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Formation of a Mental Abacus for Computation and Its Use as a Memory Device for Digits: A Developmental Study

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In order to examine whether representational changes in digit memory would be observed as a function of the extent of expertise in mental-abacus operation, five groups of operators, differing in extent of expertise (i.e., novices, lower intermediates, intermediates, junior experts, and experts), were required (a) to reproduce series of five digits either forward or backward as quickly as possible and (b) to perform a simple aural-verbal or visual-spatial task interpolated between the presentation and reproduction of a near-span series of digits. The intermediates and more skilled operators as well as a majority of the lower intermediates showed nearly equal amounts of time for forward and backward reproduction, whereas novices took a much longer time for backward than for forward reproduction. The more skilled operators were, the less vulnerable was their memory for digits to the aural-verbal interpolated task (a relation that was significant) and the more vulnerable to the visual-spatial task (a relation that was insignificant). These results strongly suggest that the advanced operators applied their mental abacus to digit memory. It is claimed that a system of representation formed through routine problem solving is transferred automatically to other cognitive tasks.

A number of investigators of "everyday cognition" have asserted that, if they solve the same kinds of problems thousands of times, people tend to form more or less general, transferable cognitive skills by which those problems are promptly solved (e.g., Hatano & Inagaki, 1983; Scribner & Cole, 1981). These skills must include, in addition to efficient solution strategies, skills for aptly representing elements involved in the problems. In complex knowledge domains like physics and mathematics (where novel problems are continually posed), experts generate an appropriate representation of each specific problem, using their rich and well-organized body of knowledge, so that they can handle the representation easily to solve the problem (for a review, see Chi, Glaser, & Rees, 1982). In domains of speeded routine problem solving commonly observed in everyday cognition (e.g., Scribner, 1984), however, experts have probably acquired a system of representation readily applicable to the whole set of problems that they expect to come across. This is because in everyday situations, we assume, knowledge about how to represent a problem is soon "compiled" and "tuned" into specific condition–action pairs that are relatively automatic (Anderson, 1982). Thus, the system of representation—the aggregate of those specific productions—will be applied to other tasks involving the same elements to produce transfer of training.

Abacus operation most clearly illustrates the formation of a powerful system of representation: Experienced abacus operators can represent an intermediate result on their "mental abacus" in the form of a mental image of the configuration of abacus beads, to which they enter or from which they remove the next number (Hatano, Miyake, & Binks, 1977; Stigler, 1984). Furthermore, Hatano and Osawa (1983) found that grand experts in abacus-derived mental calculation revealed an extended span only for digits. The experts also seemed to store a series of digits not as temporally sequenced items in the rehearsal buffer, but as a visuo-spatial image: They could reproduce the series easily either from the left or from the right, because they could "see" at least some of its elements simultaneously, and they could perform concurrent aural–verbal tasks processed by using the rehearsal buffer while holding the series.

The latter results were interpreted as evidence for representational transfer, because the experts seemed to apply their mental abacus (formed through practice in solving computational problems) to the task of memorizing a series of digits for a longer period of time without transformation. From these results alone, however, we cannot decide whether repeated practice produced transferable skills of visuo-spatial representation of a number or whether it was those few who already had such skills who could easily become proficient at mental abacus operation.

The study reported here was designed to extend the earlier research of Hatano and Osawa (1983) through a developmental analysis. It was aimed at examining whether representational

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changes in digit memory would be observed as a function of the extent of expertise in mental abacus operation (i.e., when subjects were grouped in terms of their skills). The question was, in other words: Would advanced operators readily transfer their representational skills of using the mental abacus from the much practiced task of computation to another task of digit memory without explicit instructions? It is true that by cross-sectional comparisons like this we cannot completely eliminate the possibility of "selective survival" (i.e., that those who have been more successful because of their aptitudes tend to continue the practice further and reach higher levels). However, if we could find, among a fairly large number of students, a close relation between the degree of expertise and visuo-spatial representation of digits, we could make a stronger claim for representational transfer. This is because—if one were to assume that the visuo-spatial representation of digits was the limiting variable in, not the cognitive consequence of, the development of mental abacus skills—one might expect to find some students with skills for such representation but poor abacus skills.

This study also investigated the subsidiary issue of the relation between the size of an individual's mental abacus and his or her reliance on it. With a year or two of practice on a real abacus, ordinary operators become able to add and subtract numbers quickly without the instrument (e.g., Ezaki, 1980), but the size of their mental abacus is just two or three columns. This is probably due to the fact that their visuo-spatial representation in terms of abacus beads is more fragile, less vivid, and harder to control than that of the experts. These novice operators have proceduralized to some extent the *coding scheme* (Reisberg, Rappaport, and O'Shaughnessy, 1984) for transforming numbers into image of beads, but they still require some mental effort to do so. Two contrasting predictions as to *when* the mental abacus as a memory device comes into use can thus be offered: (a) As soon as it is acquired as a device for mental calculation (i.e., even when it has just two or three columns); (b) Only after it becomes a more powerful system for digit memory than the rehearsal buffer (e.g., when it has five or more columns).

Experiment 1

Method

Subjects

In order to answer these *whether* and *when* questions, a variety of digit and nondigit (animal name) memory tasks were given to five groups of experimental subjects differing in their expertise in mental-abacus operation and, therefore, in the size of their mental abacuses. These groups consisted of 10 novices, 12 lower intermediates, 9 intermediates, 12 junior experts, and 11 experts. The first three groups were from an abacus school primarily for elementary-school children, whereas the last two groups were from another school having advanced courses for "players" (i.e., for students who participate in matches and tournaments). Thirteen third graders, who had just started practice in real abacus operation at the former school served as control subjects. Most of them became novices of mental-abacus operation within a year or two (the dropout rate is generally very low at this stage of expertise). All subjects were prompt volunteers. Their nation-wide exam-based qualifications, the expected minimal size of their mental abacuses (which is estimated from how many columns have to be handled for the qualification), and their age range are shown in Table 1. Mean forward and backward spans for digits are also shown.

Procedures

The experiment was conducted individually at each subject's abacus school. First, the forward and backward spans for digits and forward span for animal names (which represented nondigit spans) were measured as follows: The subject was aurally given series of digits and names at a speed of one item per second and, immediately after the presentation, was asked to reproduce these items vocally at his or her preferred speed. The first series consisted of three digits or names, and one more item was added after each successful reproduction. The task ended when the subject failed to reproduce correctly two series of the same length. The two "target" digit memory tasks, *timed reproduction* and *digit memory with interpolated tasks* (described below) came next. These tasks have previously clearly differentiated abacus-derived mental arithmetic experts from ordinary people (Hatano & Osawa, 1983). Finally, for the purpose of within-subject comparison, nondigit (animal name) memory with interpolated tasks was given.

Timed-reproduction task. In this task, the subject was required to vocally reproduce an aurally given series of digits either forward or backward as quickly as possible, and his or her retrieval time (RT) was measured. An experimenter, with a stopwatch in her hand, presented a series in the same way as the measurement of digit span and then gave the *begin* signal and started the stopwatch. She stopped the watch when the subject completed the reproduction of the series.

Each series consisted of randomly chosen digits from *1* to *9*, with the constraints that it could contain neither a consecutive repetition of the same digit nor a progression by adding one (e.g., . . ., 3, 4, . . .). Of the 54 experimental subjects, 39 received series of five digits. The remaining 15 received series of four digits for both forward and backward reproduction, because their performance on the initial tasks had indicated that five-digit series were beyond their (backward) span. The controls were not given this task, because the backward reproduction of four or five digits was expected to be too hard for many of them.

First, the subject was required to reproduce the given series forward until he or she got five series correct. Then, he or she was to reproduce backward. Out of the five correctly reproduced series, excluding the one requiring the largest RT, the individual average over four series was computed for forward and backward reproduction. The adjusted RT, which was used for computing means, standard deviations, and so forth, was obtained by multiplying 5/4 and the observed average RT for the four-digit series. Increment Ratio (IR; backward RT divided by forward RT) was also computed for each subject. When the increment ratio is close to 1.0, this means that backward reproduction is almost as quick as forward reproduction.

It was predicted that advanced operators would reveal significantly smaller (and closer to 1.0) IR than less advanced operators, who, still relying primarily on the rehearsal buffer, would take much longer for backward reproduction (i.e., reversing the temporal order of codes). If digits were retained on a mental abacus, however, the backward reproduction would be almost as quick as in the original order because both require the subject to "read off" the digits.

Digit memory with interpolated tasks. Each subject was required to memorize 10 series of digits that were one figure shorter than his or her span. Immediately after the presentation of each series, and before being allowed to reproduce it, the subject was given either an aural-verbal interpolated task (on the first five series) or a visual-spatial task (on the last five series)—instructions for which had been given prior to the presentation of digits. The aural-verbal task was either to answer a simple factual question (e.g., "What is the highest mountain in Japan?") or to reproduce a three-syllable familiar-object name backward, that is, by reversing the syllables (e.g., mi-sa-ha for ha-sa-mi [scissors]). The visual-

Table 1
Background Information About the Subjects

Group	Qualification[a]	Expected size of mental abacus[b]	N	Age (in years)	Average forward digit span	Average backward digit span
Experts	4th–10th dan	6	11	12–23	8.6	8.8
Junior experts	1st or 2nd dan	6	12	9–17	6.9	6.6
Intermediates	1st or 2nd kyu	4–5	9	11–15	6.8	5.1
Lower intermediates	3rd or 4th kyu	3–4	12	11–14	5.8	4.8
Novices	5th or 6th kyu	2–3	10	9–11	5.2	4.0
Controls			13	9–10	4.5	3.3

[a] *Dan* are classes for masters, and 10th dan is the highest; *kyu* are classes for beginners and intermediates, and 1st kyu is the most advanced. [b] Number of columns needed to solve the hardest problems at group's level.

spatial task was either an item from Kagan's Matching Familiar Figures Test (requiring the subject to choose out of the six alternatives the drawing that was identical to the simultaneously-presented target) or a memory item with more distinctively different drawings (i.e., the subject had to choose the identical drawing after the target was taken away).

The subject's performances for each series were classified as *complete* (correct performance of both memory and interpolated tasks), as *near complete* (correct reproduction of the series with incorrect response to the interpolated task, or with erroneous or missing, but more than half correct, reproduction of the series with correct response on the interpolation), or as *incomplete* (response patterns not satisfying the above criteria). For quantitative analysis, scores of *2, 1,* and *0* were assigned to these performances, respectively. Thus, the maximum total performance score was *10* for both aural-verbal and visual-spatial tasks. A difference score, representing how much better one managed to perform with aural-verbal interpolation than with visual-spatial interpolation, was computed by subtracting the total visual-spatial performance score from the total aural-verbal performance score.

We predicted that advanced operators would reveal larger difference scores (as defined above) than less advanced operators. We reasoned that if (and only if, probably) digits were represented on a mental abacus, the subject's digit memory would be compatible with the aural-verbal interpolated task, which was processed by using the rehearsal buffer. In addition, digit memory on the mental abacus might be more vulnerable to the visual-spatial interpolation if the latter task required a great deal of the visuo-spatial working storage capacity.

Nondigit memory with interpolated tasks. Here, each subject was given 10 series of familiar animal names (e.g., deer, monkey, cat), each of which were, again, one shorter than his or her span, and required to memorize them. Either an aural-verbal or visual-spatial task, of the same kind as described above, was interpolated between the presentation and reproduction of each series. On this task, we predicted no significant difference according to the extent of expertise, because even the advanced operators would store those names in the rehearsal buffer.

Analysis of Data

Because expertise in mental-abacus operation requires a number of years to attain and because most students started abacus learning from approximately the same age (7–8 years), there were age differences among the six groups ranked by level of expertise. Thus, in statistical analysis of the data presented here, we used age as a control variable, eliminating all the age-related developmental changes in the target skill. By using this method of analysis, the effect of expertise might be underestimated, but it could not be overestimated. We assigned a maximum age of *18* to those subjects 18 years or older.

Results

In examining the digit spans of the subjects (see Table 1), we found that both forward and backward spans were significantly different among the groups, even when the effect of age was partialed out. For the forward span, $F(5, 60) = 3.50$, $p < .01$, and the experts significantly differed at the 5% level in age-adjusted mean from all other groups except for the junior experts, who differed from the three least advanced groups. For the backward span, $F(5, 60) = 9.51$, $p < .01$, with the experts differing from all other groups, and the junior experts differing from the remaining four groups.

Next, we describe the subjects' performances on the three tasks in turn. As shown in Table 2, IR means were substantially reduced as expertise increased in mental calculation. An analysis of covariance (ANCOVA) of IR with age controlled revealed a significant group difference, $F(4, 48) = 3.66$, $p < .05$, to which age, as the covariate, did not contribute significantly. Age-controlled means were 2.1, 1.5, 1.1, 1.1, and 1.0, for the novices, lower intermediates, intermediates, junior experts, and experts, respectively. Only the novices differed significantly from the other four groups. Thus, we can conclude that, as the students gained expertise, RTs for forward and backward reproduction became nearly the same. Our first prediction was confirmed. None of the novices, except for a subject showing a very large forward RT of 4 s, showed an IR as small as the average of the intermediates. We interpreted this to mean that a majority of the intermediates and more skilled operators relied on their mental abacus when required to memorize series of 5 digits, whereas the novices could not (or did not) do so. The mean IR of the lower intermediates was 1.45, substantially different from 1.0, but this was mainly because of the exceptionally large ratios of two subjects, 4.4 and 2.5. Digit memory by subjects at this level was examined further in Experiment 2 (described below).

Also as shown in Table 2, average RTs, both for forward and backward reproduction, were reduced with increasing expertise. An ANCOVA with age controlled revealed significant differences: for the forward reproduction, $F(4, 48) = 4.43$, $p < .01$, and for the backward reproduction, $F(4, 48) = 8.81$, $p < .01$. It seems that subjects became faster in the verbal encoding of their digit representation—through practice in giving answers orally—as they gained expertise.

Performance levels in digit memory with interpolated tasks

Table 2
Adjusted Mean RTs for Forward and Backward Reproduction

Measure	Novices (N = 10) M	SD	Lower intermediates (N = 12) M	SD	Intermediates (N = 9) M	SD	Junior experts (N = 12) M	SD	Experts (N = 11) M	SD
Forward RT	2.7	0.87	1.8	0.66	1.5	0.21	1.6	0.53	1.4	0.47
Backward RT	4.9	1.79	2.6	2.12	1.7	0.43	1.6	0.48	1.5	0.28
Increment ratio[a]	1.98	0.78	1.45	0.99	1.15	0.35	1.04	0.18	1.21	0.36

Note. RT = retrieval time (in seconds).
[a] Mean of individual ratios (Backward RT)/(Forward RT).

are shown in Figure 1. An ANCOVA with age controlled revealed that mean difference scores (the total performance score with aural-verbal tasks minus that with visual-spatial tasks) were significantly different among the six groups including the control group, $F(5, 60) = 5.4, p < .01$. Age-controlled means were −4.5, −3.2, −1.6, 0.7, 1.2 and 2.1, for controls, novices, lower intermediates, intermediates, junior experts, and experts, respectively. The controls differed significantly from all other groups except for the novices, and the novices and the lower intermediates differed from the three most advanced groups. Thus, our second prediction was confirmed. Only one of the controls showed a difference score larger than the average of the intermediates, but this control student had a total performance score with aural-verbal tasks of only *2.*

The difference in the difference scores was mainly due to the group differences in vulnerability to aural-verbal interference. The total performance scores with aural-verbal tasks increased as the subjects gained expertise and significantly differed among the groups, $F(5, 60) = 5.1, p < .01$. The visual-spatial interpolated tasks, however, tended to become slightly, though insignificantly, more disruptive as subjects gained expertise.

An ANCOVA with age for the performances in nondigit (animal names) memory with interpolated tasks showed that, as predicted, the six groups did not differ significantly in either the total performance score with aural-verbal interpolation, nor in that with visual-spatial interpolation, nor in the difference score between the two scores—although with the aural-verbal tasks the controls and novices were apparently inferior to the other groups (see Figure 2). Thus, these six groups were roughly comparable in nondigit memory when their age was controlled. This further supports the interpretation that their digit memory was affected mainly by their expertise in mental-abacus calculation, not by "memory ability" in general.

Experiment 2

Experiment 1 strongly suggested that the advanced operators spontaneously used the mental abacus as a memory device for digits. However, it failed to reveal conclusively *when* the operators had come to rely on it. The lower intermediates were supposed to have a mental abacus of 3 to 4 columns. Was their mental abacus spontaneously used in digit memory? We would answer *yes,* (except for the two students whose IRs were much larger than 1.0). Seven of the 12 lower intermediates correctly reproduced five series of five digits forward and backward. How could they do so by using their small-sized mental abacus? We can reasonably assume that the number of columns of a mental abacus usable for digit memory (i.e., "static" representation) tends to be larger than that for calculation ("dynamic," manipulable representation), because the general-purpose central processor of working memory (e.g., the *central executive* of Baddeley & Hitch, 1974) is more readily available to support memory storage when not loaded with other processing demands. In addition, when the mental abacus does not have five columns for memory, one or two digits that are to be reproduced first can be put in the rehearsal buffer with minimal increment in the backward RT.

Method

In order to confirm that, soon after the mental abacus is acquired, students tend to spontaneously use it at least partially, another group of 18 lower intermediates was tested. After being measured for forward and backward digit span, each subject was given a slightly modified version of the timed-reproduction task: He or she was required to reproduce vocally, as quickly as possible and in this order: five series each of four digits forward, four digits backward, five digits forward, and five digits backward. When an erroneous reproduction was made, another series was given, up to a maximum of nine. The largest RT for each condition was excluded, and the average over four series was computed. If five series could not be reproduced correctly in any one condition, the task ended.

Next, 10 series of five digits, whose direction of reproduction was either forward or backward (depending on the experimenter's signal *after* the presentation), were given. For these 10 "mixed" series, therefore, the subjects could not anticipate which part of the series they would have to reproduce first. Finally, they were required to describe what strategies they had used for the forward and backward digit reproduction.

Results

The mean forward and backward spans for digits for these 18 subjects were 5.7 (SD = 0.75) and 4.3 (SD = 0.77), respectively, which were roughly comparable to the corresponding figures of the lower intermediates in Experiment 1. For the series of four digits, means (standard deviations follow in parentheses) in seconds for forward RT, backward RT, and IR were 2.1 (0.83), 2.3 (0.82) and 1.1 (0.21), respectively, excluding three subjects who failed to reproduce backward five series correctly out of the

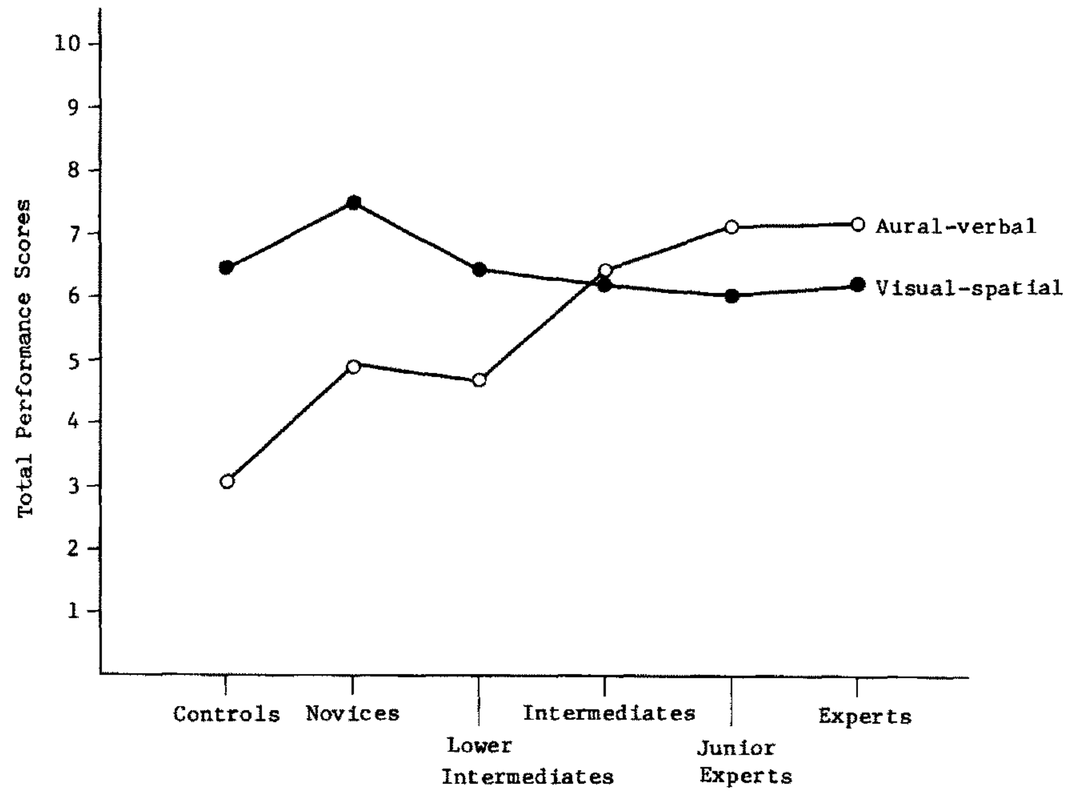

Figure 1. Digit memory with interpolated tasks.

nine. For the series of five digits—for which subjects had been told the direction of reproduction—mean forward RT, backward RT, and IR among the six subjects who could correctly reproduce five series each were 3.3 (1.05), 3.5 (1.05), and 1.1 (0.23), respectively. No one in this experiment revealed an exceptionally large IR. Out of the 12 subjects who were given all the conditions of the modified timed-reproduction task, 10 made more correct reproductions in the first five-digit series each for forward and backward reproduction, for which they had been told the order, than they made in the 10 mixed series, for which the order of reproduction was not known, whereas only 1 subject did better in the latter.

Nine subjects reported in the interview that they had relied mostly on the mental abacus, 6 on both the rehearsal buffer and mental abacus, and 3 on the rehearsal buffer only (e.g., by saying "just by reciting"). These latter 3 said that they did not use the mental abacus because they forgot to use it or because they thought they were not good at handling it. There were three types of mixed use of the two memory devices: (a) trying to store digits on both devices simultaneously, (b) relying mainly on one device and using the other as an auxiliary (e.g., putting the last two digits in the buffer), and (c) using the mental abacus only when backward reproduction had been required. These results suggest that the lower intermediates relied on a mental abacus for memorizing digits to some extent.

General Discussion

This study clearly showed that the digit memory of the mental-abacus operators became more and more visuo-spatial in nature as they gained expertise. Our prediction was confirmed both for experts' ease of backward reproduction and compatibility with aural-verbal interpolation. The operators had never been trained to use the mental abacus for digit memory nor were they explicitly instructed to do so at the time of the experiment. We interpreted this to mean that a majority of advanced operators spontaneously transferred their special system/skills for representing a number (i.e., the mental abacus) from the task of calculation to that of digit memory. The answer to the *whether* question posed at the beginning of this article is clearly affirmative.

In short-term training experiments of any skill or set of skills, transfer is always a problem. Even after extensive training, the transfer of a specific solution strategy across domains or contents requires "the recognition of problem isomorphs" (Brown, Bransford, Ferrara, & Campione, 1983) more or less at a conscious level. In other words, a relevant solution strategy can be applied across domains only when the problem is, by using conceptual or declarative knowledge, represented so aptly that the relevance of the strategy is recognized. Representational transfer (i.e., applying a system of representation to other tasks involving the same elements), however, may occur automatically and unconsciously, regardless of what types of processing are exerted on the representation of the elements.

We would claim that the system of representation acquired through extensive practice in abacus operation has a number of the characteristics of a module in Fodor's (1983) sense. It is, for example, activated by a relatively restricted class of perceived

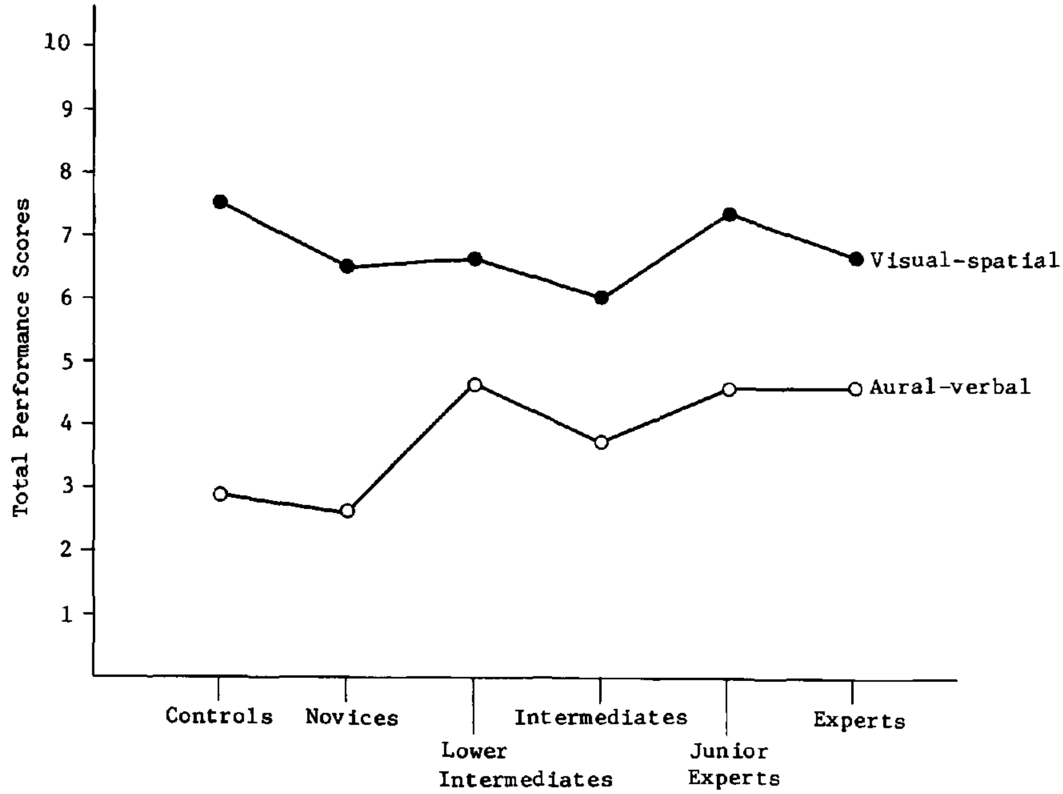

Figure 2. Nondigit memory with interpolated tasks.

stimuli (i.e., numbers and series of digits); its operation is mandatory in that experts have no choice but to place a number or digits on their mental abacus; and it is probably encapsulated (e.g., it is not influenced by prior knowledge about likely answers). Using a different set of terms, we assert that the actions of the specific condition–action pairs constituting this system of representation are triggered more or less automatically whenever the conditions are met (Anderson, 1982). Thus, we can reasonably expect the system to transfer readily, as long as an abacus expert is presented a number or series of digits to process, and the effect will be positive or negative depending on the nature of the tasks.

Similar development of a system of representation and its transfer are expected for other domains in which a fixed set of skills are repeatedly applied with emphasis on proficiency. For example, we expect that a student can acquire a unique system for representing musical pieces, if he or she performs on a musical instrument for thousands of hours. Workers may also develop a specific system of representation for a machine's behavior if they operate it many times. These systems will be transferred to other tasks whenever applicable.

We will now examine these findings in relation to the question of *when* operators start to transfer and discuss the course of expertise in mental-abacus operation in terms of the development of representation. Because abacus operation consists of a small and fixed set of procedural skills that can be learned in just a few hours, even our control subjects could calculate if a real abacus, a system of physical representation, were available. The novices, having formed a small-sized mental abacus as a system of mental representation, could solve simple calculation problems (e.g., adding several two-digit numbers) without the instrument and thus were qualified as fifth or sixth *kyu*. (*Kyu* are classes for beginners and intermediates, and first *kyu* is the most advanced.) Judging from the data on timed-reproduction, however, the novices did not apply this system to the task of digit memory. Although their digit memory was less vulnerable to aural-verbal interference than was the controls', this was probably due to their proficiency in reciting a number or series of digits, because their digit memory was also less vulnerable to visual-spatial interference. Although they could represent a number, doing so seemed to require too much effort for the system to be generalized promptly. Another possible interpretation is that they would use the mental abacus only for numbers, not for digits.

Both the findings concerning the timed-reproduction task and those from Experiment 2 suggest that, among the six groups, it was the lower intermediates who started to use the new representational system for computing as a memory device for digits, although there were large individual differences at this stage. Their digit spans suggested that the mental abacus was still small in size and not more powerful than the rehearsal buffer. Thus, the answer to the *when* question fell in between our contrasting predictions, that is, between "as soon as the mental abacus is acquired" and "after it becomes a more powerful system." When the task demand was greater than the capacity of their new representational system, the lower intermediates tried mixed use of the two systems, new and old. Probably because of this mixed use and because of their lack of full automaticity in using the mental abacus, they were not as successful as the intermediates or more advanced operators in processing aural-verbal tasks while holding a series of digits.

The intermediates and more advanced operators, however, readily applied their system of visuo-spatial representation. Differences among the three most advanced groups were quantitative rather than qualitative: As revealed in their digit spans, the more advanced operators had a significantly larger mental abacus. However, all of them seemed to have a mental abacus as a (quasi)module by which a perceived number or series of digits is represented in a visuo-spatial manner, ready for further processing. How the extension of the size of the mental abacus occurs is an interesting problem that merits future studies.

This discussion about the course of the development and use of the system of representation can incorporate earlier findings regarding the differences between the grand experts in abacus-derived mental arithmetic and ordinary college students (Hatano & Osawa, 1983). For timed-reproduction, the two grand experts, tested by Hatano and Osawa with series of 10 digits instead of 5, had IRs of 1.00 and 1.04, which were as small as the figures among the experts in this study; the mean IR for the five college students was 1.83, which was larger than for the lower intermediates here. For digit memory with interpolation, the two grand experts of the earlier study showed mean total performance scores of *7* for the aural-verbal and *4* for the visual-spatial when five items, each roughly comparable to those used in the present experiment, were chosen out of the 10 items administered. These figures could also be obtained by extrapolating the changes observed in the present study much further. Although it is possible to claim that those grand experts were special from the start, the entire picture strongly suggests that they relied exclusively on their well-developed (large-sized) mental abacus when they were required to memorize series of digits, and that their performances, although very much deviating from those of ordinary people, were "expected" in the course of expertise in mental-abacus operation.

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