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A Test of the Effectiveness of the Low-First Spaced Learning Method Applied to CAI*

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In research into CAI systems for individual instruction, various devices have been developed to select items for subsequent presentation according to individuals' answers. However, most can only be used with learning materials which have systematic or hierarchical structures. This study aims at proposing and testing a new spaced learning method which can be used for materials without such structures. The method is called "the Low-First Method", and is derived from psychological findings relating to the understanding of the cause of spacing effects in terms of changes in human memory activity. The Low-First Method is based on the following two principles : (a) sorting all the items at the end of each learning session by their weighted cumulative probabilities of recall (P_n s) in ascending order for the subsequent session ; (b) omitting items whose P_n s have reached a certain level. In the experiment, 24 participants learned HTML using two different CAI systems, one based on simple repetition and the other on the Low-First Method. The results showed that the Low-First Method was not only more effective but also more time efficient than the simple repetition method.

Key words : spacing effects, spaced learning, memory activity, CAI, the Low-First Method

1. INTRODUCTION

Recently, personal computers have become widely used, and various CAI systems and tools have been developed and become popular.

One of the most important considerations in developing CAI systems for individual learning is that of how to present learning materials in the most effective order for individual learners. Much research has already been conducted into this question. For example, Hong and Shigemasu (1990) proposed a method for optimally sequencing practice items for individual learners based on item response theory and hierarchical representation of instructional objectives, and proved its effectiveness experimentally by applying it to CAI systems for mathematics. Koizumi *et al.* (1995) proposed a method for determining the most appropriate supplementary tasks for individual learners on the basis of their attainment levels and the material structures of the tasks. Saito and Nakaura (1999) also proposed a method for selecting the optimal problem levels for individuals based on a fuzzy theory, and proved its effectiveness in educational practice, applying it to a CAI system for mathematics.

A considerable amount of research into ICAI (Intelligent Computer Assisted Instruction) systems and ITSs (Intelligent Tutoring Systems) has also been conducted with a view to optimizing the presentation sequence of learning materials. For example, Zhu *et al.* (1998) developed an ICAI system which can diagnose individual learners' knowledge structures through interaction with them and present the most appropriate instruction. Anderson *et al.* (1984, 1985) integrated their ACT* theory (Anderson, 1983), proposed in the area of cognitive psychology, with ITSs. They developed ITSs for geometry and LISP learning which can select and present the optimum questions to bring learners' knowledge structures as close as possible to the ideal structure by determining the present status of the learners' knowledge through interaction and by utilizing various psychological paradigms such as goal-mean analyses.

Most of these methods, however, are applicable only to subjects like mathematics or sciences with systematic or hierarchical content structures or

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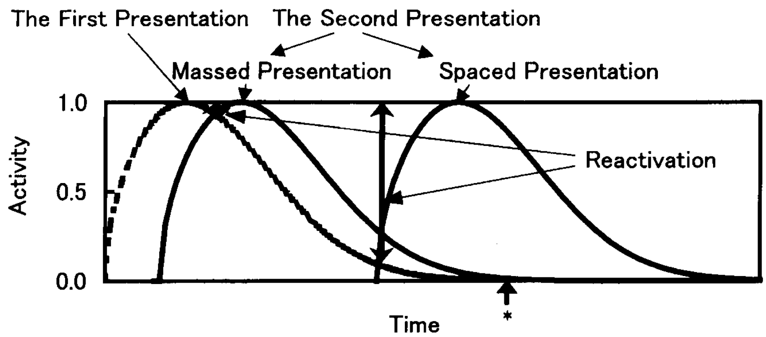

Fig. 1. The difference in reactivation between in massed presentation and in spaced presentation.

goal structures. They do not apply to subjects which lack such structures or those composed of relatively independent items like English spelling, Chinese characters, computer commands, chemical symbols, and so on. However, such information actually constitutes a large proportion of what people are required to learn, and it is essential to find effective ways of presenting such materials to individual learners.

The learning method proposed in this study, the Low-First Method, is based on several psychological findings concerning spacing effects and is applicable even to learning and memorizing materials which lack any systematic structure.

2. SPACING EFFECTS AND FINDINGS IN COGNITIVE PSYCHOLOGY

2. 1 Spaced Learning and Spacing Effects

Spaced learning is a learning method with intervals between repetitions, whereas in massed learning there are no intervals. It has been demonstrated in dozens of psychological experiments that spaced learning is more effective than massed learning, and this is called the spacing effect. The spacing effect was discovered as early as 1885 (Ebbinghaus, 1913), and is considered to be one of the most important and useful psychological findings ever made. It is an extremely robust effect and has been found in virtually all traditional learning tasks, including remembering words (Glenberg and Lehmann, 1980) or texts (Glover and Corkill, 1987) as well as understanding arithmetical rules (Gay, 1973) or the meanings of a series of scientific terms (Reynolds and Glaser, 1964).

2. 2 Reactivation Theory

Although the spacing effect is recognized as being extremely important, its cause has not yet been identified. It has been argued in review studies of spacing effects research (Greene, 1989 ; Mizuno, 1996) that the theories proposed so far to explain the cause of the spacing effect have without exception been weakened by inconsistent experimental results.

So, Mizuno (1996) reconsidered the question from the viewpoint of memory activity. This perspective is not a new one, and many researchers had already tried in vain to use theories of memory activity to explain the cause of spacing effects. For example, because, according to the spreading activation theory (Collins and Loftus, 1975), activity is supposed to decay with spreading, it was assumed that memory activity at relearning should have decayed more in spaced learning than in massed learning. However, this consideration fails to account for the fact that the lower the probability of recall at relearning is, the greater the ultimate probability of recall will be. This is called *a strength paradox* (Landauer and Bjork, 1978), and is an idea which prevented many researchers from explaining the cause of the spacing effect from the viewpoint of memory activity.

However, Mizuno (1996) focused not on the activity itself but on the reactivation which increases as the activity decays. She found that various experimental results could be explained by assuming that the spacing effect is caused by the larger reactivation in spaced learning than in massed learning because memory activity has decayed more by the time relearning takes place (see Fig. 1). She named this theory *reactivation theory*, and established its validity by measuring reactivation at various intervals in several priming experiments which revealed a correlation between reactivation and probability of recall (Mizuno, 1998 a).

2. 3 Reactivation Model

The reactivation model is a model of the occurrence processes of spacing effects based on reactivation theory.

In cognitive psychology, active memory, that is, memory that has been activated above some critical threshold, is called working memory, and stable memory that has not been activated above this threshold is called long-term memory (Anderson, 1990 ; Cantor and Engle, 1993). This means that it is working memory that is reactivated at relearning if an interval is small enough for the memory to remain activated, and, on the other hand, it is long-term memory that is reactivated if an interval is too large for the memory to remain active.

So, Mizuno (1997 a) began by modeling the mechanism of working memory reactivation for relatively short intervals. She first modeled the changes in working memory activation on the basis of a substantial number of experimental results as shown in Equation (1). Here the threshold was set at 0 for convenience.

$$act = \alpha\sqrt{t}\ \exp^{-\frac{(t-\beta)^2}{\gamma+4.0(n-1.0)}} \qquad (1)$$

act : memory activity ($0 \leqq act \leqq 1.0$)
t : time
n : number of presentations
α, β, γ : parameters

Then she examined the relationship between the estimated reactivation of working memory derived from Equation (1) and the probabilities of recall in the experiments to find that there was a logistic correlation between them which could be expressed by Equation (2) (see Fig. 2).

$$Pr = \frac{\delta}{1.0+\exp^{-\varepsilon(react-\zeta)}} \qquad (2)$$

Pr : probability of recall
$react$: reactivation
$\delta, \varepsilon, \zeta$: parameters

Then, she considered the mechanism of long-term memory reactivation for relatively long intervals and its influence on the spacing effect.

It was found that spacing effects did not become larger when the interval exceeded a certain length. She thought that this was due to reactivation of relatively stable long-term memory. The certain length corresponded to the point marked * in Fig. 1.

It was also discovered that, even if the number of presentations was increased from 2 to 3, the spacing effects were not enhanced so much when long-term memory had been repeatedly reactivated as when working memory had been repeatedly reactivated. In terms of the reactivation model, this can be explained as follows. With only one presentation, memory is not necessarily consolidated in long-term memory. Therefore, it is highly probable that reactivation of long-term memory at the second presentation is impossible.

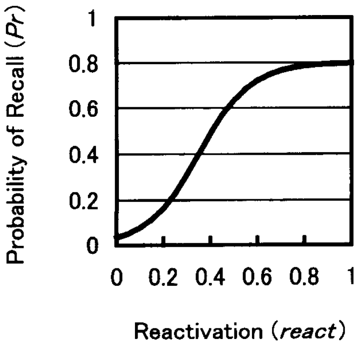

Fig. 2. Logistic correlation between reactivation and probability of recall.

This would leave the speed of memory decay unaltered, and reactivation at the third presentation also impossible.

In another study using relatively long intervals (Glenberg, 1976), it was found that the less successful the learning at the first presentation had been, the smaller the interval of repetition should be made in order to get a spacing effect. In terms of the reactivation theory, this must be because the speed of forgetting is faster and long-term reactivation soon becomes difficult when the learning is insufficient.

Subsequently, Mizuno (1997 a) considered the hypothesis that the probability of recall might be an index of long-term memory consolidation, and that long-term reactivation could be estimated from this index. So she conducted a simulation of long-term memory reactivation and examined its influence on the spacing effect. In the simulation, the probabilities of recall at the third presentation were estimated by putting the reactivation calculated by the index, namely the probability of recall at the second presentation, into Equation (3). The result of this simulation approximated to the experimental results quite well. And she concluded that probability of recall could be used to estimate long-term memory reactivation, and that long-term reactivation had the same logistic correlation with probability of recall as working memory reactivation had (see Equation (2)).

2. 4 *Modified Reactivation Model*

Mizuno (1998 b) examined the occurrence process of spacing effects in spaced learning with triple presentation to find that the second interval should be enlarged in direct proportion to the probability of recall at the second presentation in order to get a large spacing effect. She thought that this was because the speed of memory decay had been delayed in relation to reactivation (see Fig. 3).

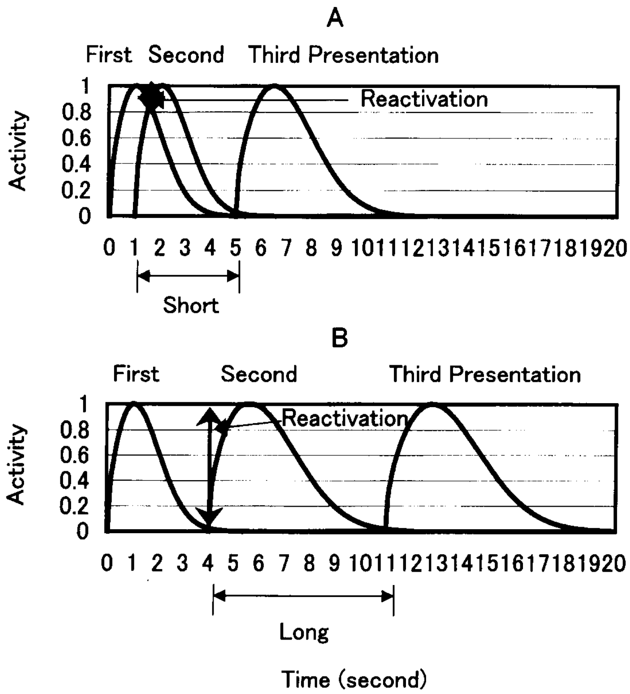

Fig. 3. The difference in the most advantageous spaces dependent on reactivation.

She then conducted a priming experiment to examine the activity change both when the reactivation at the second presentation was small and also when it was large, and demonstrated that the speed of memory decay is delayed as reactivation increases.

On the basis of this finding, Mizuno (1997b) modified Equation (1) to give Equation (3) thus making the activation decay speed variable as a function of the previous reactivation. She then demonstrated its validity by correlating the results of the simulations with the experimental results.

$$act = \alpha\sqrt{t}\ \exp^{-\frac{(t-\beta)^2}{\gamma\sqrt{1.0+react}}} \qquad (3)$$

react : reactivation at learning

3. EFFECTIVE SPACED LEARNING SCHEDULE

Let us consider the probabilities of recall in the sequential learning of many items on the basis of the reactivation model. In such a situation, when repetition is necessary, learners usually repeat learning the items in the same order. For example, in the following sequence, A_1, B_1, C_1, D_1, E_1, F_1, G_1, A_2, B_2, C_2, D_2, E_2, F_2, G_2, there are 6 items between A_1 and A_2.

The activity decay speed for the items that could not be recalled at the first learning remains fast and reactivation does not occur even at the second learning because the interval is relatively long. This situation could conceivably be repeated indefinitely and the items might never be remembered. On the other hand, the activity decay speed for the items that could be recalled at the first learning gets slower and reactivation does occur at the second learning. If this situation were repeated, it would result in redundant repetitions of the learning process. All of this suggests that the two most important considerations in making an effective and time efficient spaced learning method are firstly to enhance the probabilities of recall of the items whose probabilities of recall were low, and secondly to avoid redundant repetition.

On the basis of these ideas, a new spaced learning method will be proposed and its validity will be shown by a psychological experiment.

3. 1 *The First Prediction Derived from the Reactivation Model*

According to the model, when reactivation at learning is small, that is, when probability of recall is low, the next interval should be relatively small to obtain sufficient reactivation at the next learning because the speed of activation decay will be fast (see Fig. 3, A). On the other hand, when the reactivation at learning is large and probability of recall is high, the next interval should be relatively large because the decay speed will be slow (see Fig. 3, B). These considerations led to the prediction that the largest spacing effect could be obtained when the intervals between repeated items were determined according to their reactivation, that is, their probabilities of recall.

3. 2 *The Second Prediction Derived from the Reactivation Model*

In order to avoid redundant repetition, we can make use of the logistic correlation between reactivation and probability of recall.

As shown in Fig. 2 and Equation (2), the probability of recall becomes relatively stable when reactivation reaches a certain magnitude. At this point further reactivation will not necessarily give any improvement in the probability of recall, and by determining where this threshold lies, we can avoid redundant repetition in the learning process.

3. 3 *Two Principles Derived from the Two Predictions*

Ideally, all the intervals between repeated items should be determined according to their probabilities of recall. However, this is effectively impossible because for some items the most advantageous presentation positions would overlap. This is even truer when the number of items or the

Table 1. An example of rearrangement of presentation orders based on the answers according to the Low-First method

Session		Item Numbers							Rearranged order for subsequent session
		1	2	3	4	5	6	7	
1	True/False[a]	1	1	1	0	0	0	0	
	(P_1)	(0.5)	(0.5)	(0.5)	(0)	(0)	(0)	(0)	4567123
2	True/False	1	0	0	1	1	0	0	
	(P_2)	(0.75)	(0.25)	(0.25)	(0.5)	(0.5)	(0)	(0)	672345
3	True/False	—	1	0	1	0	1	0	
	(P_3)		(0.625)	(0.125)	(0.75)	(0.25)	(0.5)	(0)	73562

Note : a) True : 1, False : 0.

repetition times of learning are increased.

So the author devised a new spaced learning method applicable to any sequential learning irrespective of the number of items or repetition times, and at the same time consistent with the two predictions derived from the reactivation model.

The new spaced learning method was named "the Low-First Method" after its first basic principle, but is actually composed of two principles.

The first principle. The first principle is to rearrange the presentation order of all the items according to their weighted cumulative probabilities of recall, P_n s (Equation (4)), in ascending order, for the subsequent learning session.

With this principle, the items with low probabilities of recall are presented after a relatively short time and those with high probabilities of recall after a relatively long time, which should enable all the items to be presented with the most advantageous intervals possible, thus resulting in effective spaced learning. The details of the procedures used in applying this principle are as follows.

In the first session, all the items are learned sequentially in an arbitrary order. Then, they are sorted according to the first principle for the subsequent learning session. This procedure is repeated at the end of each of the following sessions. If P_n s for several items are the same, their relative positions remain unchanged.

$$P_n = \sum_{i=1}^{n} 2^{-(n-i+1)} * P_i \qquad (4)$$

P_n : weighted cumulative probability of recall of an item after the nth session

n : number of present session

p_i : probability of recall of the item in the ith session

P_n is, so to speak, an index of the degree of memory consolidation at any given point. The reason why a more recent probability of recall should be given more weight is because it has been found that more recent reactivation has a greater effect on the final probability of recall (*e.g.*, Mizuno, 1997 b, 1998 b). This method of weighting was also based on the idea that memory is more consolidated in a case where successful recall occurs after a failure to recall than in the reverse case where failure to recall follows successful recall.

The second principle. The second principle is to omit items whose P_n was equal to or more than 0.75, corresponding to the case in which an item was successfully recalled twice or more in succession (see Table 1).

The value for this threshold was determined using both Equation (2) and the experimental results obtained so far which indicated that participants seldom failed to recall items which they had previously recalled twice in succession.

With this principle, redundant repetition will be avoided, and efficient spaced learning will occur.

In the experiment, this Low-First Method composed of these two principles will be applied to a CAI system, and its effectiveness and efficiency will be examined.

4. EXPERIMENT

CAI programs were written in HTML and Java Script supplemented by CGI scripts in Perl to record the answers of individual learners, rearrange the presentation order according to the first principle, and omit learning items according to the second principle. All the CAI programs and scripts as well as the answers and access times were loaded onto a Web server and utilized through a network using Web browsers.

Table 2. Topics and answers of Material 1 and Material 2

Material 1		Material 2	
Topics	Answers	Topics	Answers
Chapter 1. Images			
1. Alignment of Images	bottom	1. Including an image	img src
2. Borders of Images	border	2. White space around images	hspace
Chapter 2. Links			
3. Links to Another File	a href	3. Links to Another Part within a File	a name
4. Links to Specified Parts of Another File	#no 5	4. Links to Another File in Another Server	http :
Chapter 3. Tables			
5. Table Rows	<tr>	5. Vertical Position of Data	valign
6. Number of Rows	rowspan	6. Nested Table Cells	<td>
Chapter 4. Frames			
7. Rows and Columns	frameset cols	7. Target Frame Specification	"txt"
8. Frame Border	frameborder	8. Resize of Frames	noresize
Chapter 5. Forms			
9. Multi-Line Text Fields	textarea	9. Single-Line Text Fields	text
10. Scrolled List Boxes	select name	10. On/Off Switches	checkbox
Chapter 6. Other Tips			
11. Font Names	face	11. Inline Comments	-->
12. Sounds	.wav	12. Image Maps	usemap

4.1 *Purpose*

The purpose of the experiment was to prove the efficiency of the Low-First Method.

4.2 *Method*

Participants. 24 undergraduates (12 female and 12 male). They were equally divided into two groups, Group A and Group B.

Materials. 24 items were selected from a CAI tool for learning HTML previously made by the author. The materials were divided into two, Material 1 and Material 2 (see Table 2), so that the difficulties could be distributed as evenly as possible and so that the answer for each item would be independent. The subjects in Group A were asked to learn Material 1 in the control condition, *i.e.*, using a simple repetition method, and Material 2 in the experimental condition, *i.e.*, using the Low-First Method. On the other hand, those in Group B were asked to learn Material 2 in the control condition and Material 1 in the experimental condition. Therefore, neither the differences between the subjects nor those in the materials should have influenced the test scores of the two conditions.

The repetition times for the control condition were determined according to the following criteria. If the total numbers of accessed items had differed very much between the control condition and the experimental condition, it would have become impossible to make a direct comparison of the test scores of the two conditions because there would have been too great a discrepancy between their respective learning efficiencies. But if the number of repetitions had been pre-determined and had been equal for all subjects, there would have been a significant disparity between the learning efficiencies of individual participants, and the results would have been ambiguous.

In this study, the main focus was on the efficiency of the Low-First Method for individual learners. Therefore, it was decided that the number of repetitions in the control condition for each participant should be the integer calculated by rounding the quotient for the total number of accessed items in the experimental condition divided by the total number of learning items in one session, namely, 12.

It was necessary, therefore, that the trials in the experimental condition preceded those in the control condition. The repetition might have had a positive influence on the scores for the control condition. But, on the other hand, the participants might also have been negatively affected by

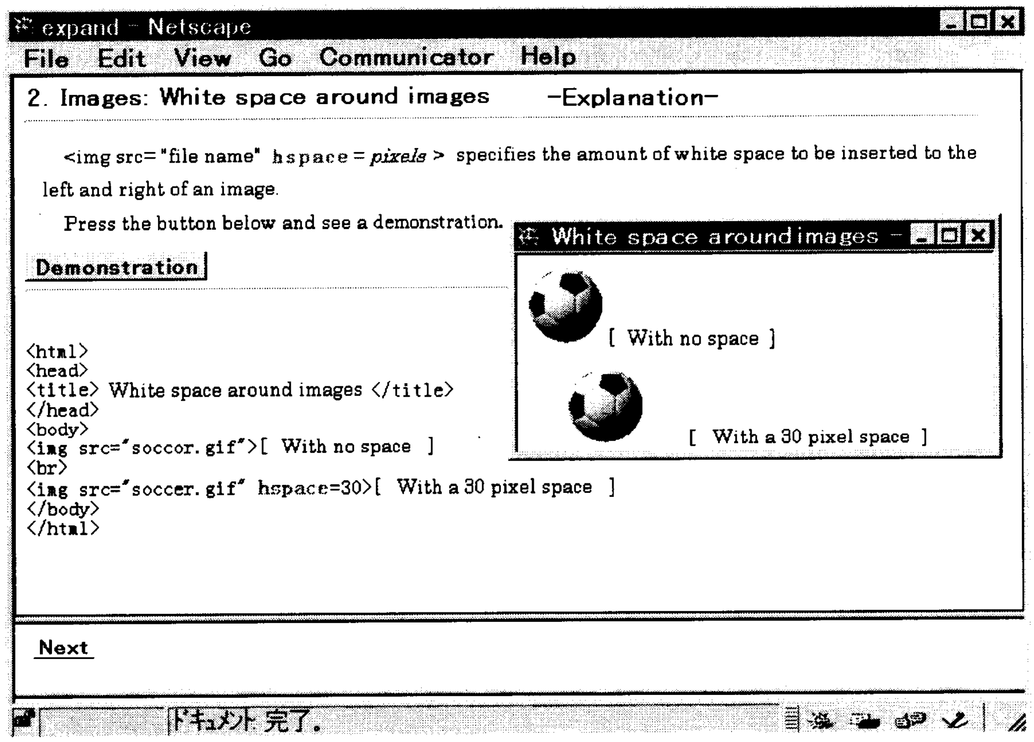

Fig. 4. An example of an explanatory page (originally in Japanese).

fatigue. These repetition and fatigue effects were viewed as counterbalancing one another.

Besides, if the repetition effects were more advantageous, they would also have been so for the control condition. Therefore, if the mean test score in the experimental condition were still higher than that in the control condition, there would be no problem.

Finally, lest fatigue effects should have become too influential, the trials for the control condition were conducted on the day following the trials for the experimental condition.

Procedure. Participants were tested individually. The command tool bar and the locations bar of the Web browser were concealed to prevent participants from confirming their answers by going back to the explanatory page. Participants accessed the CAI programs by inputting the URL, their IDs, and the password given to them beforehand. They were then told to write their full name in the box on the initial screen and to click a hot text, "START", to begin learning.

The procedure for the trials in the first experimental condition was as follows.

On clicking "START", the explanatory page (see Fig. 4) for the first item would appear, and participants read and attempted to learn it. If they wanted to see the demonstration of the program, they could click "Demonstration" and see it in a new pop-up window. Then they proceeded to the practice page (see Fig. 5) by clicking "Next". Here, they were asked to fill in the blanks with answers, and then clicked "Confirm" to get feedback. The word "Correct" appeared in the bottom frame and a chime was heard when the answer was correct. The word "Wrong" and an alarm signaled a wrong answer and the correct answer was then displayed in the bottom frame. If they did not fill the blank with an answer but clicked "Confirm", the warning message "Fill in the blank" appeared. If they clicked the button twice, the message "You can confirm only once" appeared. On clicking "Next", the explanatory page for the subsequent item was presented.

This procedure was repeated until the session was over. At the end of each learning session, the number of correct responses was shown and all the answers and the record of accessed pages with times were sent to the server. On the basis of this data, the presentation order for the next session was arranged and, where necessary, items were omitted according to the Low-First Method.

Learning sessions were repeated in this way until no items were left.

The participants then proceeded to the final test screen. This comprised 12 questions, and the forms of the answers were analogous to those in the practice pages. On finishing the test, they clicked "Submit" and saw their test scores. Once again the data was sent to the server, and the

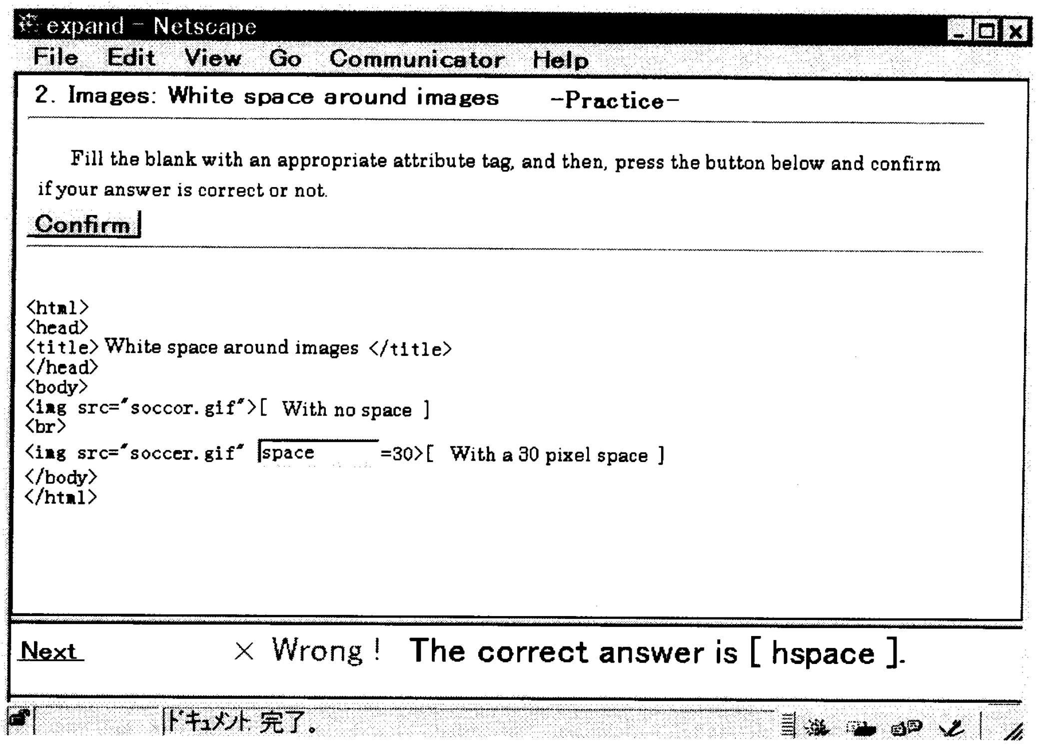

Fig. 5. An example of a practice page (originally in Japanese).

repetition times for the control conditions on the next day were calculated.

On the following day, the trials in the control condition were conducted using the same procedures except for the rearrangement of the presentation order and item omission, and learning sessions were repeated according to the calculations made on the previous day.

4. 3 Results and Discussion

Table 3 shows learning processes and test results in the control condition and in the experimental condition for a participant selected at random.

Total numbers of accessed items and learning times. To make sure that rounding of the quotient did not create a bias in the repetition times, the total numbers of accessed items in the control and the experimental conditions were compared. The mean (*SD*) in the control condition was 33.00 (8.11), that in the experimental condition was 32.25 (6.02) (max : 47, min : 25), and there was no significant difference between them ($t\ (23)=1.10$, *ns*).

Then the learning times of both conditions were compared. The mean (*SD*) in the control condition was 39 : 03 (10 : 15), that in the experimental condition was 41 : 50 (11 : 03), and again there was no significant difference ($t\ (23)=1.98$, *ns*).

Therefore, it can be said that the rounding caused no bias and that it is possible to estimate the efficiency of the learning method according to the test scores alone, as shown in the following analysis.

Test scores. The means (*SD*) in the control and the experimental conditions are shown in Fig. 6. They differed significantly ($t\ (23)=4.54$, $p<.01$), and the mean in the experimental condition was higher than that in the control condition.

Therefore, it is clear that the Low-First Method is more effective and efficient than a simple repetition method.

The differences in the test scores for the two conditions were analyzed for individual participants. For 17 participants out of 24, the test scores in the experimental condition were significantly higher than those in the control condition, and for only 2 participants were the scores in the control condition significantly higher than those in the experimental condition. For the other 5 participants, there were no significant differences in the scores for the two conditions, which in both cases were extremely high.

Therefore, it can be concluded that the Low-First Method is, as a whole, more effective and more efficient than a simple repetition method.

Learning processes. In order to confirm the effectiveness of the basic first principle of the Low-First Method, it was necessary to check if the unrecalled items in a session were really recalled in the next session or not.

Table 3. Learning processes and test results in the control and the experimental conditions for a participant selected at random

Control Condition (a simple repetition method)

Session	Presentation Order (True : 1/False : 0)											Total Numbers of Access : 36
1	1(1)	2(1)	3(0)	4(1)	5(1)	6(0)	7(1)	8(1)	9(0)	10(1)	11(1)	12(1)
2	1(1)	2(0)	3(0)	4(1)	5(0)	6(0)	7(1)	8(1)	9(1)	10(0)	11(1)	12(1)
3	1(1)	2(1)	3(1)	4(1)	5(1)	6(0)	7(0)	8(1)	9(1)	10(0)	11(1)	12(1)

Test Results												Score : 8
Item No.	1	2	3	4	5	6	7	8	9	10	11	12
True/False	1	0	1	1	1	0	1	1	0	0	1	1

Experimental Condition (the Low-First method)

Session	Presentation Order (True : 1/False : 0)											Total Numbers of Access : 36
1	1(1)	2(1)	3(0)	4(0)	5(1)	6(1)	7(1)	8(0)	9(1)	10(0)	11(1)	12(1)
2	3(1)	4(1)	8(1)	10(1)	1(1)	2(1)	5(1)	6(1)	7(0)	9(1)	11(1)	12(0)
3	7(1)	12(1)	3(1)	4(0)	8(1)	10(1)						
4	4(1)	7(1)	12(1)									
5	4(1)											

Test Results												Score : 11
Item No.	1	2	3	4	5	6	7	8	9	10	11	12
True/False	1	1	1	1	1	0	1	1	1	1	1	1

So the numbers of repeated errors (see the boxes in Table 3) for the control condition and the experimental condition were compared. The mean (*SD*) in the control condition was 2.58 (2.24) and that in the experimental condition was 1.29 (1.78), and there was a significant difference (t (23) = 4.34, $p < .01$).

Therefore, it is apparent that the basic first principle was valid and prevented futile repetition of errors.

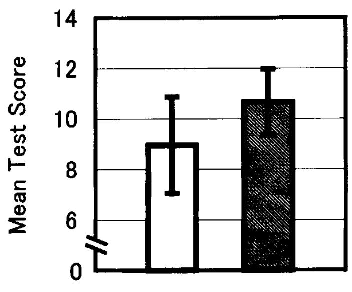

Fig. 6. Mean test scores in the control and the experimental conditions.

5. CONCLUSION

5. 1 Summary

All of the experimental results in this study indicate that the Low-First Method is not only more effective but also more time efficient than an ordinary simple repetition method.

5. 2 Suggestions

The Low-First Method is based on the reactivation model, which was derived from numerous findings concerning the mechanism of human memory and the occurrence process of the spacing effect. The reactivation model has been verified using a number of psychological experiments and simulations and has been found to be a very reliable, concrete, and realistic model. Indeed the reactivation model is such a concrete and realistic model that it enables us to predict problems in various special situations and tells us how to modify the Low-First Method to meet such challenges. For example, it tells us that the number of items in a session should be reduced when the materials are extremely difficult because their memory activities decay fast. It also indicates that the threshold for omission should be lowered when the materials are such that learners would seldom fail to recall once they had first succeeded, because they have already been consolidated in long-term memory, or that the interval should be narrowed when the items are closely related because their memory activities would affect one another.

It is now necessary to conduct further experiments under various conditions in order to improve the Low-First Method and to make it more flexible and more widely applicable.

The principles of the Low-First Method are applicable not only to CAI but also to classroom instruction. For example, they could be applied in the following ways. Teachers should review or represent material earlier when it is difficult or hard to remember because such material will be soon forgotten and only be reactivated with difficulty. They should give students practice of difficult problems earlier than easy ones, which will increase the probability of reactivation of the former and enlarge the magnitude of reactivation of the simpler material. In order to avoid redundant repetition, they should avoid reviewing material which is so easy that all of the students have already understood or remembered it.

What is required now is to apply the Low-First Method to other more practical learning situations and to examine its overall validity as an educational technique.

REFERENCES

ANDERSON, J.R. (1983) *The Architecture of Cognition*, Harvard University Press, Cambridge, Massachusetts.

ANDERSON, J.R. (1990) *Cognitive Psychology and its Implications*, W.H. Freeman and Company, New York.

ANDERSON, J.R., BOYLE, C.F., and REISER, B.J. (1985) Intelligent tutoring systems, *Science,* **228**, 456-462.

ANDERSON, J.R., FARREL, R.G., and SAUERS, R. (1984) Learning to program in LISP, *Cognitive Science,* **8**, 87-129.

CANTOR, J., and ENGLE, R.W. (1993) Working memory capacity as long-term memory activation : An individual-differences approach, *J. Exp. Psychol. : Learning, Memory, and Cognition,* **19**, 1101-1114.

COLLINS, A.M., and LOFTUS, E.F. (1975) A spreading-activation theory of semantic processing, *Psychological Review,* **82**, 407-428.

EBBINGHAUS, H. (1913) *Memory* (H.A. Roger, and C.E. Bussenius, Trans.), Teachers College, New York (Original work was published in 1885).

GAY, L.R. (1973) Temporal position of reviews and its effect on the retention of mathematical rules, *J. Educ. Psychol.,* **64**, 171-182.

GLENBERG, A.M. (1976) Monotonic and nonmonotonic lag effects in paired-associate and recognition memory paradigms, *Journal of Verbal Learning and Verbal Behavior,* **15**, 1-16.

GLENBERG, A.M., and LEHMANN, T.S. (1980) Spacing repetitions over 1 week, *Memory & Cognition,* **7**, 95-112.

GLOVER, J.A., and CORKILL, A.H. (1987) Influence of paraphrased repetitions on the spacing effect, *J. Educ. Psychol.,* **79**, 198-199.

GREENE, R.L. (1989) Spacing effects in memory : A two-process account, *J. Exp. Psychol. : Learning, Memory, and Cognition,* **15**, 371-377.

HONG, X., and SHIGEMASU, K. (1990) Using item response theory and hierarchical representation of instructional objectives for optimally sequencing of exercise items, *Jpn. J. Educ. Technol.*, **14**, 73-80.

KOIZUMI, N., MATSUI, T., and TAKEYA, M. (1995) A method for determining supplementary student activities which reflect the structure of the teaching materials, *Jpn. J. Educ. Technol.*, **19**, 1-13.

LANDAUER, T.K., and BJORK, R.A. (1978) Optimum rehearsal patterns and name learning. *In* M.M. Gruneberg, P.E. Morris, and R.N. Sykes (eds.), *Practical Aspects of Memory*, Academic Press, London.

MIZUNO, R. (1996) Theories of spacing effects : Review and proposal of a new theory, *Bulletin of Shizuoka Institute of Science and Technology,* **5**, 181-197.

MIZUNO, R. (1997a) Exploring the cause of spacing effects : A test of a reactivation theory by experiments and simulations, *Cognitive Studies : Bulletin of the Japanese Cognitive Science Society,* **4**, 20-38.

MIZUNO, R. (1997b) A test of the modified reactivation model of the spacing effect : The comparison of experimental results and simulations, *Educational Psychology Forum Report*, FR-97-003.

MIZUNO, R. (1998a) The cause of the spacing effect : A test of the influence of reactivation amount. *Jpn. J. Educ. Psychol.,* **46**, 11-20.

MIZUNO, R. (1998b) Realization of an effective spaced learning schedule based on a reactivation theory of the spacing effect, *Jpn. J. Educ. Psychol.*, **46**, 173-183.

REYNOLDS, J.H., and GLASER, R. (1964) Effects of repetition and spaced review upon repetition of a complex learning task, *J. Educ. Psychol.,* **55**, 297-308.

SAITO, N., and NAKAURA, S. (1999) Development of an individual learning system that adopts a method of selecting the optimal problem level, *Jpn. J. Educ. Technol.*, **22**, 215-225.

ZHU, Z., WANG, Q., KONDO, K., and FAR, B.H. (1998) Learning Aid by Using an Adaptive Knowledge-map Based on a CBR Approach, *Proceedings of the Annual Convention of the Japanese Society for Artificial Intelligence in 1998*, pp. 606-609.