AN ADAPTIVE, AUTOMATED INSTRUCTIONAL SYSTEM TO SUPPORT THE LEARNING OF FACTUAL INFORMATION

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> *"The value of a psychological theory is judged not only by its explanatory and predictive power, but also by its operational power to improve human functioning." (Bandura, 1986)*

Introduction

An important goal of educational research is to facilitate the acquisition and retention of knowledge in an effective and efficient manner. Gruneberg (1988) argued that while psychologists have been successful in conducting laboratory and field experiments that have yielded significant findings, they have not applied their newfound knowledge outside of those settings. "What we need," he wrote, "in addition to our Galileos, our Newtons and indeed our Alexander Flemings, in memory research, is our Marconis and our Alexander Graham Bells."

One area of research, Aptitude Treatment Interactions (ATI), has been extensively researched over the last several decades. (See Cronbach & Snow, 1977 for the seminal review. For more reviews, see also Tobias, 1989; Corno & Snow, 1986; Gustaffson & Undheim, 1996.) ATI researchers seek to understand the nature of individual differences (usually aptitudes) and to determine which instructional methods lead to differences in student achievement. Reviews of ATI research are as plentiful as replicated ATI's are rare—the universal finding is that ATI's are not consistent, replicable, or robust. One source of inconsistent findings may be the result of the lack of classification schemes for instructional methods and student characteristics. (Experimental research is predicated upon a design where two (or more) groups are highly similar except for the variable being investigated.) In addition, much of ATI research is driven by inconsistent instructional theory, often fueled by speculations generalized from research in other fields.

One researcher (Martinez, 2003) studying the interaction of individual aptitudes with instructional methods asserts that, "…Learning Orientation (LO) research integrates the recent advances in the neurobiology of learning and memory research. It integrates the biology of learning with the more traditional psychological and behavioral aspects." Martinez has claimed that "much of [her] initial work was based on the information of James Ledoux" (M. Martinez, personal communication, March 22, 2003). Ledoux's research is focused on the role of the amygdala in emotion using a task called "classical fear conditioning" (Schafe, Atkins, Swank, Bauer, Sweatt, & LeDoux, 2000). The connection between the neural circuitry associated with the autonomic freezing behavior in the rat and higher-level cognitive instruction is tenuous at best.

Another researcher, David Jonassen, who authored a textbook on "Individual Differences, Learning, and Instruction," (Jonassen & Grabowski, 1993), admits that "many of our implications and predictions are *not* [author's emphasis] validated by existing research" (p. ix). He also points out that "many of the research inferences are flawed by a dearth of research, inconsistent results, inadequate methodologies, and a lack of reliability or validity" (p. xvi), but then goes on for 488 pages to prescribe instructional treatments anyway. Curiously, Jonassen's own data suggest that there may be no interaction between cognitive styles and learning outcomes. In an interview (Jonassen, 2003), Jonassen said:

> *…the most interesting [research project] to me was, by most publishing criteria, a failure. I was looking at the role of cognitive styles on four types of learning outcomes. Having measured nearly 30 styles, I had to factor analyze those. Four factors emerged. I regressed those factor scores on the four learning outcomes. One factor emerged as the only significant predictor of all four types of learning. It seems that intelligence, even though I intentionally avoided measuring it, emerged like the Phoenix from the ashes of the data.*

(See Jonassen, 1980 for the original study.)

A final note on ATI research—perhaps Sig Tobias said it best when he wrote:

> *Unless I, and the other reviewers of research in this area, have missed the publication of tons of replicated findings there is no evidence of stable interactions between learning styles and instructional methods. Why then do otherwise knowledgeable educators and educational researchers persist in making unverified claims for learning styles? I can only conclude that they cling to what Jeanne Chall called a romantic, as opposed to rational, view of education. Such folks cling to their fancies irrespective of research findings.*

If there is a prescription to be found, then, in ATI research, it might be that instructional treatments should be based on consistent, replicable, and robust outcomes from empirical research. The ideal solution would be one that produces the "two sigma" effect described by Bloom (1984) and sought after by many researchers since.

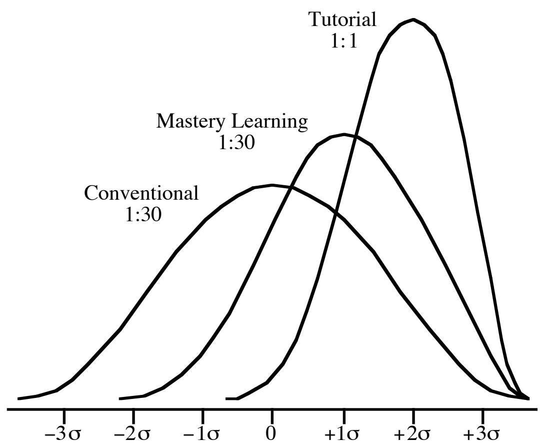

Figure 1: The average student under mastery learning is one standard deviation above the average of the conventional class—the tutored student is two standard deviations above.

Scope

In order to describe and instructional treatment, one must first recognize that there are as many types of instruction as there are learners and content. The first challenge, therefore is to narrow the scope of inquiry. Several researchers have identified different types of information. A table that contains the most recognized taxonomies (Jonassen & Hannum, 1995) is shown in Table 1 below.

Not surprisingly, the researchers are in agreement on the categories of information and cognitive processes but diverge as their taxonomies move to higher order levels. They do, however, universally agree that factual knowledge is an important learning objective. Gagné (1985) goes on further to say that the most basic form of learning, information, is not just another condition of learning, it is a *prerequisite* to all other learning (pp. 54-55).

	Bloom 1956	Gagné 1966,1977	Leith 1970	Merrill 1983	Mager & Breach 1967
	Knowledge	Information	Stimulus discrimination Response learning Response integration	Facts Procedures	Memorization Procedural
	Comprehension	Concrete examples Defined concepts	Learning set formation Concept learning	Concepts	Comprehension
	Application			Rules	
	Analysis	Principles	Hypothetico-deductive inference Learning schemata	Principles	
	Evaluation				
	Synthesis	Problem solving Cognitive strategies			

Table 1: Five taxonomies.

Robert Bjork (1998) made the following statement regarding the importance of learning factual information:

> *It is a fact of life that much of what we need to learn to function efficiently are arbitrary assignments of labels, symbols, and numbers. For many tasks, such as name learning, precious little understanding can be brought to bear on the problems: The task is essentially rote. Complex intellectual skills such as language and chess are undergirded by prodigious amounts of rote memorization. Rather than regarding such learning as inferior, we should recognize that it is essential, and we should get on with the job of making such learning as efficient and painless as possible.*

Accordingly, the purpose of this paper is to describe a system, and its theoretical underpinnings, that support the learner in their acquisition of factual knowledge using the most effective, efficient, and humane means possible. Put simply, I will describe an "electronic flashcard system." This description is as misleading, however, as describing Microsoft Excel as an "electronic ledger," or Microsoft Word as an "electronic typewriter." By transferring the system from paper to a computer, tremendous advantages can be realized as will be shown.

Theoretical Basis

The Forgetting Function

There is little or no debate over the fact that we forget. And since 1885, the general time-course of forgetting has been known—the majority of newly learned material is forgotten within the first 24 hours as indicated by the steep decline in Figure 2a; the remainder of forgetting occurs much more gradually.

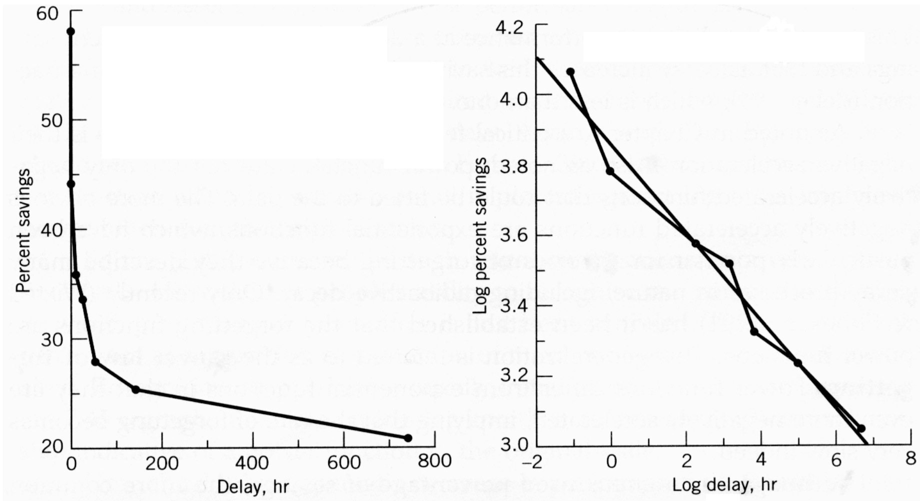

Figure 2: Retention data from Ebbinghaus (1885) (a) showing percentage of savings as a function of retention interval; (b) with both scales log transformed to reveal a power relationship of the form $y=ax^{-b}$.

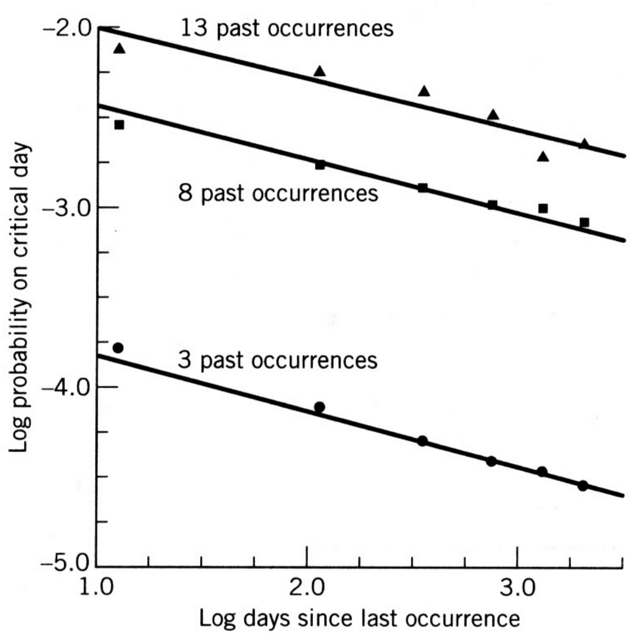

Figure 3: Log probability of a word occurring in a *New York Times* headline as function of log time since last occurrence for three levels of frequency (Anderson & Schooler, 1991).

Anderson and Schooler (1991) investigated the relationship of recency and frequency of past usage of information to the statistical likelihood of its reappearance in the environment. In one study they recorded the occurrence of words in New York Times headlines over a period of two years. More specifically, they calculated how many times a word appeared in the last one hundred days and how recently it occurred. Figure 3 above shows the probability of a word appearing on the current day as a function of the recency of its last occurrence and how many times it occurred in the last 100 days. It is clear from this data that information that has appeared recently is the most likely information to reappear. Also, information that has appeared frequently in the past is likely to appear again in the near future. When predicting tomorrow's headlines, your best bet is to look to recent headlines as well as the words that have occurred frequently in the past.

A similar pattern can be seen in the neural activity of the brain. Barnes (1979) examined how long-term potentiation (LTP) in the hippocampus decreased with time. When brief, high frequency stimulation is administered to brain cells, there is a long-term increase in the magnitude of the response of the cells to further stimulation (Bliss & Lomo, 1973). This change, called long-term potentiation, occurs immediately and lasts for weeks. Because it is a long-lasting change and depends on the activation of two or more neurons, it is though to be involved in some types of associative learning.

Barnes investigated how LTP decreased with time for different cases where she varied the frequency of stimulations from one to four. The data are very similar to that in Figure 3 and 2 where the rates of decay, on a log-log scale, are approximately linear and parallel.

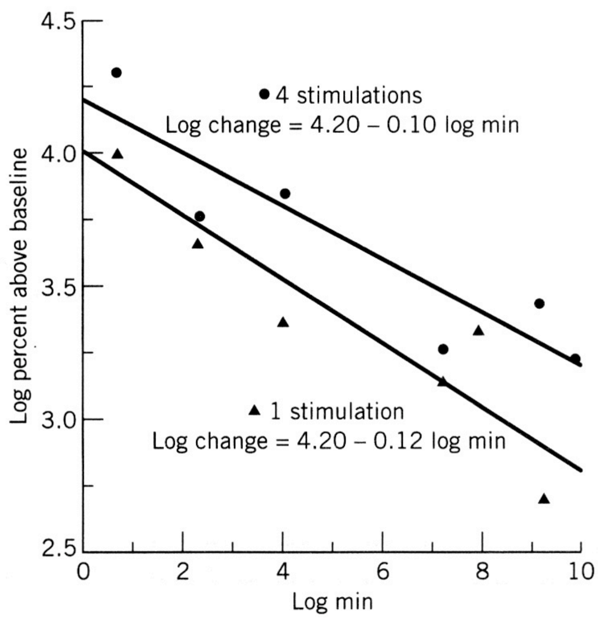

Figure 4: Percentage of LTP as a function of delay for two levels of practice (Barnes, 1979).

It appears that from Barnes' investigation of neural plasticity, as well as Anderson and Schooler's study of the statistical nature of information in the environment—which both match behavioral observations made by Ebbinghaus and many others subsequently—that our brains' ability to store information has been optimized at the neural level to make available the information most likely to be needed, while discarding (forgetting) information less likely to be needed. For a memory system with finite capacity, this adaptation is effective and efficient. The design of an instructional system would similarly be effective and efficient if the presentation of information was designed around the very algorithms the brain uses to sort out what should be remembered versus what should be forgotten. The algorithm based on these findings will be described later in the System Description.

Metacognition

Learners do not always know what conditions produce the best learning. It is often difficult to assess one's true state of knowledge and skill. Teacher, trainers, and instructors are often misled by assuming that the conditions that enhance performance during training are also the conditions that enhance posttraining performance. Bjork (1994) states: "What one sees during training is current performance, which is an unreliable indicator of the learning that can support the longer-term performance that is the goal of training." He goes on to point out that many instructional strategies that speed the rate of learning such as massed practice, providing very frequent feedback, and keeping the conditions of practice constant, are the very worst training conditions in terms of long-term retention and the ability to transfer and generalize the training.

An effective and efficient system, therefore, would be one that does not base the scheduling and presentation of information on factors related to immediate success, but rather on those factors that underlie optimal long-term retention and performance. These factors include the spacing of practice on an intra-trial and inter-trial basis, allowing for errors (which vary in proportion to correct responses according to individual needs to maintain the balance between boredom and frustration), as well as varying the conditions of practice. These factors will be described in more detail in the System Description section below.

Automaticity

Another factor that must be considered in the development of a factual knowledge training system is the performance condition. Individuals must be able to access factual knowledge automatically. More precisely, automaticity can be defined as rapid, accurate processing of information that requires minimal awareness and attention (Swanson, 1987). Because automatic processing does not demand much attention, it is fast and effortless (Logan, 1990). Guidance for the development of a system that produces automatic retrieval of factual information is drawn from behavioral and neurophysiological research.

There are a number of studies that show how response strength varies with the CS-UCS interval. Three representative studies with human subjects (Spooner & Kellogg, 1947; Moeller, 1954; Kimble, Mann, &Dufort, 1955) used conditioned responses of hand movement, galvanic skin response, and eyelid blink, respectively. These experiments consistently show that conditioning is most rapid and response strength is greatest when the conditioned response precedes the unconditioned response by about one half second.

Figure 5: The maximum frequency of conditioned responses occurs when the conditional stimulus precedes the unconditioned stimulus by about a half second. The curve labeled "Present study is from the data of Spooner and Kellogg (1947). (From Deese & Hull, 1967.)

The implication for the factual information training system is that the cue (or known item such as an English vocabulary word) should precede the presentation of the response (or unknown foreign vocabulary word) by about a half second. This leaves no time to reconstruct the target word—the learner simply knows the response or doesn't. Presenting the known/unknown pair a number of times (according to a schedule described below) produces a state of "knowing." The use of mnemonics and other retrieval cues, in comparison, allow a student to recall information in classroom test conditions where time is not a critical factor, but rarely in real-world performance conditions where instantaneous recall is often required.

It should be noted that generalizing observations made about classical conditioning to operant conditioning is justified in this case. Both kinds of conditioning show the same effects of practice, both extinguish in the same when way when the contingency is eliminated, and both show spontaneous recovery. Both kinds of conditioning are hurt if a delay is placed in the contingency. And both paradigms result in successful conditioning only if there is a contingency among the elements—not just contiguity (Anderson, 1995).

Cognitive Load

A further benefit from the development of automaticity is that basic skills that are automatic do not use up a person's limited capacity for information processing leaving more capacity available for execution of higher level skills (Hasselbring, Goin, & Bransford, 1998). Information processing research has found that rapid retrieval of component facts and skills from long-term memory is necessary for proficient performance in complex problem-solving (Gagné, 1983; Pellegrino & Goldman, 1987).

Humane Instruction

Instruction should not only effective and efficient, but humane as well. A study by Wittman, Marcinkiewicz, and Hamodey-Douglas (1998) found that high and low anxiety boys and girls achieved automaticity level performance of multiplication facts using computer assisted instruction, and that training of multiplication facts to the automaticity level resulted in significant reductions of mathematics anxiety ratings.

Overlearning

Automaticity is often achieved by "overlearning." Overlearning is learning beyond the "mastery" state where the learner is able to recall a correct response to a question. It is learning that continues, building additional associative strength, and is often measured by latency of response. Rosenberg and Stevens (1986) related overlearning to automaticity and the benefits to long-term retention and information processing in this statement:

> *Overlearning is particularly important for hierarchical materials such as mathematics and elementary reading. Unless there is overlearning to the point of automaticity, it is unlikely that the material will be retained. Furthermore, hierarchical material requires the application of previously learned skills to subsequent new skills. The advantage of automaticity is that students who master the material can then concentrated their attention on learning new skills or applying the skills to new situations. For example, automaticity of decoding skills frees the students' attention for comprehension, just as automaticity of computations frees the students' attention for mathematical problem solving.*

For a meta-analysis that found that overlearning produces a significant effect on retention see Driskell, Willis, and Copper (1992).

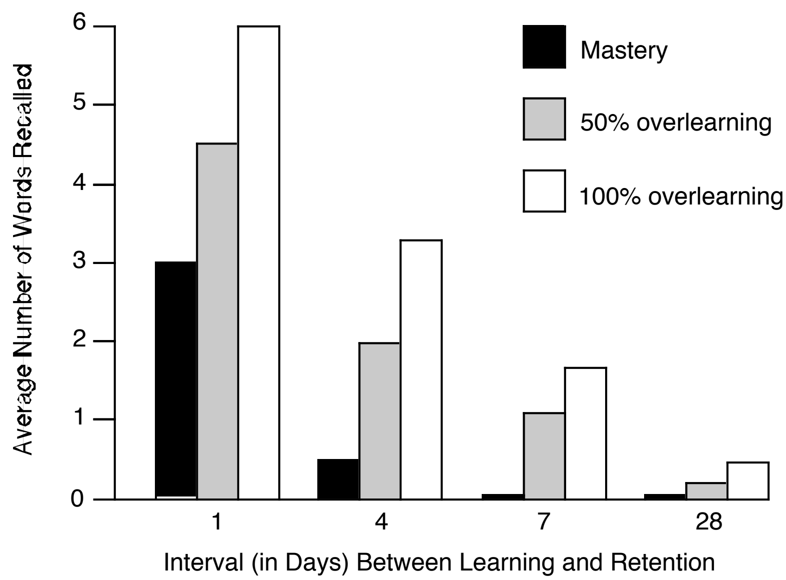

Figure 6: Overlearning leads to increased retention (Jones, 1967).

Retention Rates

Finally, when fast and slow learners (who, by definition, differ in the time needed to learn a given amount of material) are equated in amount learned (by, for example, giving the slow learners more exposure to the material than fast learners), research has consistently shown that they will recall about the same amount at a later test of retention. Underwood (1954) wrote, “When suitable methodology is applied to the problem, there is no difference in rate of forgetting for fast and slow learners” (p. 276). One suitable method will be described in the next section.

System Description

The proposed system is made up of two modules: Learn, which is used to introduce new information, and Review, which is used to review information learned in previous lessons.

Learn Module

In the Learn Module, students learn one lesson at a time. Each lesson is typically comprised of 8 to 14 cue and response pairs called items. Items are presented in a sequence (of known and unknown items) that focuses most of the attention on the unknown item to be learned, with the remaining effort directed to the review of previously learned (known) items within that lesson. This sequence continues until the unknown item becomes learned. It then becomes one of the known review items for the next unknown item to be learned. This process continues until all items within the lesson have been learned and reviewed to the desired degree. A typical sequence is as follows: For the first unlearned or unknown item, the cue is presented and the student must then actively recall the answer. After a specified period of time—typically one half second—the response is shown, *whether the item has been recalled or not*. If the student’s response consistently matches the displayed response over several trials, the student may interrupt the process, designating the item as a known item. The next unknown item is displayed and the process is repeated. If there is no interruption, the unknown item is presented over and over, interleaved with previously learned items, until it is learned. The unknown items (U) are interleaved with known items (K) in ever growing numbers. That is, for one unknown item, the Learn Module generates sequences such as U K U K K U K K K U K K K and so forth, until the students interrupt the presentation sequence to indicate that they know U.

Review Module

Following the initial session within the Learn Module, relatively rapid forgetting occurs as was described previously and shown in Figure 2. The purpose of the Review Module is to ensure that the students re-attain and maintain high memory strength for previously learned items.

When an item is learned for the first time within the Learn Module, the item is tagged with the date and is scheduled for review according to a schedule described below. Every day, the Review Module checks the database of previously learned items to see if there are any items scheduled for review that day. If there are, the Review Module presents them one at a time until all items are re-strengthened to the degree of initial learning.

In each review session, the number of presentations vary for each item. Based on quantitative measures, such as the adequacy of the student’s response to the presented cue, an item will either stay in the review group for additional presentations, or be dropped out. For each item, the student attempts to actively recall the answer. Next, the student rates the quality of their response after comparing their response to the correct response. A high rating will result in the item being dropped out; a low rating will carry the item over for additional review.

The Review Module attempts to rebuild memory strength as measured by the three dependent variables: probability of recall, latency of recall, and savings in relearning. The quality of response rating is a direct measure of the probability of recall. From the second round on, the latency of response influences whether or not to review the item further. If the student can quickly recall the answer, the quality of response rating is used to determine whether the item will go to another round of review. If it is not recalled quickly, the item will be reviewed anyway, independent of the rating. Only a short latency of response and a high rating score will result in the item being dropped out. Finally, the number of review rounds is a direct measure of the savings in relearning measure of memory strength: the more rounds, the more relearning was required, indicating relatively low memory strength at the beginning of the Review session. Note, that to successfully terminate a round, a student must quickly recall the correct responses. At the end of a review session, like at the end of a Learn session, all items are known to the level of automaticity.

The Review Module uses an expanded rehearsal series to develop long-term retention. During the initial presentation of an item in the Learn Module, memory strength increases from zero to a high level that corresponds to a level of automaticity (see the first climb of the trace in Figure 7). Relatively rapid forgetting follows. The first review session, scheduled when the Review Module predicts that the memory strength for this particular item has decreased to the minimum desired retention level, brings memory strength back to a level of automaticity. Although memory strength decays once again after this first review, this time, however, the rate of decay is slower. After another review, scheduled when memory strength has once again decreased to the minimum retention level, the rate of decay is smaller yet. Eventually, review sessions are spaced so far apart in time that the item has entered a state of permanent storage, or "permastore" (Bahrick, 1984). The item reviewed according to this expanded rehearsal series is then known for the lifetime of the learner.

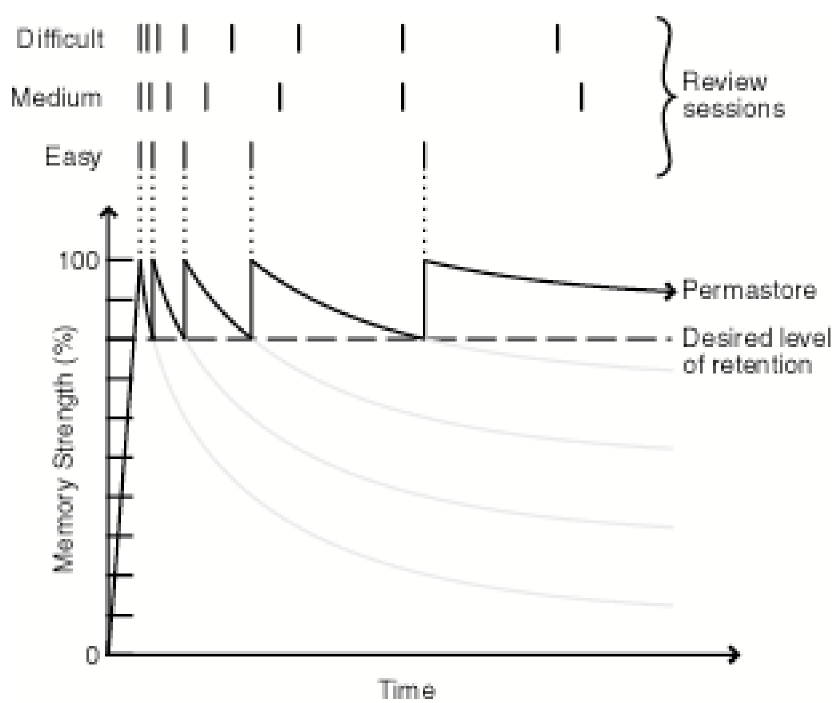

Figure 7: The spacing effect and expanded rehearsal series calculated based on the varying rates of forgetting on an item-by-item basis. Items vary in difficulty and are therefore reviewed according to

different schedules. In all cases, reviews are scheduled to maintain the desired level of retention in the most efficient manner possible.

Note how this method makes use of the nature of human memory described in the Theoretical Basis section: it uses mathematical models of human memory decay to calculate the timing of reviews.

Forgetting for specific items does not always follow a predetermined forgetting power function, however. Because of interference, or failures of consolidation or retrieval, some items that may have seemed initially easy to learn could be more difficult to remember a few days later, or vice versa. Thus, a review curve that accurately models the forgetting rate of a particular item for a particular learner early in the review schedule may become inaccurate at some later date. The system must, therefore, account for this effect by allowing the items to be reviewed to move from one review schedule to another, as shown in Figure 8.

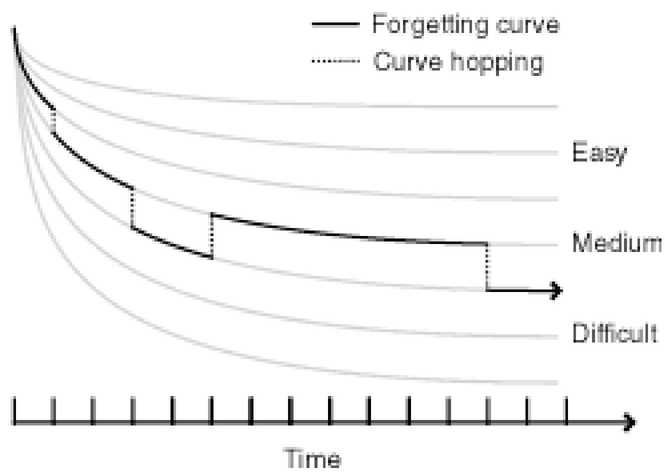

Figure 8: Review schedule curves, with hopping between curves.

In the example shown in Figure 8, an item originally designated as "medium-easy" and is placed on the third curve from the top—one that has relatively long intervals between review sessions. The student did not perform as well in the first review session as predicted (based on self-report) so the item was moved to a more “difficult” review curve. In the second review session, the subject once again does not perform as well as predicted so the item is moved again. In the third review session the student performs better than expected on the item so the curved is adjusted accordingly.

Conclusion

This paper describes a system designed to provide automated support of the acquisition of factual knowledge—a prerequisite for all other learning. It adapts to the learner, not by predicting characteristics or aptitudes of the learner *a priori*, but rather by making changes to the presentation of new information and to the scheduling of review based upon actual performance.

Because the system is algorithmic and takes measurements during the entire process, the overall system can be improved over time based upon empirical evidence linking instructional conditions to student outcomes.

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