# Digit Memory of Soroban Experts: Evidence of Utilization of Mental Imagery

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SUMMARY

Two experiments were conducted to demonstrate that skilled soroban (Japanese abacus) operators can improve digit memory retention by manipulating the beads of a 'mental soroban' which is analogous to the actual one. In Experiment 1, soroban experts and control subjects were given two digit memory tasks. In one task, pictures of a soroban figure and in the other, pictures of digit sequences, were presented to the subjects during the retention interval. Soroban experts experienced greater interference from presentation of the soroban figures than the digits; on the other hand, the reverse was true in the control subjects. In Experiment 2, the soroban experts and control subjects were given the same digit memory tasks under three conditions—soroban pictures, pictures of digit sequences, and human faces were presented to subjects during the retention period of 15 s. The soroban experts were more affected by the presentation of the soroban figures than by the faces or digits, whereas the controls showed more interference from the digits than by the presentation of faces or soroban pictures.

The purpose of the present study was to investigate the effects of extensive practice of soroban, or Japanese abacus, on memory for digits.

The soroban was adopted from China about 400 years ago and consisted of a wooden-framed instrument made up of 23 columns of beads. The soroban is used to represent numbers using a base of 10. Each column of beads has a place value of 'ones', 'tens', 'hundreds', and so on. According to the operator's convenience, an arbitrarily selected column of beads is defined as the 'ones' and, once it has been defined, all other columns are valued relative to it. Each column of beads is divided into an upper part which contains one bead and a lower part which contains four beads separated by a bar. The upper section is equal to 5 times the value of the column when it is pulled down towards the bar. When it is pushed away from the dividing bar it is equal to 0. Each of the four beads in the lower section corresponds to 1, the same value as the column when pushed up toward the dividing bar, and 0 when pulled down from the bar.

The soroban has been employed as a calculation instrument for 300 years, and has long been regarded as the one of the most basic abilities to be acquired by Japanese people. Even now, skill at soroban is widely respected in Japan, and soroban training for children is organized in both school and extracurricular programmes. Japanese children are given an introduction to soroban for 8 hours in

0888–4080/89/010023–11$05.50

*Received 22 September 1987*
*Revised 6 January 1988*

the third grade and 2 hours in the fourth grade as part of the official curriculum and approximately 5 million children go to extracurricular schools. Rating of soroban skill begins at 10th kyu and rises to 1st kyu, and then 1st dan to 10th dan. Generally, 1st dan to 3rd dan can be regarded as experts, and 9th dan to 10th dan as grand masters.

Hatano and Osawa (1983) demonstrated that grand masters (who had won the championship of the nationwide tournament in Japan) can recall between 13 and 20 digits accurately in both a backward and forward direction. They suggested that grand masters might have access to a mental abacus or a specific device to represent such large numbers visuospatially, and that this skill is domain-specific. These experiments were aimed at examining directly the plausibility of their suggestion that soroban experts might have a 'mental soroban'. If their suggestion is correct, then the presentation of a picture of a soroban as a secondary concurrent task which represents unrelated numbers during the retention interval may interfere with the recall of a digit sequence. On the other hand, the presentation of a picture of a digit displays of unrelated numbers (Experiment 1) or presentation of pictures of a human face (Experiment 2) during the retention interval should not interfere with the recall of the digits.

Further, if soroban experts have access to a mental abacus (i.e. the image of a soroban-like figure), a special form of error should occur. The abacus is divided into upper and lower sections. The beads in the loweer section represent one each, and the upper bead represents five. If the hypothesized mental abacus is used, errors of the upper bead will be more frequent than in the other retention method. This kind of error is 6 to 7 times more frequent with the abacus than in other calculating methods (Stigler, Chalip and Miller, 1986).

## EXPERIMENT 1

### Subjects

Twenty-nine right-handed soroban experts (10 males and 19 females) participated as experimental subjects. They were rated as 1st dan to 7th dan (mean = 2.41, SD = 1.6) and had between 4 and 11 years of soroban training experience, mainly at extracurricular schools. Their mean age was 20.04 years (SD = 2.99). Seven were working in offices and 12 were at high school and college students. Twenty-nine right-handed university students (10 males and 19 females) served as control subjects; their mean age was 21.03 years (SD = 2.51). All subjects in the control group had less than 2 months, or in some cases zero, soroban training experience. None of the subjects in both groups had visual, hearing or other neurological problems.

### Apparatus

Two tape recorders, one for stimulus presentation and the other for recording of subjects' responses, and two types of interference stimuli were used.

**Stimuli**

The stimuli to be memorized for 15 seconds were 28 sequences of either six or 12 digits. These were read by a female voice. Each number of the sequence had been randomly arranged. Each condition was made up of two sessions. Two kinds of interference stimuli were prepared: pictures of soroban figures and pictures of digit sequences, both of these were presented to the subject during the period of memory retention.

Samples of both kinds of interference stimuli are shown in Fig. 1.

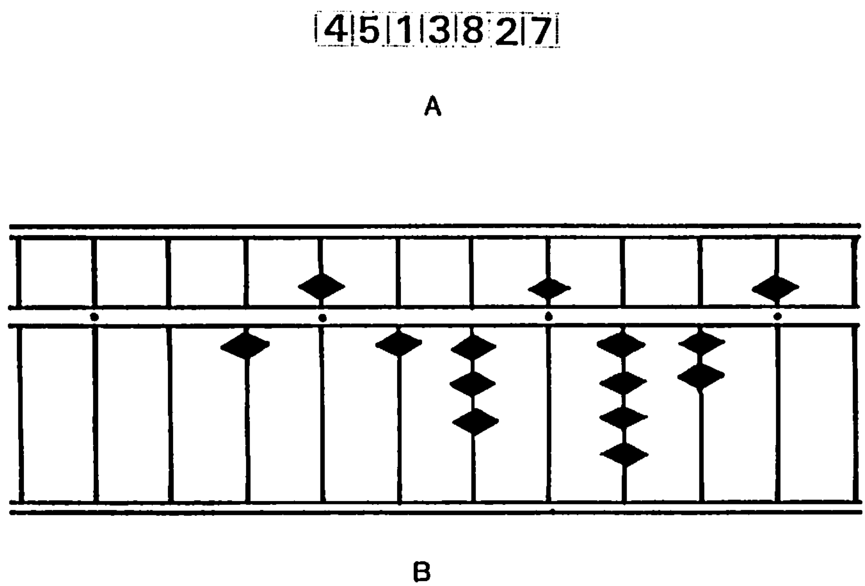


Figure 1. Samples of the used interference stimuli in Experiment 1 (A): picture of digit sequence; (B): picture of soroban figure

**Procedure**

Wearing headphones, each subject sat at a table and was given the following instructions: 'You will hear digit sequences through the headphones. Please keep the digit sequence in your memory for 15 s. When 15 s have passed, you will hear a beep. Then, please report the digit sequence in the order you have heard. You have 10 s to report the answer. During the retention period the experimenter will present picture-cards on the stand in front of you; please study the pictures carefully.'

The randomly arranged digit sequence was read at the rate of one digit per second. The first 10 sequences were read under a control condition in which no picture was presented during the retention period of 15 s. Subsequently came the soroban condition, where pictures of soroban figure were presented at the rate of one picture per second during the retention interval, and finally the number condition, where pictures of digit sequences were presented at one picture per second. The order of the last two conditions was reversed for half the subjects, who were given the control condition first, the number condition second and the soroban condition last. Again, the numbers represented on picture cards were not connected to the memorized digit sequence. That is none of the sequences of distracting digits was related to the sequence of memory items. A 5 min rest period was given between experimental conditions.

## RESULTS

### Correctly recalled numbers of figures

This index refers to the mean number of figures correctly recalled in order before any error was made; that is if a subject correctly recalled the first three and the last three digits of a seven-digit sequence, but made an error on the fourth digit, the score of this trial was only three. Table 1 shows the mean score of each subject.

Table 1. Mean number of figures correctly recalled in each condition. SDs are shown in the parentheses

| Condition | Control | Soroban | Number |
|---|---|---|---|
| Experimental group | 5.88 | 4.90 | 5.25 |
| | (1.44) | (1.46) | (1.23) |
| Control group | 5.14 | 4.82 | 4.72 |
| | (1.17) | (1.25) | (1.18) |

First, the performances of the experimental and control groups during the control condition were compared. The results indicate that the experimental group remembered more numbers correctly than the control group ($t$ = 6.43, d.f. = 56, $p < .01$). This shows that soroban experts have a superior ability to memorize digits compared with ordinary people.

Second, an analysis of variance (between and within subject mixed design) was conducted to investigate the effects of the picture cards on memory retention. The result showed that the interaction between groups and types of presentation pictures was marginally significant ($F1,56 = 3.52$, $p < .061$). But further analyses revealed there was no significant performance difference among conditions in the control group ($F1,56 = 0.28$). However, in the experimental group the performance was superior in the number condition compared to the soroban condition ($F1,56 = 4.51$, $p < .05$).

### Reduction rate

To examine the interference effects of the picture cards on memory retention more precisely, the reduction rate was calculated by the following formula for each subject;

$$R = C - (S \text{ or } N)/C$$

where $C$ = number of figures correctly recalled in the control condition, $S$ =

number of figures correctly recalled in the soroban condition, and $N$ = number of figures correctly recalled in the number condition.

Table 2 shows the reduction rate of the experimental and control groups in both conditions.

Table 2. Mean reduction rates (percentages) for the experimental and control groups in each condition. SDs are shown in the parentheses

| Condition | Soroban | Number |
|---|---|---|
| Experimental group | 17.1 | 10.2 |
| | (3.8) | (2.3) |
| Control group | 6.2 | 7.2 |
| | (1.1) | (1.2) |

An analysis of variance (between and within subject mixed design) revealed that the main effect of group was significant ($F1{,}56 = 3.44$, $p < .05$) and the interaction between groups and condition was also significant ($F1{,}56 = 4.99$, $p < .01$). Examination of this interaction indicated that the performance of the experimental group was reduced more strongly by the presentation of soroban pictures ($F1{,}56 = 6.34$, $p < .005$) than by the presentation of digital pictures, whereas no difference was shown between both conditions in the control group ($F1{,}56 = 0.41$).

## Number five error

This index refers to a special type of error which is probably due to the misreading of a soroban instrument, that is adding or deleting a necessary bead above the dividing bar. For example, 6 instead of 1, 7 instead of 2, 3 instead of 8, 4 instead of 9, and so on (see Fig. 1). Table 3 represents the mean percentages of number five errors for both subject groups.

Table 3. Mean percentages of number five errors in each group

| Group | Experimental | Control |
|---|---|---|
| Mean | 4.76 | 2.52 |
| SD | 2.52 | 1.80 |

An analysis of variance revealed that the soroban group made more number five errors than did the control group ($F1{,}56 = 13.32$, $p < .001$).

Experiment 2 was designed to examine the following questions: (1) whether the findings in Experiment 1 can be replicated by other group of soroban experts, (2) whether the size difference between soroban and Arabic numerals pictures was a crucial factor in producing different distraction effects, (3) whether pictures of human faces which are as familiar as soroban pictures produce the same interference effects as soroban pictures in the experimental group, and (4) whether people who have once mastered the use of the mental abacus can employ it after 5 years absence of training?

## EXPERIMENT 2

### Subjects

The experimental group consisted of twenty soroban experts (mean = 2.01 dan, SD = 1.2) and 20 students participated as the control group subjects. They were all right-handed university students and their mean ages were 20.91 and 21.04, respectively. All subjects in the control group had no special soroban learning experience, while subjects in the experimental group had approximately 6 years of soroban training. Subjects in the experimental group had not trained for 4 or 5 years since leaving high school. None had visual, hearing, or other neurological problems.

### Apparatus

The apparatus was the same as that of the Experiment 1.

### Stimuli

The same stimuli, i.e. tape-recorded random digit sequences, were employed. Three kinds of interference stimuli were also prepared: pictures of soroban, pictures of digit sequences, and pictures of human faces. The sizes of pictures in the three types were approximately the same, 12 × 10 cm.

### Procedure

Generally, the testing procedure was the same as that in Experiment 1. Each subject was asked to remember the digit sequence which was given auditorily for 15 s, and to recall it aurally. There were four conditions, as follows:

(1) nothing was presented during the retention period of 15 s (*N*);
(2) pictures of soroban were presented at the rate of one picture per second during the retention period (*S*);
(3) pictures of digit sequences were presented at the rate of one per second (*D*);
(4) pictures of human faces were presented at the rate of one per second (*F*).

The numbers represented on interference pictures were unconnected to the digit sequences to be remembered. The four experimental conditions were given to the subjects in a randomized order.

## RESULTS

Scoring procedure of the subjects' performance was the same as that of Experiment 1. Three indices, correctly recalled numbers of figures, reduction rate, and number five error, were calculated.

Table 4 shows the mean correctly recalled numbers of figures. First, the performances of the experimental and control groups during the control condition

Table 4. Mean number of figures correctly recalled in each condition. SDs are shown in parentheses

| Condition | Control | Soroban | Digits | Human faces |
|---|---|---|---|---|
| Experimental group | 6.75 | 4.71 | 5.82 | 6.11 |
| | (0.70) | (0.63) | (0.80) | (0.75) |
| Control group | 6.10 | 5.72 | 5.01 | 6.58 |
| | (0.91) | (1.11) | (0.65) | (0.67) |

(*N*) were compared. The result showed that the experimental group recalled more digits correctly than the control group ($F1,38 = 4.88$, $p < .047$). This confirmed that soroban experts have a superior ability to memorize digits compared with ordinary people.

An analysis of variance (one between and three within subject, mixed design) was conducted to examine the effect of picture presentation on memory retention. The results showed that the interaction between group and types of picture was significant ($F2,76 = 24.88$, $p < .001$). The main effect of conditions was significant ($F2,76 = 41.36$, $p < .001$); however, the effect of group was not significant ($F1,38 = 1.20$). The interaction showed that (1) the control group recalled more digits than the experimental group in *S* condition ($F1,144 = 15.27$, $p < .001$); (2) the experimental group recalled more than the control group in *D* condition ($F1,144 = 10.10$, $p < .001$); and (3) there was no significant difference between the groups in recalled numbers in the *F* condition ($F1,144 = 3.33$).

## Reduction rate

To examine the interference effects of picture presentation on memory retention, reduction rate was calculated by the same formula as Experiment 1. Table 5 shows the reduction rate of the experimental and control groups for three conditions.

Table 5. Mean reduction rates (percentages) in each condition. SDs are shown in the parentheses

| Condition | Soroban | Digits | Human faces |
|---|---|---|---|
| Experimental group | 30.8 | 13.8 | 8.4 |
| | (4.4) | (1.8) | (1.0) |
| Control group | 6.4 | 18.9 | −7.8 |
| | (1.2) | (3.0) | (1.1) |

An analysis of variance (one between, three within subject, mixed design) revealed that both main effects, group and condition, were significant ($F1,38 = 9.17$, $p < .044$; $F2.76 = 44.01$, $p < .001$, respectively). The interaction between main effects was significant ($F2,76 = 26.72$, $p < .001$). The interaction reflected that (1) the experimental group showed more interference than the control group in the *S* and *F* conditions ($F1,44 = 28.52$ and $12.54$, $p < .001$, respectively); and (2) there was no difference between the groups in the reduction rate in the *D* condition ($F1,144 = 1.43$).

**Number five error**

Table 6 shows the mean percentages of number five errors for the experimental and control groups. The definition of this index was the same as that in Experiment 1.

Table 6. Mean percentages of number five errors in each condition. SDs are shown in parentheses

| Condition | Soroban | Digits | Human faces |
|---|---|---|---|
| Experimental group | 3.90 | 2.20 | 2.20 |
| | (1.87) | (1.72) | (1.99) |
| Control group | 2.00 | 1.30 | 1.60 |
| | (1.73) | (1.27) | (1.28) |

An analysis of variance revealed that the main effects of group and condition were significant ($F1,38 = 8.05$ and $8.59$, $p < 0.01$) while the interaction was not significant ($F2,76 = 2.33$). This indicates that (1) the experimental group made more number five errors than the control group in all conditions, and (2) the number five errors occurred more in the *S* condition than in the other conditions.

## DISCUSSION

Psychological investigations of working memory have been conducted by many researchers (Paivio, 1971; Pylyshyn, 1973; Braddeley and Hitch, 1974) and characteristics or effects of imagery on working memory have been revealed by these investigations. For example, a recent study by Johnson (1982) indicated that actual and imagined movements possess functionally equivalent effects on memory retention. He used a short-term memory linear positioning task in which a novel movement interpolated between initial and recall of a criterion movement length can bias recall, and found that a similar bias occurred when the interpolated novel movement was imagined rather than performed.

Matthews (1983) suggested that a concurrent secondary task possesses strong effects on learning and recall. He demonstrated that, when a secondary task intended to prevent the use of imagery was employed, recall of high-image words was selectively impaired. Logie (1986) showed that some visual material, even if it was unattended, has some effects on accessing short-term visuo-spatial memory storage and recall. He compared successively presented visual patterns coupled with rote rehearsal or a visual imagery mnemonics for learning lists of concrete words presented auditorily (Experiment 1) and instead of visual matching, with visual presentation of unattended pattern (Experiment 2) or colour patterns (Experiment 3). The results suggested that even if secondary concurrent tasks were not attended, their presentation disrupts memory storage and recall, i.e. picture presentation disrupts use of visual mnemonics, while speech disrupts rote rehearsal. From these findings, Logie (1986) suggests that use of a concurrent secondary task to influence working memory appears to be a simple and tractable method.

Although it had been well known that soroban experts possessed superior competence in arithmetic calculation, the characteristics, as well as implications, of their superior cognitive functions have not been explored until quite recently. Hatano and Osawa (1983) reported a pioneer work concerning the memory function of three soroban grand champions. While they demonstrated that (1) they could recall a larger number of digits (13 to 16), they could not recall more than between five and nine alphabet letters and fruit names; (2) their digit memory was disrupted more by concurrent visual–spatial tasks such as matching of figures than aural–verbal tasks such as answering questions; and (3) they could not recall the digits they stored at all after they were told to erase them. From these results they proposed that soroban grand masters have a specific device to visuo-spatially represent a larger number of digits just long enough for calculation.

Hatta (1985) and Hatta and Ikeda (1987) examined the hemisphere functioning of soroban experts with a time-sharing task devised by Kinsbourne and Cook (1971), where both sequential finger-tapping and mental arithmetic tasks were given simultaneously. They demonstrated that soroban experts showed a larger performance reduction when tapping with their left hand than when using their right hand in both auditorily and visually administered mental calculation problems, whereas control subjects showed the reverse tendency. From these findings they suggest that the right hemisphere engages more in mental calculation than the left, in soroban experts, while the position is reversed in non-expert subjects.

These pioneer studies seem to suggest that soroban experts are able to utilize special techniques to process numbers or calculate efficiently, and that probably they rely on the employment of visuo-spatial strategy. However, the kind of visuo-spatial strategy they employ in these situations is not clear, and we tried to examine this with a secondary concurrent task paradigm.

The findings of Experiment 1 seem to offer some answers concerning this point. The first finding, that soroban experts had a much superior ability in digit memory, is in accordance with previous reports. The second finding, that the digital memorization competence of soroban experts was reduced by the presentation of pictorial soroban figures but was not reduced by the presentation of digits, seems to indicate that experts utilize images which are analogous to the actual soroban as an aid to hold numbers in memory. The third finding, that soroban experts made special types of error, such as the number five error, more than control subjects, also seems to suggest that soroban experts utilize soroban images; frequent occurrences of this type can only be explained by soroban visualization errors.

The results of Experiment 2 were essentially the same as those of Experiment 1. First, soroban experts had a superior ability in digit memory. Second, soroban experts experienced more interference from the presentation of soroban-like pictures than from digits or human faces. Third, soroban experts produced more number five errors than ordinary people did. The only discrepancy between the results of Experiments 1 and 2 was that there was no significant difference in the *D* condition. Both groups showed the same level of interference effects from the presentation of pictures of digits. The reason is not clear, but the fact that the experimental group in Experiment 1 consisted of experts under training, whereas the experimental group in Experiment 2 were more experienced, may have contributed to the difference.

The present two experiments showed that soroban experts use a mental soroban to improve digit memory retention, but ordinary subjects who have negligible soroban learning experiences do not employ such an imagery-based strategy.

This hypothesis is, in general, consistent with the proposal by Logie (1986), previously described, that a concurrent presentation of visual material affects access to auditorily presented memorized material at storage and recall. And it is also consistent with the proposal by Stigler (1984) who investigated Chinese children. He showed that (1) the calculation times increased with the increase addends in novice children but remained constant in soroban-expert children; (2) when subjects were asked to answer questions about intermediate states in calculations that are unique to soroban calculation, soroban experts could answer correctly and the amount of time required to answer was a linear function of the position of the intermediate state. From these findings he proposed that skilled soroban operators can visualize a mental image of the soroban which is analogous to the actual one. Further, as the results of Experiment 2 showed, once people have mastered the way in which the mental abacus is employed to improve number processing, people can use it hereafter without special training.

As our experiments suggest, soroban experts utilize imagery to conduct calculation tasks. This conclusion, which is supported by previous studies of soroban experts, means that they use their right hemispheres to engage in mathematical activity as a result of a substantial amount of practice, and that their superior competence compared with the ordinary person arises from this (Brain, 1964; Critchely, 1953; Hatta, 1984; Hecaen, Angelergues and Houllier, 1961).

Needless to say, this is a tentative hypothesis at present, and further experimentation is essential to verify this, and also to the amount of practice needed to achieve imagery-based calculation.

## ACKNOWLEDGEMENT

The authors are much indebted to the League for Soroban Education, Japan for providing the opportunity to examine cognitive function in soroban experts.

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