retention function for original learning at many delays following interfering learning should be determined to partition the total amount of unlearning into transient and permanent components in order to see whether there is a systematic effect of the delay of interfering learning on the magnitude of either component.

Wickelgren (1974b) obtained retention functions for $A-B$ word pairs over retention intervals varying from 1.25 to 75 min in a continuous recognition memory paradigm. Separate retention functions were obtained for the control condition, in which no $A-C$ interfering learning occurred in the retention interval for $A-B$ and for three experimental conditions in which a single trial of $A-C$ interfering learning occurred at delays of 15 sec, 1 min, or 3.75 min following the single trial of $A-B$ learning. Significant interference in subsequent recognition memory for the $A-B$ pair was obtained in all three interference conditions, but the magnitude of the interference was independent of the delay between $A-B$ and $A-C$ learning. This result contradicts the Landauer (1974) inhibition of consolidation theory and also the Wickelgren (1972b) pure interference theory. It is consistent with the theory of Wickelgren (1974b) that the decreasing fragility of the trace affects only a time decay process, with the susceptibility of the trace to interference being independent of trace age. Since it does not appear to be possible to explain the invariance of interference with delay of interpolated learning using a pure interference theory of storage loss, this finding provides support for the assumption of a time decay process in addition to an interference process.

Wickelgren (1974b) also found a somewhat slower rate of forgetting for $A-B$ pairs followed by $A-C$ interfering pairs compared to a control condition, but the effect was not statistically significant. Such an effect, if consistently obtained in other studies, would support some transient component of unlearning (associative suppression). However, Wickelgren (1974b) still found significant unlearning at retention intervals exceeding an hour, suggesting that at least a portion (and perhaps all) of the unlearning is permanent. As discussed previously, further studies need to be

performed to assess the degree to which unlearning is transient or permanent.

C. Extraexperimental Interference

Underwood and Postman (1960) noted that an important step in establishing interference as the sole mechanism producing forgetting was to show that the large amount of forgetting which occurs outside the laboratory is due to interference from learning occurring outside the laboratory (extraexperimental interference). Another indirect, but strong, argument supporting a time decay process contributing to storage loss, is the consistent failure, despite considerable effort, to demonstrate that the forgetting which occurs outside the laboratory over retention intervals of a few days is primarily due to interference from prior or subsequent learning outside the laboratory (see reviews by Keppel, 1968, 1972). Such a result is quite parsimoniously explained by the assumption that most of this forgetting is due to time decay, rather than interference.

It would be foolish to argue that there is no interference from material learned outside the laboratory, but the magnitude of this interference as estimated within the single-trace theory of Wickelgren (1974b) is so small that virtually all of the forgetting observed over a period of a few days must be attributed to the time decay process. Thus, even gross differences in the magnitude of interference would be difficult to demonstrate.

However, because of the nature of interference and the slowing down of the rate of time decay with increasing trace age, according to the theory, interference would be expected to exert an increasing influence at longer retention intervals. Hence, it might well be possible to demonstrate extraexperimental interference with retention intervals on the order of several weeks or months, provided that time decay rate and susceptibility to interference are not too highly correlated.

D. Sleep and Memory

The classic studies of Jenkins and Dallenbach (1924) and van Ormer (1932) demonstrated that sleep facilitates recall. For a long time thereafter, this effect was interpreted to support interference as the sole or dominant cause of forgetting. In addition to the evidence just discussed to the effect that interference is often a minor cause of extraexperimental forgetting over a period of hours or days, there are now three findings concerned specifically with the effects of sleep on memory that seem inconsistent with the explanation of the beneficial effects of sleep in terms of a presumed reduction in interference.

First, Yaroush, Sullivan, and Ekstrand (1971) and Gann (reported in Ekstrand, 1972) have demonstrated that forgetting is substantially slower over the first half (3.5 or 4 hr) of a night's sleep than over the final half (3.5 or 4 hr). In fact, the second half of a night's sleep seems to have little or no beneficial effect on memory compared to an awake control condition. Such findings seem inconsistent with a reduction-of-interference explanation of the sleep effect.

Second, Hockey, Davies, and Gray (1972) have demonstrated that it is not sleep per se that retards forgetting, but rather the time period that sleep normally occupies in the human day-night cycle (circadian rhythm). By manipulating whether recall was required after 5 hr of sleeping or waking during either the night or the morning, Hockey, Davies, and Gray demonstrated that retention over night was superior to retention over the same amount of time during the morning, irrespective of whether subjects were awake or asleep. There was also a very slight difference in favor of the sleeping as opposed to the waking condition. In view of the importance of this finding, it obviously needs to be replicated with different materials and under different conditions, but the result is consistent with the previously discussed differences between the first and the second half of the night. Apparently, the "sleep effect" has something to do with metabolic, arousal, or other nervous system rhythms. It is quite reasonable to imagine that the rate of time decay, while independent of experience, is nevertheless dependent upon some features of the internal state of the nervous system. An interference explanation of this result seems impossible.

Third, studies in three different laboratories discussed by Ekstrand (1972) have demonstrated that the point of interpolation of sleep plays a significant role in the sleep effect. Specifically, sleep immediately following learning followed by a period of wakefulness produces far superior retention over the same total retention interval compared to wakefulness during the initial portion of the retention interval followed by sleep. Since there appears to be no effect of point of interpolation of interfering learning on recognition tests and the reverse effect of point of interpolation on recall tests (namely, better retention if the period of high interference follows learning rather than immediately preceding retention), the effects of point of interpolation of sleep cannot be given an interference explanation. However, this effect is exactly what is predicted by the two-process single-trace fragility theory (Wickelgren, 1974b). According to that theory, the decreasing fragility of the trace has no effect on the magnitude of interference (unlearning), but does affect the rate of time decay. Hence, explaining the beneficial effects of sleep (or nighttime) by a reduction in time decay rate leads to the prediction that sleep during the early portion of a retention interval would be far more beneficial for retention than sleep during a later portion of the retention interval.

The theory of Wickelgren (1974b) provides an interesting combination of the decay and consolidation explanations of sleep effect, almost precisely as envisioned by Ekstrand (1972). According to this theory, consolidation consists of a reduction in trace fragility. This process is not presumed to occur more rapidly during sleep than during waking within the present theory, though this would be a trivial modification of the theory. However, according to the theory, fragility is very high immediately following learning. If sleep reduces the time decay rate, the most beneficial period in which to reduce it is when the memory trace is most fragile. By contrast, less benefit is derived from an equivalent period of sleep near the end of the retention interval, since the trace is much less fragile, the older it gets. This prediction is trivial to derive mathematically from single-trace theory, and provides another argument in support of a time decay process in addition to an interference process in storage loss.

IV. INTERACTION OF ACQUISITION AND STORAGE

When an individual fails to remember an event known to have occurred previously in his presence, ordinary people and frequently even memory researchers say the individual "forgot" the event. However, the meaning of the term "forgetting" is not at all clear. Not only are there many possible causes of forgetting, but the critical events producing the retention failure may be primarily during the acquisition or retrieval period, instead of or in addition to the storage period. If the individual was asleep at the time the event occurred initially or at the time of the retention test, presumably most of us would not use the term "forgetting" to refer to such an acquisition or retrieval deficit. Extreme cases such as this produce no confusion, but it is quite possible that many other causes of retention failure are simply less extreme or less obvious instances of acquisition or retrieval deficits. The purpose of this section is to briefly outline some possible interactions of acquisition and storage; in the final section of the chapter I will consider the interaction of retrieval and storage.

A. Activity Traces

Retention tests administered immediately after acquisition may yield a very high level of performance, as a consequence of the persistence of a non-associative activity trace (sensory, motor, or conceptual). The persistence of the activity trace can be presumed throughout any period of conscious rehearsal for whatever portion of the material is within the rehearsal span. For this reason, studies of short-term retention should ignore performance

on truly immediate tests of retention in studying the dynamics of associative memory. Whether it is only the last processed element that possesses an activity trace or the last N elements where N is some small number is by no means definitely established. Although a number of findings have been interpreted by Crowder and Morton (1969) in support of the existence of an acoustic activity trace that can persist over the last four or five items, with auditory presentation, the analysis of memory traces into component parts is such a complex question that this cannot be regarded as completely established. Nevertheless, it is quite likely that immediate testing of the last item taps an activity trace as well as one or more associative memory traces.

B. Short-Term versus Long-Term Acquisition

Along the same line, if there were good reason to distinguish short-term and long-term associative memory traces (which I contend there is not), an analogous distinction would arise there, namely, that a high level of performance shortly after learning would not necessarily indicate a high level of acquisition in long-term memory.

C. Modalities and Levels of Encoding

Even without believing in a dynamic distinction between short-term and long-term memory traces, it is quite likely that there are different modalities and levels of modalities within which traces can be established. Thus, rote rehearsal may establish a relatively strong memory trace at some (lower) phonetic level, but virtually no memory trace at any (higher) semantic level of the verbal modality. Since many phonetic memory traces are very likely rapidly lost due to interference, in such cases one would see a high immediate level of performance followed by substantial "forgetting." Perhaps one would wish to refer to this as forgetting, but in some important sense the "cause" of forgetting was the failure to acquire a semantic trace in the first place. Obviously, it is arbitrary whether one refers to this as forgetting ("a word means what I choose it to mean . . ."), so long as the meaning of the term is clearly defined.

D. Distinctiveness

This brings up the more general point that the acquisition conditions and the properties of the memory trace resulting from different conditions of acquisition may make a substantial difference in the susceptibility of that

trace to forgetting, though it is by no means established that they do. The principal acquisition variables alleged to reduce the rate of forgetting include a higher degree of learning and overlearning resulting from increased study time (for example, Melton, 1963), spacing of learning trials (for example, Keppel, 1964), absence of proactive interference (for example, Underwood, 1957), high arousal (for example, Levonian, 1972; Uehling, 1972), and the use of semantic or visual mnemonics in coding, as opposed to rote rehearsal (for example, Anderson & Bower, 1973; Bower, 1972).

Some of these effects on retention are not found in all studies. Some may depend on the nature of the dependent measure of trace strength, for example, on whether one uses probability or correct recognition, d' , $\log d'$, etc. Finally, some of the effects hold for recall, but not for recognition, such as effects due to retrieval interference from competition and response suppression and recovery. For example, proactive interference appears to increase the forgetting rate in recall, but to have no effect on the forgetting rate in recognition memory (Postman, Stark, & Fraser, 1968; Wickelgren, 1974b).

However, irrespective of the locus of the effect of acquisition conditions on forgetting rate, the general point is clear that conditions during acquisition can produce a trace whose properties are such as to make it more or less susceptible to forgetting during storage or more or less susceptible to various retrieval interference factors.

At present, it appears that some of these differences in retention as a function of acquisition conditions cannot be explained simply by differences in the strength of original learning. One approach to this problem is to assume multiple traces in different modalities or levels of a modality. Another approach is to describe the memory trace by a second property in addition to strength at the end of acquisition. It would be parsimonious to assert that this additional property is fragility, with certain conditions during learning producing greater reduction in trace fragility during acquisition than other conditions. Greater reduction of fragility during acquisition would produce slower decay during the retention interval especially at short delays. However, the reduction in decay rate appears to be equal at all delays, not primarily at short delays. Thus, this approach appears to be incorrect.

It may be necessary to add a third property to the description of memory traces. I call this property, "distinctiveness." During acquisition, traces increase in strength and may also increase in distinctiveness, depending on the nature of the encoding process. A higher level of distinctiveness is approximately the same as what Craik and Lockhart (1972) mean by a higher level of processing.

According to this theory, mnemonic encoding and high arousal (which may be correlated with a higher level of processing) produce a more distinctive encoding, which is somehow more resistant to forgetting at all delays

following learning. Greater distinctiveness of encoding should reduce the interference similarity parameter (π) in Eq. (1), but, at present, it also appears necessary to assume that greater distinctiveness can also slightly reduce the time decay rate parameter (ψ). The effect of distinctiveness on ψ is probably best interpreted as producing a greater rate of consolidation (reduction of fragility) for more distinctively encoded traces. In some instances, greater study time is correlated with a higher level of processing, though this may not always occur and indeed the relationship between study time and forgetting rate is somewhat variable. Spacing effects have sometimes been explained by both a higher arousal accompanying spaced practice and a greater variety of encodings (more distinctive encoding?) resulting from spaced practice as opposed to massed practice.

The preceding discussion is extremely speculative and should be taken merely as an example of some possible interactions between acquisition and storage. Current understanding of these matters is so poor, it is conceivable that with the proper theory and with degree of learning properly controlled, there would actually be no differences in forgetting rate to be taken into account.

V. RETRIEVAL FACTORS

One of the most elementary and fundamental distinctions in the field of learning and memory is the distinction between learning and performance. An individual may have learned and remembered an $A-B$ association at a high level of strength up until the retention test and nevertheless fail to perform correctly due to a large number of retrieval factors that produce retention failure.

In discussing these retrieval factors it is often important to distinguish recall and recognition. In general, recall of the B associate to an A stimulus is more susceptible to retention failure due to retrieval factors than is recognition of the A stimulus alone or the $A-B$ association. However, it is quite clear that recognition memory is sensitive to some retrieval factors.

A. Attention, Arousal, and Fatigue

Little is known about many of the conditions that may possibly affect retrieval. For example, at the extremes, *arousal* and *attention* can affect retrieval in that an organism that is asleep, or whose attention is completely distracted by some other cues, will not respond to a memory test. However, when human subjects are awake and properly instructed as to what to attend to, there is no convincing evidence that degree of attention or arousal has any effect on memory retrieval, but this is far from being estab-

lished. Nor is there evidence that any type of *fatigue* has a deleterious effect on memory retrieval, but it might.

B. Motivation

Obviously, if a subject is not motivated to produce the correct response, one can observe retention failure for reasons that have nothing to do with the level of the memory trace. Controlling *motivation* is a considerable problem in animal learning and memory studies, but we usually assume that human subjects can be motivated by instructions, in combination with the desire to do well or please the experimenter, to a point where motivation is not a significant retrieval factor. When motivation has been manipulated in human memory retrieval, by the magnitude of monetary incentive and even electric shock, the incentive condition at the time of recall had no significant effect in two studies (Heinrich, 1968; Wickens & Simpson, 1968), though it did have a very small effect in another study (Loftus & Wickens, 1970).

C. Repression

One specific extreme form of the hypothesis that motivation can influence retrieval is the *repression* hypothesis, that events associated with unpleasant experiences will be more difficult to recall than events associated with neutral or pleasant experiences. According to Freud and other psychoanalysts, there is considerable clinical evidence to indicate that some emotionally disturbed individuals can (subconsciously) prevent recall of unpleasant memories, even when they are forced to attend to cues that would be completely adequate to produce recall of comparable memories in a normal individual. The memory is assumed to be there, but because it is directly or indirectly associated to some unpleasant emotion, it is blocked from retrieval, except under special conditions of free association, dreams, or hypnosis. The scientific status of repression is quite uncertain, but one possible experimental demonstration of repression was obtained by Glucksberg and King (1967).

D. Time

One retrieval factor that affects both recall and recognition is the retrieval time permitted the subject. As might be expected, greater retrieval time leads to greater accuracy in both short-term recall (Murdock, 1968), long-term recall (Houston, 1968), and recognition memory (Reed, 1973). Very

little is known about retrieval dynamics for different types of associations under different conditions, but the use of speed-accuracy tradeoff functions (for example, Reed, 1973) promises to greatly expand our understanding of both retrieval processes and the structure of memory. A speed-accuracy tradeoff function is a plot of accuracy as a function of reaction time, with reaction time generally being largely manipulated by the experimenter, for instance by using an auxiliary cue signaling the subject when to respond.

For example, in a conventional paced anticipation test of recall, Houston (1968) found that recall of the *B* associate to an *A* stimulus in an *A-B*, Rest paradigm reaches asymptote in approximately 1.5 sec, but recall of the *B* associate to an *A* stimulus in an *A-B*, *A-C* paradigm is still far from asymptotic at 2 sec. Houston used a retention interval of 1 week following both *A-B* and *A-C* learning, so response suppression was presumably not a factor. Unlearning might be presumed merely to lower the asymptotic level of recall. Hence, the slower rate of recall of *B* associates in an *A-B*, *A-C* paradigm may be evidence for a transient competition or blocking effect of multiple associations at the time of retrieval using recall. It is a matter of some theoretical interest whether a similar effect on the speed-accuracy tradeoff function would be obtained in recognition. The serial search theory of Anderson and Bower (1973) predicts that it will. The direct-access strength theory I currently favor predicts that it will not.

E. Compound Stimulus Change (Altered Relevant Cues)

If a nonsense syllable is used as a stimulus in a paired-associative learning task and a later test of retention presents only the second letter of that nonsense syllable as a cue, subjects will perform less adequately than if the entire nonsense syllable is presented. Relevant cue deletion depresses performance either because subjects have selected primarily that attribute of the compound stimulus to attend to during learning or because subjects have a greater total strength of association to all of the attributes of a compound stimulus than to any single attribute, even the dominant one. There are situations in which cue selection is so strong that some dominant stimulus attribute is as effective as the entire compound (provided one selects the dominant attribute as the retrieval cue). However, any fluctuation in the cue selection process or any tendency to encode the entire stimulus as a single "chunk" will generally produce the result that no single attribute is as effective as the whole compound stimulus in producing recall or recognition.

Besides the deletion of relevant cues, recall and recognition can also be depressed by the addition at the time of retrieval of irrelevant cues con-

sidered by the subject to be relevant. For example, if the nonsense syllable is presented as a hidden figure embedded in some complex display, it may be extremely difficult for a subject to detect the relevant portion of the stimulus to be recognized or to which to recall the correct response.

For a review of empirical work on compound stimulus change see Richardson (1971), and for both empirical and the theoretical research on the problem within the general framework of stimulus sampling theory see Binder and Estes (1966), Estes and Hopkins (1961), and Friedman, Trabasso, and Mosberg (1967).

Over the years, there has been a persisting tendency on the part of some investigators to confuse work on the effects of altered relevant cues after compound stimulus learning with the effects of altering irrelevant cues, as in studies of context change. For example, McGeoch and Irion (1952, pp. 448-451) make no distinction between altering relevant and irrelevant cues.

More recently, the same confusion occurs in a series of studies supposedly concerned with the effects of altering context as a retrieval interference factor in recognition memory (DaPolito, Barker, & Wiant, 1971; Light & Carter-Sobell, 1970; Thompson, 1972; Tulving & Thomson, 1971; Winograd & Conn, 1971; Winograd, Karchmer, & Russell, 1971). The sort of phenomenon illustrated by these studies is that if an adjective-noun pair such as "raspberry jam" is presented during learning, there will be a reduction in recognition memory of the noun alone ("jam"), if at the time of the retention test, the noun is presented with an adjective that biases a different meaning of "jam," such as "traffic jam." Since both elements of the stimulus compound were considered relevant by the subjects during learning, these studies exemplify the deletion of a relevant cue from the acquisition to the retrieval phase. To the extent that subjects treat the biasing adjective in the retention test as a relevant cue (despite the instructions), the studies also frequently involve the addition of irrelevant cues at the time of retrieval.

F. Context Change (Altered Irrelevant Cues)

When each stimulus of an eight-item paired-associate list is printed in a different color, color is a relevant stimulus cue for determining the correct response within the set of responses. When color is deleted or changed on a retention test, one is observing the effects of altering relevant cues in compound stimuli. However, when all the stimulus items are presented in the same color at the time of learning, clear terminology requires that color be considered an irrelevant (context) cue at the time of learning. The same classification as a context cue holds for such variables as the

nature of the person running the experiment, the characteristics of the experimental room, the presence of background music, the postural status of the subject (for example, standing or sitting), etc. Although McGeoch and Irion (1952) attempted to make a strong case for the effects of changes in background context as a retrieval factor depressing recall, careful examination of the studies cited by them reveals that when studies that changed relevant cues are eliminated, the effect of context change has generally not been observed.

However, a change in background context from a first to a second list appears to reduce proactive and retroactive interference (for example, Dallett & Wilcox, 1968; Strand, 1970). Since context change between two lists makes the context cues relevant, the effects of context change on interference are actually completely consistent with the general proposition that context cues which are nominally irrelevant are, in general, functionally irrelevant to the encoding of the memory trace.

It would not be at all surprising to falsify this generalization under some circumstances. Background context is probably occasionally incorporated into memory traces. Furthermore, it appears to be necessary to assume that subjects form some concept of the experimental situation and various portions thereof, such as the first and second list in an *A-B*, *A-C* paradigm. Consideration of the conceptual encoding of the experimental context on the part of the subject is frequently of some importance in theoretical analysis of the differentiation of several learning tasks. However, the available evidence indicates that such encoding is by means of rather abstract concepts that are formed by the subject, which have little to do with most of the specific physical stimuli comprising the background context. In support of this, Strand (1970) found as much reduction of retroactive interference when subjects were taken from a room and brought back to the same room as when they were brought to a different room between the learning of two lists.

Since it would be extremely dysfunctional for memory retrieval to depend in any substantial way upon irrelevant context cues, it is both fortunate and unsurprising that it does not.

G. Encoding Variability

It is both logically necessary and empirically established that changes in at least some of the nominally relevant cues from acquisition to retrieval will produce a reduction in performance on both recall and recognition tests. Therefore, it has seemed reasonable to many memory theorists to assume that this process may go on spontaneously (even when there is no change in the functional stimulus) as a result of subject-produced changes in

stimulus encoding. Although the basic idea of encoding variability has been around for a time, the enormous theoretical potential of this idea for explaining a variety of learning and memory phenomenon was realized in a precise and systematic way only after the development of stimulus-sampling theory (Estes, 1950). To get an idea of the application of stimulus-sampling theory incorporating the hypothesis of encoding variability, see Atkinson and Estes (1963), Bower (1972), and Neimark and Estes (1967).

The hypothesis of encoding variability can be used to account for a wide range of phenomenon in verbal learning and memory (see Bower, 1972; Martin, 1968). However, as pointed out by Postman and Underwood (1973), there are now several studies suggesting that under many conditions, subjects show little or no variability in the encoding of the same nominal stimulus on different occasions (Goggin & Martin, 1970; Postman & Stark, 1971; Weaver, McCann, & Wehr, 1970; Williams & Underwood, 1970). However, there might well be a greater magnitude of encoding variability when more time intervenes between repetitions of the same nominal stimulus than in these studies. On intuitive grounds, it seems likely that encoding variability is a substantial source of retrieval interference in the recall of childhood memories, since children are rapidly expanding the set of concepts with which they encode events in the world. Thus, while encoding variability may often be controlled so as to play very little role in certain human learning and retention experiments, it is almost certainly an important retrieval factor under other circumstances.

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