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Spacing Effects and Their Implications for Theory and Practice

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There is considerable evidence, gathered in a variety of settings and across many different types of materials and procedures, that spaced repetitions—regardless of whether they are in the form of additional study opportunities or successful tests—are a highly effective means of promoting learning. Research on spacing effects is reviewed and its theoretical and educational implications are examined. It is concluded that spacing effects can best be understood in terms of the "accessibility" hypothesis, and that spaced repetitions have considerable potential for improving classroom learning.

KEY WORDS: memory; practice; learning; cognition.

THE SPACING EFFECT

Ask almost any student of learning and memory and he/she will tell you that the spacing effect refers to the finding that for a given amount of study time, spaced presentations yield significantly better learning than do presentations that are massed more closely together in time. The spacing effect is, in fact, one of the most thoroughly studied phenomena in psychology. However, what is not so widely appreciated is just how remarkable the spacing effect is.

Consider, for example, its impressive length of service as a subject of scientific inquiry. The earliest documented studies of the spacing effect were recorded by Ebbinghaus in his seminal work on memory, originally published in 1885. With himself as the subject, Ebbinghaus noted that for a single 12-syllable series, 68 immediately successive repetitions had the effect of

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making possible an errorless recital after seven additional repetitions on the following day. However, the same effect was achieved by only 38 distributed repetitions spread over three days. Mainly on the basis of this finding, Ebbinghaus concluded that "with any considerable number of repetitions a suitable distribution of them over a space of time is decidedly more advantageous than the massing of them at a single time" (Ebbinghaus, 1885/1913, p. 89). Soon after, the spacing effect gained formal recognition in the form of Jost's Law, which states that "If two associations are of equal strength but of different age, a new repetition has a greater value for the older one" (McGeoch, 1943, p. 140).

As might be expected, these two developments in the 19th century were followed by a flurry of related research in the early 1900s, addressing the general problem of the "economy of distributing work and rest periods" [see Ruch (1928) for a review]. Although interpretation of the results of these studies (e.g., Dearborn, 1910; Perkins, 1914) is complicated by other, potentially confounded variables, the results tend in general to confirm the earlier work of Ebbinghaus and Jost.

Since then, the spacing effect has been documented in dozens of studies, many of which were conducted in the 1960s and 1970s (see reviews by Hintzman, 1974; Melton, 1970; and Glenberg, 1979). More recently, interest in the spacing effect has remained strong, and there is little reason to believe that it will not continue to be an intellectually active area [see Dempster (1988) for a review]. Thus, the spacing effect is neither just a historical curiosity nor a johnny-come-lately. Fads come and go in psychology, but research on the spacing effect has withstood the test of time and significance; it continues to yield new discoveries and ideas relevant to other areas of psychology.

Another remarkable feature of spaced repetitions is the sheer size of the effect. Whereas many of the traditional learning variables studied in the laboratory have relatively weak effects, two spaced presentations often are about twice as effective as two massed presentations (e.g., Bahrick and Phelps, 1987; Dempster, 1987; Underwood, 1970), and the difference between them tends to increase as the frequency of repetition increases (Underwood, 1970). Moreover, longer retention intervals tend to favor the spacing of repetitions more than do short retention intervals (Austin, 1921; Bahrick and Phelps, 1987; Glenberg and Lehmann, 1980; Young, 1966, cited in Melton, 1970). For example, Bahrick and Phelps (1987) retested subjects who had learned and relearned foreign language vocabulary words after an interval of eight years—an interval much longer than those typically used in learning research. One variable of interest was the interval between successive relearning sessions—either 30 days, 1 day, or 0. Their data show that intersession interval had a robust effect on retention, with the recall probability associated with the 30-day interval about 2.5 times the probability associated with the zero interval.

Also remarkable is the fact that the spacing effect is one of the most dependable and replicable phenomena in the learning literature. Nevertheless, the spacing effect cannot be taken for granted. For example, it appears to be subject to certain boundary conditions. First, it has been found that under certain circumstances spaced presentations are no better than (Austin, 1921) and sometimes even worse than (Gordon, 1925) massed presentations in tests of immediate recall. For example, Austin found that massed readings (e.g., five times in one day) of text material proved as effective as spaced readings (e.g., daily for five days) in tests of immediate recall; whereas the spaced readings were much more effective in delayed tests, especially if they came two to four weeks after learning. Second, much of the research that has focused on the acquisition of lists of nonsense syllables has yielded weak effects of spacing at best. According to Underwood (1961) who reviewed 10 years of research in this area, "Facilitation by distributed practice. . .occurs only under a highly specific set of conditions, and the magnitude of the effect when it does occur is relatively small" (p. 230). However, in many of the studies reviewed by Underwood, study and test trials were not separated. Thus, in these instances also, recall was immediate. Third, it has been found that massed practice often is more efficient for certain simple, isolated skills, such as writing the products of number pairs as rapidly as possible (Thorndike, 1916).

As might be expected, the history of research on the spacing of presentations also includes some anomalies. For example, Toppino and Gracen (1985) conducted a series of nine experiments on spacing in standard verbal learning tasks, and failed to replicate the spacing effects reported in a study by Glenberg (1979). Another inconsistent set of findings in the spacing literature pertains to the effects of paraphrasing. Recently, two studies have shown that the spacing effect can be eliminated if paraphrased rather than verbatim versions of the repeated materials are used (Dellarosa and Bourne, 1985; Glover and Corkill, 1987). In addition, Dellarosa and Bourne found that a change in the speaker's voice at the time of repetition also eliminated the effect. By contrast, a much older study using similar paraphrased repetitions (e.g., "The ghosts who protect the men in war are offered melons" vs. "melons are offered to the ghosts who protect the men in war") found that changing the phrasing of a sentence when it is repeated did not remove the depressing effect resulting from massed repetition (Rothkopf, 1966).

Also puzzling is a study by Toppino and DiGeorge (1984) who found that the spacing effect did not apply to preschool-age children, even though it was present in the recall of first-graders. Previously, the spacing effect had been reported for infants (Cornell, 1980); and in a recent developmental study, the spacing effect was obtained in every age group tested, including preschool-age children (Rea and Modigliani, 1987).

Finally, the length of the spacing interval has had inconsistent effects on learning. Some studies have found that beyond a certain spacing interval, further increases in spacing are not always associated with further increases in learning. For example, English *et al.* (1934) found that four readings of a text at 3-hr intervals were associated with better learning than four consecutive unspaced readings; however, readings at 3-hr intervals were no better than readings at either 1- or 3-day intervals. Similarly, Lyon (1914), Peterson *et al.* (1935), and Sones and Stroud (1940) reported essentially no differences in retention between groups with rereading reviews spaced 1 and 7, 1 and 9, and 1 and 17 days after original learning. These findings were later corroborated by Ausubel (1966) and by Gay (1973, Experiment 1). On the other hand, differences favoring the longer of two or more very well-spaced intervals have been reported by Gay (1973, Experiment 2), and by Bahrick and Phelps (1987).

These various failures to obtain the effect aside, the spacing effect is truly remarkable in the scope of its application. Unlike many learning phenomena, it is not confined to one or two paradigms or stimulus domains. It has been found in virtually all traditional verbal learning tasks, including paired-associate learning, free recall, recognition memory, and in the distractor paradigm (see reviews by Hintzman, 1974; Melton, 1970). To-be-remembered materials have included nonsense syllables (e.g., Ebbinghaus, 1885/1913), words (e.g., Glenberg and Lehmann, 1980), sentences (e.g., Rothkopf and Coke, 1966), pictures (Hintzman and Rogers, 1973), and faces (Cornell, 1980; Goldstein *et al.*, 1987).

In addition, the spacing effect has been found in a variety of tasks with clear classroom analogues. In fact, several early demonstrations of the spacing effect reviewed by Ruch (1928) were, as he put it, "intended for schoolroom application" (p. 20). Pyle (1913), for example, found that addition facts were recalled better by children who were drilled once a day for 10 days than by those who were drilled twice a day for 5 days.

Spacing effects also have been demonstrated in science and mathematics concept and rule-learning tasks. In one study, the meanings of a series of scientific terms were learned much more effectively when repetitions were spaced than when they were massed (Reynolds and Glaser, 1964). In another study, arithmetical rules presented on a computer monitor were learned better when reviews occurred 1 and 7 days after the initial presentation than when they occurred 1 and 2 days following original learning (Gay, 1973, Experiment 2).

Another focus of spacing research has been vocabulary learning, and here too substantial spacing effects have been reported. In a study by Dempster (1987), for example, 38 uncommon English words and their definitions were presented three times, either with each repetition of any given word separated by every other word (i.e., each repetition of a word was separated by 37 other words) or with each repetition of a word massed in succession. In three experiments in which spaced vs. massed presentations were evaluated in this manner, spaced presentations yielded substantially higher levels of vocabulary learning than did massed presentations. In some cases, in fact, the number of word meanings recalled was 50–100% greater under spaced conditions than under massed conditions.

Finally, spacing effects have been demonstrated repeatedly in a variety of text processing tasks (Dempster, 1986; English *et al.,* 1934; Glover and Corkill, 1987; Kraft and Jenkins, 1981). For example, Dempster (1986) found that two readings of a text separated by a 48-hr interval or a 30-min interval was significantly more effective than two readings of a text separated by 30-sec and 5-min. Also English *et al.,* (1934) found that four readings of a text at 3-hr intervals were associated with better learning than four consecutive unspaced readings. Similarly, Glover and Corkill (1987) observed the spacing effect (0 lag vs. a 30-min lag) in subjects' memory for paragraphs they read as well as for brief lectures they heard. Since students spend so much time reading and listening to lectures, these findings would appear to have considerable practical significance.

THE TEST-SPACING EFFECT

Memory is affected not only by what happens during presentations (i.e., on study trials), but also what happens on test trials. Although it surely complicates matters scientifically, the act of measurement has an effect on that which is measured (e.g., quantum physics), and memory is no exception. As Lachman and Laughery (1968) put it, "Test trials, though they may be designed to measure changes in the state of the human memory system, have profound and perhaps residual effects on the state of that system" (p. 40).

Research on learning – specifically research on the effectiveness of tests – has made it abundantly clear that tests do more than simply test; they also promote learning, even when no corrective feedback is provided and when there are no further study opportunities (e.g., Allen *et al.,* 1969; Anderson and Biddle, 1975; Donaldson, 1971; Gates, 1917; Hogan and Kintsch, 1971; Izawa, 1971; Jones, 1923-1924; Lachman and Laughery, 1968; Nungester and Duchastel, 1982; Petros and Hoving, 1980; Rea and Modigliani, 1985; Rothkopf, 1966; Runquist, 1986; Slamecka and Katsaiti, 1988; Spitzer, 1939). In many cases, the effect has been strong. For example, Jones (1923-1924) found that the retention test scores of previously tested students was twice that of untested students. In other words, taking a test can confer substantial benefits on the retention of the same material tested on a later date, even when no corrective feedback is provided and when there are no further study opportunities.

The "test-spacing effect" refers to the fact that spaced tests are more effective than massed tests, especially if the intertest intervals are of an expanding nature (Landauer and Bjork, 1978; Modigliani, 1976; Rea and Modigliani, 1985; Whitten and Bjork, 1977). In a study of name learning, for example, a pattern of increasing intervals between successive tests, in which subjects attempted to write the last names of fictitious characters in response to their first names, was superior to a pattern of uniform spacing (Landauer and Bjork, 1978).

In a related study, Rea and Modigliani (1985) investigated the effect of tests on the retention of grade-appropriate multiplication facts and spelling lists. In the massed uniform condition, the subjects received four evenly spaced tests occurring relatively close together in time; whereas in the expanded condition, the interval between each of the successive tests increased by roughly 50%. Following the fourth test, a final test was administered. For multiplication facts, retention in the expanded condition was almost twice that in the massed condition. For spelling lists a more modest, but still significant, difference in the same direction was obtained. Furthermore, expanded testing was equally beneficial for children of all ability levels.

Research on testing, has revealed a number of other conditions that either diminish or heighten the effects of tests, whether massed or spaced. First, tests are most effective if the material to be learned is first tested relatively soon, but not immediately after its presentation (Anderson and Biddle, 1975; Modigliani, 1976; Spitzer, 1939). This phenomenon is nicely illustrated in a study by Spitzer (1939), who tested the entire sixth-grade population of 91 elementary schools in Iowa. Each child read a highly factual article and then was tested one or more times at various intervals following reading. An especially significant outcome, from a practical perspective, was that students whose initial test occurred 1 and 7 days after reading scored 15 to 30% higher on a final test 2 weeks later than did students whose initial test occurred 14 and 21 days following reading.

Second, information tested but not recalled at the first opportunity is not as likely to be recalled later as is information that was tested and remembered (e.g., Anderson and Biddle, 1975; Jones, 1923-1924; Modigliani, 1976; Runquist, 1986). Thus, the so-called "potentiating effect" of test trials applies mainly to test questions with successful outcomes. Finally, the facilitating effects of tests are greater for repeated questions than for new items (Anderson and Biddle, 1975; Nungester and Duchastel, 1982; Runquist, 1986; Sones and Stroud, 1940). For example, Rothkopf (1966) had college students study a lengthy selection from a book on marine biology, followed by questions on the passage. On a later test, these students performed substantially better than a control group on repeated items and modestly better on new items (an indirect effect), even though knowing the answer to one question should not have given the answer to another. However, as Anderson and Biddle (1975) noted, the aggregate indirect benefit is likely to be greater than the direct benefit. "Only the points of information about which . . . questions are asked could be directly affected, whereas presumably every point in the text could be indirectly influenced" (p. 92).

THEORETICAL IMPLICATIONS

A satisfactory theory of learning should answer the kinds of questions a curious lay person would ask about the sorts of learning which occur in everyday life. Surely, some of those questions would pertain to the role of practice or repetition in learning. Indeed, as Hilgard and Bower (1975) noted, these are the very same questions which tend to give rise to theories of learning. Thus, the effects of repetitions on memory, whether in the form of presentations or tests, should be fertile soil for constructive inquiry into the mechanisms of learning.

In fact, spacing effects have attracted a great deal of theoretical attention, yet the theoretical picture that emerged was for many years rather confused, despite numerous attempts at clarification. In his highly influential review, Hintzman (1974) considered five theories of the spacing effect, which he later classified under two general headings: encoding variability theories and deficient-processing theories (Hintzman, 1976).

Encoding Variability Theories

Encoding variability theories appear to owe much to the work of Bower (1972) and Martin (1972), who fostered the notion that contextual variations had much explanatory power. The basic assumption is that there are a number of different ways in which to-be-remembered information can be encoded; and as the number of different encodings increases, the number of potentially effective retrieval routes increases. Further, it is assumed that as the spacing between presentations increases, the number of different subjective contexts in which the information is encoded also increases.

As Hintzman (1974) noted, one of the original problems with encoding variability theory is that the nature of the contextual elements involved was not worked out in sufficient detail; however, later work has resulted in a more exact specification of the elements involved (e.g., Glenberg, 1979). Nevertheless, there is still a major problem with the theory—namely, the assumption that a change in context benefits recall. In some cases, in fact, changes in context have been associated with poorer recall. For example, Murdock and Babick (1961) repeated a single word in a constantly changing context and found no benefits whatsoever from repetition. More recently, Postman and Knecht (1983) investigated the encoding variability hypothesis by systematically increasing the number of explicit contexts in which the to-be-remembered item was embedded. They found that recall levels were actually lower following variable encoding than after constant encoding. Finally, Dempster (1987) found that whereas spaced presentations yielded significantly better vocabulary learning than did massed presentations, there was no independent effect of a manipulation designed to affect the number of retrieval routes to the word meanings. Here again, and in a later related study (Dempster, 1989), contextual change during presentation tended to be associated with poorer recall.

In short, encoding variability theory, even in its most sophisticated form—namely, component-levels theory (Glenberg, 1979)—cannot be considered a general explanation for the spacing effect (see Toppino and Gracen, 1985). For the most part, it is only in highly contrived situations, as when a homograph is presented in different contexts, that differences in favor of the different-encoding condition occur (Hintzman, 1974; Postman and Knecht, 1983).

Deficient-Processing Theories

Deficient-processing theories postulate that massed repetitions receive less processing than their spaced counterparts, and that recall is a function of the amount of processing information received. At the time of Hintzman's (1974) writing, four mechanisms had been advanced to account for variations in processing, two of which can be considered involuntary (consolidation and habituation) and two voluntary (rehearsal and attention).

The consolidation hypothesis (Landauer, 1969) proposes that the transfer of information from a relatively transient state in memory to a more permanent retrievable state in memory takes time, and that this process can be interrupted if a repetition of the to-be-remembered information occurs prior to "consolidation." Thus, if two repetitions are massed, the total amount of consolidation will be less than if the two repetitions are spaced. The consolidation hypothesis seems remarkably similar to the much older perseveration hypothesis which was originally advanced by Muller and Pilzecker to account for the facts of retroactive inhibition. In fact, the two hypotheses, at least as they apply to the spacing effect, seem identical. However, there is still no evidence for consolidation-perseveration beyond the facts they are invoked to explain. In addition, the time course for consolidation has been estimated to range from 15 sec to 1 hr (Baddeley, 1976). According to that estimate, it would not provide an adequate account of spacing effects either when the spacing interval was very short, as in many studies, or when the intervals in question were relatively long (e.g., Bahrick and Phelps, 1987).

The habituation hypothesis has the same problems as the consolidation hypothesis. For example, Hintzman *et al.* (1975) concluded that habituation would have to asymptote in less than 2.2 sec for the habituation hypothesis to be supported. If this were true, there would be no difference between spacing intervals greater than 2.2 sec, contrary to actual findings. Unlike the consolidation hypothesis, however, it attributes deficient registration to a mechanism that adapts or "turns off" for a short period following registration. Under massed conditions, then, assuming that the spacing interval is less than the time needed for recovery from habituation, a repetition would receive something less than full processing. Although Hintzman (1974) found this hypothesis intriguing, it has been largely ignored.

The rehearsal hypothesis received some early support in a study by Rundus (1971) who found that spaced items received more rehearsals than massed items during the spacing interval, which of course is longer under spaced conditions than under massed conditions. Since frequency of rehearsal is often directly related to recall, one could argue that a differential amount of rehearsal underlies spacing effects. However plausible, the rehearsal hypothesis has not fared well overall. Most decisively, manipulations that should have affected rehearsal, such as an interpolated task (Bjork and Allen, 1970) and difficult to rehearse complex visual stimuli (Hintzman and Rogers, 1973), have not had the effects on memory that the rehearsal hypothesis predicts. Moreover, the fact that spacing effects have been found with very young children (Cornell, 1980; Rea and Modigliani, 1987), who are not inclined to rehearse spontaneously (e.g., Naus and Ornstein, 1983), is inconsistent with the rehearsal hypothesis.

The final deficient processing theory considered by Hintzman (1974, 1976) was the voluntary attention hypothesis. According to this account, the subject chooses to pay less attention to repetitions when they are massed than when they are spaced. Thus, this hypothesis places the locus of the spacing effect squarely on the second and subsequent presentations of an item. Processing of the first presentation is in no way affected by the spacing interval.

In 1974 Hintzman ranked this hypothesis just behind the habituation hypothesis as the one most likely to be correct, largely because there was no decisive evidence against it and because of some evidence in its favor. For example, Elmes *et al.* (1972) compared the free recall of words that occurred immediately following either massed repetitions or spaced repetitions, and found that recall was better following massed repetitions. This result suggests that subjects treat the massed repetition as a rest opportunity which enables them to devote more attention, and thus more processing resources, to the next word on the list.

Since then, the attention hypothesis has received further support. In a study by Dempster (1986), for example, college students responded to a questionnaire administered following a recall test of a twice-read passage, with the two readings spaced either 30 min apart or 5 min apart. The questionnaire consisted of 10 items, each followed by a 10-point rating scale, which was designed to elicit self-reports of various cognitive and affective states and processes during reading and testing. Included were questions concerning levels of attention, interest, anxiety, rehearsal, and changes of interpretation (subjective context) from one reading to the next. Group differences emerged on only two of the items: specifically, one asking the subjects to indicate how "interested" they were during the second reading, and one asking them to indicate how much "attention" they paid during the second reading. In both cases the average ratings of students in the spaced condition (those who also did best on the recall test) were higher than those in the massed condition. Moreover, a correlational analysis, applied to the scores of both groups combined, revealed a significant correlation between recall and only one of the questionnaire items (i.e., the attention paid during the second reading). Those who reported having paid more attention tended to have learned more from the text. These findings dovetail nicely with those of Magliero (1983) who found that pupil size associated with the second of two repeated items increases as the spacing between presentations increases. Since pupil size is a well-accepted measure of attention and is known to vary directly with amount of processing, this finding also suggests that differences in attention underlie at least some spacing effects.

However, why should spaced presentations receive more attention than massed presentations? The voluntary attention hypothesis assumes that processing effort can be allocated in a flexible way at the subjects' discretion. Thus, there must be something about the subjects' beliefs, expectations, or preferences that are affected by the spacing between repetitions. One possibility, suggested by the work of Zechmeister and Shaughnessy (1980) is that massed presentations inspire a false sense of knowing or confidence. In this study, college students rated the likelihood of recall of individual words presented for free recall learning. They found that the students were more confident, they would remember material repeated under massed conditions than under spaced conditions, even though they remembered significantly less under massed conditions.

Another possibility, suggested by Dempster's (1986) findings, is that subjects somehow find spaced repetitions more interesting than massed repetitions—perhaps because they are less redundant and thus more informative than massed presentations. To the extent that interest has an affective component, this explanation is consistent with the results of an earlier study which found that subjects tended to judge spaced words as more "pleasant" than massed words (Elmes *et al.*, 1983).

There are, however, a number of difficulties with the voluntary attention hypothesis, regardless of the specific mechanisms postulated. First, certain manipulations that should have induced subjects to attend to massed presentations have failed to attenuate the spacing effect (e.g., Hintzman, 1976). Second, substantial spacing effects have occurred in incidental learning tasks (Rowe and Rose, 1974; Shaughnessy, 1976) and with preschool age children (e.g., Rea and Modigliani, 1987)—circumstances in which voluntary control processes should not have been much of a contributing factor. Finally, the very generality of the spacing effect seems to be an argument against a purely voluntary process. How reasonable is it to assume that the same or similar voluntary processes would operate under all sorts of task conditions, with so many different subject populations?

In view of these shortcomings, the key to understanding most spacing effects may lie in the operation of an involuntary mechanism that controls attention. But what might that mechanism be? Recently, a growing number of researchers have suggested that the accessibility of previous encodings may be crucial to the explication of the spacing effect. A variety of formulations that share this theme have been proposed (e.g., Dellarosa and Bourne, 1985; Dempster, 1988; Jacoby, 1978; Rose, 1980, 1984; Rea and Modigliani, 1987). The basic idea is that when a unit of information is repeated, an attempt is made to retrieve the previous encoding of that item. If the spacing between occurrences is relatively short, the results of the previous encoding(s) will be more accessible than if the spacing between repetitions is relatively lengthy. Thus, the subject will need to devote more attention or processing effort to spaced repetitions than to massed repetitions.

To date, efforts to test the "reconstruction" or "accessibility" hypothesis have led to mixed results. In one study (Glenberg and Smith, 1981) the repetition was in a modality different from that of the first presentation, and a different orienting question was used during each presentation. Since these manipulations should have made the original encodings more difficult to retrieve, it was assumed that the repetition required constructive processing, regardless of the spacing interval. However, the spacing effect on a test of recall was not attenuated. In two other studies, the accessibility of memory traces was operationally defined in terms of the time needed to respond to a question that accompanied the repetition. Whereas Maskarinec and Thompson (1976) found no effect of spacing upon reaction time, Rose's (1984) findings were generally consistent with the reconstruction hypothesis, which predicts that longer reaction time to questions should occur under spaced conditions.

In its favor, the reconstruction hypothesis is consistent with the fact that both spaced presentations and spaced tests strengthen the memory trace. Logically, a test that strengthens a memory trace would be one that is attention-demanding owing to a not-so-accessible trace. Moreover, it seems capable of accommodating a wide range of spacing intervals, including expanding intervals. In general terms, the assumption is that repetitions are effective to the extent that they engender successful retrieval of the results of earlier processing, and that the effort involved in a successful retrieval operation increases with spacing.

The ultimate utility of the reconstruction hypothesis may very well depend on the resolution of another issue—namely, do repetitions in the form of presentations and tests have the same or different effects on memory? Research relevant to this issue is equivocal. On the one hand, there is some evidence that experimental conditions affect each of them differently, suggesting that they have differential effects on learning. For example, Sones and Stroud (1940) provided seventh-graders with either a test or a review at various intervals following the reading of an article. Forty-two days after the reading, a multiple-choice retention test was administered. For subjects who received a prior test, retention test performance decreased as the interval between original reading and the test increased. By contrast, the effect of the review on retention was independent of the interval between original study and the review.

On the other hand, more recent work which has focused on the rate of forgetting has yielded mixed results. Runquist (1983) found that whereas further study increased the overall level of recall, it did not, as did a test, reduce the slope of forgetting. However, this study has been criticized by Slamecka and Katsaiti (1988) who found no evidence that prior tests influenced the rate of forgetting.

Nevertheless, there has been considerable speculation that the operations occurring during review primarily help to "fix" or to set a trace, whereas the operations that accompany successful tests with successful outcomes primarily serve to sharpen the person's ability to retrieve the trace (e.g., Halff, 1977; Lachman and Laughery, 1968; Runquist, 1983, 1986). Intuitively, this is an attractive notion since tests normally afford fewer retrieval cues than additional study opportunities. In addition, it is in the spirit of a multiprocess view of learning in which retrieval is regarded as a rather complex process, involving the transition from the use of a general heuristic, which is fallible, to the use of a specialized algorithm which, at least in principle, is not (e.g., Brainerd *et al.*, 1985; Greeno, 1970; Runquist, 1986).

In its original form, the attention hypothesis left much to be desired from a strictly psychological point of view. As Underwood (1970) noted, if learning is depressed under massed conditions "because of inattention by S, it would be trivial; learning cannot take place without input" (p. 580). The evolution of the attention hypothesis in terms of retrieval/reconstructive operations, the exact nature of which are still decidedly vague, however, presents a meaningful challenge to learning theorists who seek to explain the effects of repeated encounters with nominally identical or similar events. Meanwhile, the accessibility or reconstructive hypothesis implies a theory of learning that promises to inform adjacent areas of scientific inquiry. For example, it may help to understand our inborn preference for novel as opposed to familiar stimuli (e.g., Moscovitch, 1984), and the tendency of rats in a classical conditioning paradigm to ignore stimuli from which it is already deriving maximal information (e.g., Rescorla and Wagner, 1972).

EDUCATIONAL IMPLICATIONS

Given the long and eventful history of research on spacing effects, one might assume that their implications for classroom practice would already be well-known, at least among psychologists. However, this does not appear to be the case. Even those who have studied spacing effects from a theoretical perspective are unlikely to be aware of much of the more applied research, especially studies that were conducted around the turn of the century (e.g., A. M. Glenberg, personal communication, September 1987). Furthermore, the ahistorical character of applied research (e.g., Dempster, 1988) makes it difficult to appreciate the range of school-like situations in which spacing effects have been found effective. In addition, there is no evidence of any serious effort to disseminate the results of spacing research to the educational community. In a recent sampling of practitioner-oriented textbooks suitable for use in teacher education programs, I found either little or no mention of the spacing effect (e.g., Good and Brophy, 1986; Kim and Kellough, 1987; Mayer, 1987; Slavin, 1988; Woolfolk, 1987), and on test-spacing effects I was able to find even less. Tests are regarded mainly as instruments for making decisions about grading and pacing, not as a means of promoting learning (Kuhs *et al.*, 1985).

As might be expected then, spacing effects have not yet captured the attention of teachers, teacher educators, or curriculum specialists, and they are not widely exploited in the classroom. For example, review—a prerequisite to the spacing of presentations—is not a common practice in the classroom. In a study of the effectiveness of an experimental mathematics teaching program, the teachers summarized the previous day's lessons only about 25% of the time, and homework was checked only about 50% of the time (Good and Grouws, 1979). Many topics, it seems, are presented just once (e.g., Armbruster and Anderson, 1984). Clearly, review is a teaching function that could be done more frequently in most classrooms (Rosenshine and Stevens, 1986).

As to the use of spaced reviews in textbooks, the situation appears to be pretty much the same. In surveys of mathematics textbooks, the use of a distributed method of presentation, with frequent use of spaced review, is clearly the exception rather than the rule (Saxon, 1982; Stigler *et al.*, 1986). In part, this may be due to the fact that the spacing effect is not intuitively obvious (Bjork, 1976; Zechmeister and Shaughnessy, 1980). Even experienced educators, when judging the instructional effectiveness of text passages, tend to rate prose in which the repetition of information is massed as better than those in which it is spaced (Rothkopf, 1963).

Research also suggests that many, if not most, courses of instruction offer far less than optimal testing patterns. It is not unusual, for example, for postsecondary classes to have only two (a midterm and a final) or three tests in a term, and relatively few of these appear to be cumulative. Tests are also not an integral part of teachers' regular instruction at the elementary level, even though a particular subject may be taught three to five times a week. In one survey, fourth- and sixth-grade mathematics teachers reported having administered an average of about 18 curriculum-embedded tests per year, or approximately one test every two weeks (Burry *et al.*, 1982). Worse, it appears that teachers test more frequently in mathematics than in reading, and that grade level and amount of testing are inversely related (Yeh, 1978). Thus, there are reasons to believe that tests also are underutilized in the classroom in terms of their potential for improving learning.

Arguably, the beneficial effects of an increase in the use of spaced reviews and tests in the classroom would extend beyond their effects on learning. Recall that distributed reviews and tests have been found to be more "attention-grabbing" than similar massed events (e.g., Dempster, 1986; Magliero, 1983; Zechmeister and Shaughnessy, 1980). Thus, spaced repetitions are likely to promote student time-on-task, a highly valued classroom behavior. In addition, research suggests that students will find spaced repetitions an interesting and agreeable classroom practice (Burns, 1970: Dempster, 1986; Elmes *et al.*, 1983). Burns (1970), for example, reported that his sixth-grade pupils found review questions spaced throughout instruction both "useful" and "interesting." In short, the use of frequent spaced reviews and tests might help students develop and sustain positive attitudes toward school and learning (see also Anderson and Biddle, 1975, p. 128).

Also on the benefits side of the ledger, if indeed reviews and tests have differential effects on learning as some theorists suppose, reviews and tests may be used to serve two different learning-related purposes in the classroom. For material that is not well learned, reviews may be more productive than tests. But when degree of original learning is high, a test, as Nungester and Duchastel (1982) determined, may result in significantly better retention than an equivalent amount of time spent in review. As Sones and Stroud (1940) noted:

> Since testing reviews are more effective when placed in early positions, the effectiveness of such reviews should vary directly with the degree to which the material is originally learned. Moreover, for material that is well learned, recall, as in the form of a test, should be more productive than relearning, as in rereading (p. 675).

These considerations raise the question of how best to put into practice the results of research on reviews and tests. It would appear that spaced reviews and tests can be successfully incorporated into a variety of instructional activities, including asking questions about concepts and skills taught in previous lessons, assigning and checking homework, having students prepare a written summary of previous lessons, and providing feedback on quizzes covering material from previous lessons. By distributing homework exercises concerning a particular topic across a number of weekly assignments, for example, students will receive repeated spaced exposures to the same educational objective. The same result, of course, can be achieved by frequent spaced (e.g., daily, weekly) reviews.

Process-outcome research (reviewed in Brophy and Good, 1985) indicates a positive relationship between frequency of academic questions addressed to students and size of gain in student achievement. Moreover, the largest achievement gains are seen in classes where most, perhaps 75% of the teachers questions are answered correctly (as the results of testing would predict), and most of the rest yield partially correct or incorrect answers rather than no responses at all (Brophy and Evertson, 1976).

Ideally though, questions aimed at specific educational objectives should be repeated according to a pattern of increasing intervals between successive questions. Questions administered soon after the material is introduced are likely to have a favorable outcome, engender feelings of success and accomplishment, and strengthen the information sufficiently to survive a somewhat longer interval. A recent example of just this sort of application has been provided by Siegel and Misselt (1984), who conducted a study in which college students were taught foreign language vocabulary using a computer-assisted instruction program. When a student made an error he or she received corrective feedback, and then the missed item was programmed to reappear according to an expanded ratio practice schedule. For example, the first retesting of a missed item might occur after an interval of three intervening items; if that test had a successful outcome, the third test would occur after an interval of six intervening items, and so forth. If at any time during practice an item was missed, the entire procedure was reset.

Posttest performance revealed that the use of this procedure was successful. Unfortunately, most programs developed for use with computers are modeled after the traditional flash card drills, and tend not to be guided by investigations of sequences of events which might be optimal for efficient and effective learning (McDermott and Watkins, 1983). As Siegel and Misselt (1984) point out, their procedure could be expanded to guide instruction in a variety of areas, including spelling, arithmetic, and concept learning.

RECOMMENDATIONS FOR FUTURE RESEARCH

Clearly, we do not need any more demonstrations that spaced repetitions "work." However, there are a number of issues relative to spacing that may be fruitfully investigated.

One such issue pertains to the effects of paraphrasing on repetitions. As noted earlier, the effects of paraphrasing on the spacing effect have been inconsistent (Dellarosa and Bourne, 1985; Glover and Corkill, 1987; Rothkopf, 1966), and the reason for these conflicting results is unclear. This issue also has relevance to the test spacing effect, inasmuch as test questions that entail paraphrase and application of principles and concepts to new situations may be especially facilitative—particularly, when later tests make similar demands (Anderson and Biddle, 1979; Watts and Anderson, 1971).

Obviously, the effects of paraphrasing on repetitions are of both theoretical and practical importance. On the theoretical side, paraphrased repetitions should render the original encodings more difficult to retrieve, resulting in full processing even under massed conditions. Thus, the results of studies by Dellarosa and Bourne (1985) and Glover and Corkill (1987) are consistent with hypotheses that attribute spacing effects to differential attention, such as the reconstruction hypothesis. Also consistent with these hypotheses is a study by Glanzer and Duarte (1971) who found that repeating words in a different language to bilinguals attenuated the spacing effect relative to same-language repetitions. Thus, Rothkopf's (1966) seemingly atypical findings deserve special attention.

The effects of paraphrasing also have important implications from a practical perspective. If, in most cases, massed paraphrased repetitions are as effective as spaced repetitions, the significance of the spacing effect for the classroom will be somewhat limited, since paraphrased reviews are probably the rule rather than the exception. Thus, spacing research aimed at explaining the conditions under which paraphrasing attenuates and does not attenuate the spacing effect should have high priority.

Another focus of spacing research that has yielded conflicting evidence is developmental. In this domain, though, Toppino and DiGeorge's (1984) failure to find the spacing effect among preschoolers is probably due to sampling error or to lack of experimental precision. As Rea and Modigliani (1987) noted, Toppino and DiGeorge's (1984) procedures can be questioned. In any case, the preponderance of evidence suggests that the spacing effect does not emerge with development, and thus that it reflects an automatic process, such as involuntary attention (e.g., Cornell, 1980; Rea and Modigliani, 1987; Toppino and DeMesquita, 1984). Future developmental research will be useful to the extent that it helps to specify the actual mechanisms that underlie spacing effects.

The absence of a detailed specification of just how spacing effects work is, in fact, the major theoretical shortcoming associated with spacing research. Most importantly, the exact nature of the retrieval operations involved need to be worked out in sufficient detail to generate specific hypotheses concerning the influence of retrieval on existing memory representations. Jacoby (1978) suggested that massed repetitions involve fewer retrieval operations than spaced repetitions, and that this detracts from the distinctiveness of the memory trace. That is, since there are fewer operations to be recognized, the number of potential bases of retrieval is reduced. Alternatively, research by McDaniel and Masson (1985), though spacings were not manipulated, raises the possibility that spaced repetitions may allow for a more elaborate memory trace. But how retrieval accomplishes this, and what type of elaborate encodings emerge, is just as unclear as are the mechanisms underlying distinctiveness.

A closely related theoretical issue concerns the relation between reviews and tests, and the extent to which the spacing effect and the test spacing effect are the same or different phenomena. In some cases, at least, testing is not simply further study. Once some to-be-learned information is stored in memory as indicated by a correct response to a test, further test trials tend to enhance performance more than study trials (Brainerd *et al.,* 1985; Halff, 1977; Nungester and Duchastel, 1982), even when the test questions and review statements contain the same content (Bruning, 1968). One possibility is that acquisition and forgetting obey different laws (Brainerd *et al.*, 1985), and that further study increases the number of immediately assessible items, whereas testing increases their resistance to forgetting (Runquist, 1986). However, for progress to be made relative to this issue, the effects of testing, in particular, need to be depicted in greater detail.

A more detailed depiction of testing effects should also include an explanation of indirect effects. At the present time research suggests that, at least to some extent, a quiz may cause the learner to review mentally the material covered by the quiz, including material not directly tested (McGaw and Grotelueschen, 1972). However, it might also be the case that indirect effects are due to specific associations to the test questions themselves. In either case, it is not clear whether the critical variable in indirect effects is spaciotemporal or topical-semantic similarity (Anderson and Biddle, 1975).

Obviously, indirect effects have a great deal of educational significance; if we knew their cause, teachers could structure their tests in such a way so as to maximize their overall effect.

CONCLUSIONS

Research on spacing effects has had a lengthy and distinguished history, involving the active participation of some of psychology's foremost contributors, including Ebbinghaus, Thorndike, Ausubel, and Melton. The fruits of this research are in many ways remarkable: spacing effects are among the most dependable, robust, and ubiquitous phenomena in the entire psychological literature. Although the test-spacing effect is less well-known than the spacing effect, indications are that this gap is closing.

One indicator is that the effects of spaced presentations and spaced tests are increasingly becoming understood in terms of the same psychological mechanisms—namely, involuntary attention processes mediated by the accessibility of previously encoded information. This is not to say, however, that there is likely to be one cause of all spacing effects. In some situations (e.g., under short lag conditions) a voluntary process such as rehearsal, may be responsible for the spacing effect. As Hintzman recently noted, theoretical work on the spacing effect may have suffered early on from the way the problem was formulated. "[O]ne possibility is that there is more than one cause of the spacing effect, or to put it differently, that there are several 'spacing effects'" (personal communication, October 1987).

A second indicator is that the spacing of repetitions, whether in the form of presentations or tests, has clear and verifiable implications for educational practice. Spaced reviews and tests are underutilized in the classroom in terms of their potential for improving learning. That potential appears to be vast, although it is unlikely to be realized until those who are familiar with the research on spaced repetitions are willing to relate it explicitly to educational issues. Spacing effects must be transformed into specific educational procedures and techniques that will enhance student learning and achievement before widespread application can be expected. Fortunately, for those who have a primacy of commitment to research, this effort is likely to result in a *quid pro quo:* widespread application should yield new and exciting data bases and theoretical insights.

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