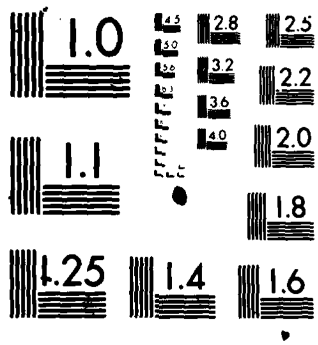
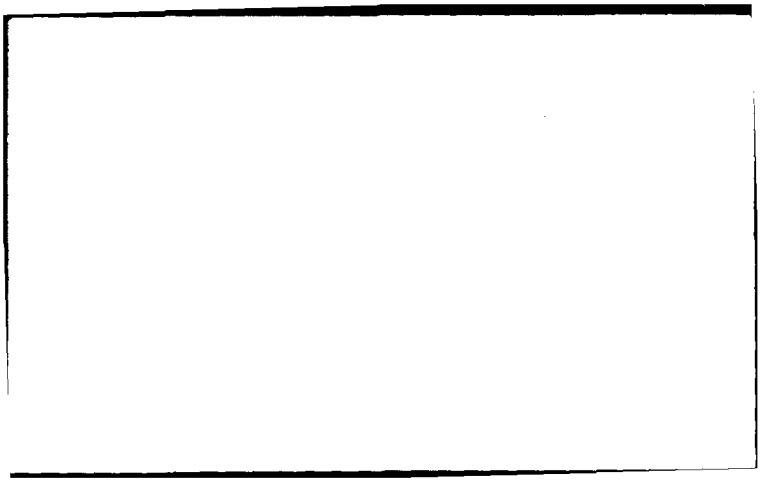
AD-A114 635 CARNEGIE-MELLON UNIV PITTSBURGH PA DEPT OF PSYCHOLOGY F/G 5/10
SKILLED MEMORY.(U)
UNCLASSIFIED NOV 80 W G CHASE, K A ERICSSON N00014-79-C-0215
TR-5 NL

END
DATE FILMED
6-82
DTIC



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A



(12)

Skilled Memory

William G. Chase and K. Anders Ericsson

Carnegie-Mellon University

Pittsburgh, PA 15213

Technical Report No. 5

6 November 1980

Paper to appear in J.R. Anderson [Ed.], Cognitive Skills and their Acquisition, Hillsdale, N.J.; Lawrence Erlbaum Associates, in press.

This research was supported by Contract N00014-79-C-0215 with the Advanced Research Projects Agency of the Office of the Secretary of Defense, which is monitored by the Office of Naval Research.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A114 635	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SKILLED MEMORY		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) William G. Chase K. Anders Ericsson		8. CONTRACT OR GRANT NUMBER(s) N00014-79-C-0215
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Psychology Carnegie-Mellon University Pittsburgh, PA 15213		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel and Training Research Programs Office of Naval Research Arlington, VA 22217		12. REPORT DATE 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

To appear in J.R. Anderson (Ed.), Cognitive Skills and their Acquisition, Hillsdale, NJ: Lawrence Erlbaum Associates, in press.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Memory	Computer simulation
Mnemonics	Skilled Performance
Cognitive Psychology	Learning

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A single subject was able to increase his digit span from 7 digits to 80 digits with about 250 hours of practice. Verbal protocols and various experimental procedures were used to analyze the cognitive processes underlying the acquisition of this skill, and a computer simulation model of the skill was developed and tested. The two essential components of the skill were a mnemonic system for coding digit groups into meaningful units, and a retrieval structure for retrieving these units from long-term memory. The theoretical implications of our research are discussed in terms of three principles of skilled memory.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

In this paper, we describe our analysis of a single subject (SF) who has become an expert at the digit-span task. Over the course of 2 years, involving over 250 hours of laboratory practice, SF has steadily increased his digit span from 7 digits to about 80 digits. SF's current digit span exceeds that of normals by more than a factor of ten, and his span is four times higher than has ever been recorded in the literature before. In this paper, we present our analysis of the cognitive processes underlying this memory feat, and we want to use this specific example to develop what we think are the important theoretical principles that we have discovered about skilled memory.

What we mean by skilled memory is the rapid and efficient utilization of memory in some knowledge domain to perform a task at an expert level. Without the knowledge base, task performance by a novice is poor or nonexistent. It is the goal of our present project to understand how memory skill is developed and how memory is utilized by the expert to produce skilled performance.

The contrast between novice and expert memory performance is striking. Normal people's memory spans fall in a very narrow range (around 7 ± 2 items), and this span is fairly stable over a wide range of types of material (Miller, 1956). This relative invariance in the memory span is taken by most cognitive psychologists as an index of one of the most fundamental and stable properties of the human memory system: the limited capacity of short-term memory (Brown, 1958; Peterson & Peterson, 1959). This limit places severe constraints on people's ability to process information and solve problems (Miller, 1956; Newell & Simon, 1972), and further, memory span has been related to scores on intelligence tests (Bachelder & Denny, 1977a,b).

The inability of normal people to hold more than about seven unrelated items in short-term memory stands in apparent contrast to reported feats of memory experts. Persons with trained memories can use mnemonic systems to memorize long lists of names, numbers and other arbitrary items if they are given enough time between items to allow their systems to work (Bower, 1972; Yates, 1966). Chess masters are able to reproduce virtually an entire chess position of 32 pieces after a brief (5 sec) presentation of a chess board, whereas a novice can only remember the location of 3 or 4 pieces (Chase & Simon, 1973; de Groot, 1966). Mental calculation experts are able to store many intermediate computations in their head while doing mental arithmetic, and as a side-effect of their skill, they generally exhibit a digit span that is two or three times as large as normal (Hatano & Osawa, 1980; Hunter, 1962; Mitchell, 1907; Müller, 1911). Expert telegraphers are able to lag behind by as much as 15-20 words when receiving Morse code (Bryan & Harter, 1899).

In every case, memory performance of the expert seems to violate the established limits of short-term memory. How is it possible for the expert to bypass the limits of short-term memory in the domain of his expertise? It is the analysis of this problem that we set out to study in the domain of memory span for digits.

It has often been disputed whether skills are the result of extensive practice or whether some exceptional ability is also necessary for their development. The standard approach for studying expertise has been to bring a recognized expert into the laboratory and study the scope and limits of his performance on a variety of tasks. This approach has some limitations, though. First, for advanced experts there is little, if any, objective data on how they developed their skill. Second, there is a correlational problem of self-selection: With already-existing experts, one never knows how important initial abilities were for the eventual mastery of the skill. We avoid both these objections by studying the development of a skill from the beginning and by starting with someone with average memory abilities.

Studies of the development of memory skill are rare. In one early study in 1925, a group of kindergarten children was able to increase its average digit span from 4.3 to 6.4 digits after 78 days of practice (less than an hour a day), but this improvement was temporary and disappeared within 5 months (Gates & Taylor, 1925). In another early study in 1929, two motivated college students were able to increase their memory spans to 14 digits after about 50 hours of practice (Martin & Fernberger, 1929). These early studies, however, provide little insight into the cognitive mechanisms responsible for changes in the memory span. Nowadays, with better theories of memory and better techniques for studying memory, it is possible to analyze the underlying cognitive components of skill acquisition in the memory domain.

In what follows, we first describe our data on SF's memory span performance, and then we present our analysis of SF's skill in terms of the two principal cognitive mechanisms: the mnemonic system and the retrieval structure. In the final two sections of the paper, we pursue the question of what additional mechanisms are involved in SF's skill and the implications of our findings for a theory of skilled memory.

The Learning Curve

An undergraduate (SF) with average memory abilities and average intelligence for a college student was paid on an hourly basis to participate in the experiment. SF was run on the memory span task for about an hour a day, 2 to 5 days a week, for over two years. The basic procedure was to read random digits to SF at the rate of one digit per sec, followed by ordered recall. If the sequence was reported correctly, the length of the next sequence was increased by one digit, otherwise the sequence length was decreased by one digit. Immediately after each trial, SF was asked to provide verbal reports of his thought processes during the trial.[1] At the end of each session, SF was also asked to recall as much of the material from the session as he could. On some days, experimental procedures were substituted for the regular sessions.

During the course of 25 months of practice, involving over 250 hours of laboratory testing, SF

demonstrated a steady improvement in his average digit span from 7 digits to over 80 digits (Fig. 1). Furthermore, there was a parallel improvement in his ability to remember digits following the session. In the beginning, SF could recall virtually nothing after an hour's session; now SF can recall well over 90% of the digits presented to him.

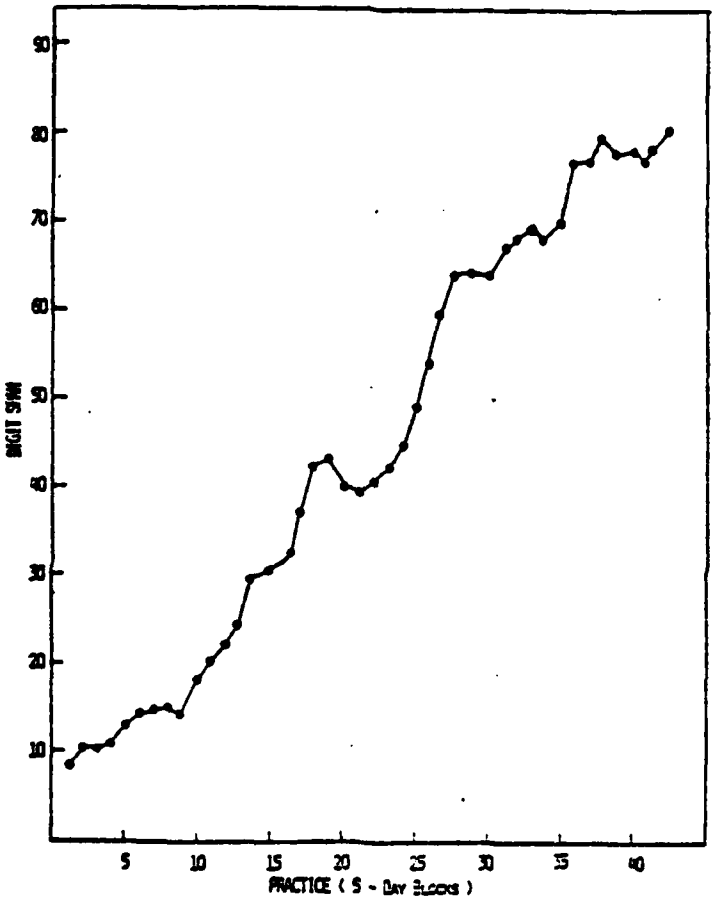


Figure 1: Average digit-span for SF as a function of practice in 5-day blocks. Each day represents about 1 hour's practice and ranges from 55 trials per day in the beginning to 3 trials per day for the longest sequences. The 43 blocks of practice shown here represent about 215 hours of practice; interspersed among these practice sessions are approximately 75 hours of experimental sessions [not shown].

Figure 2 compares the early part of SF's learning curve with those of Martin and Fernberger's (1929) two subjects. This figure shows the maximum digit span as a function of the number of trials to obtain it. The interesting thing to notice about the figure is how similar the learning curves are.[2]

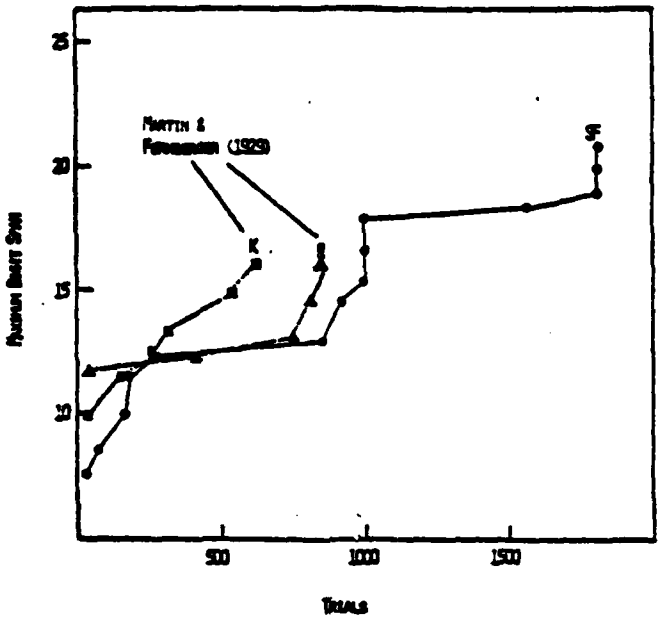


Figure 2: This graph compares SF to Martin and Fernberger's [1929] two subjects on the same scale. Plotted here are the successive highest number of digits recalled by each subject as a function of the number of trials it took each subject to reach each maximum. Martin and Fernberger's subjects practiced about 3 months before the experiment was terminated.

With only a couple of hundred hours of practice, SF would be classified as a beginner at most skills. However, in his field of expertise, memory for random digits, SF compares favorably with the best-known mnemonists, such as Luria's (1968) S and Hunt and Love's (1972) VP. For example, we gave SF the task of recalling a matrix of 50 digits because data on this task are also published for both S and VP. After about 6 months of practice, SF's study times and recall times were at least as good as those of the life-time memory experts, and after a year and a half of practice, SF's performance was substantially better than the experts' performance. There is one important difference between SF on the one hand and S and VP on the other, in that SF's skill is limited to digits. For other types of stimuli, like random consonants, SF's memory span is normal, about 7 symbols.

The Mnemonic System

So far, we have simply reported the magnitude of SF's memory performance. We have seen an average subject who, with the help of a couple of hundred hours of practice, turned himself into a memory expert with the largest digit span ever recorded in the literature. How did he do it? The answer comes from an analysis of SF's verbal reports, various experimental tests we have conducted

on SF, and a computer simulation model that we have constructed. In this section, we describe the most essential mechanism underlying SF's skill--his mnemonic system.

The Verbal Protocols

SF started out just like virtually all the naive subjects we have ever run. He simply attempted to code everything into a phonemic code, and then he rehearsed this code until recall. Like most subjects, SF noticed a few patterns (such as ascending sequences), and he utilized a rudimentary grouping strategy (to be described later), but for the most part, SF relied on the rehearsal buffer as the major mechanism for short-term retention.

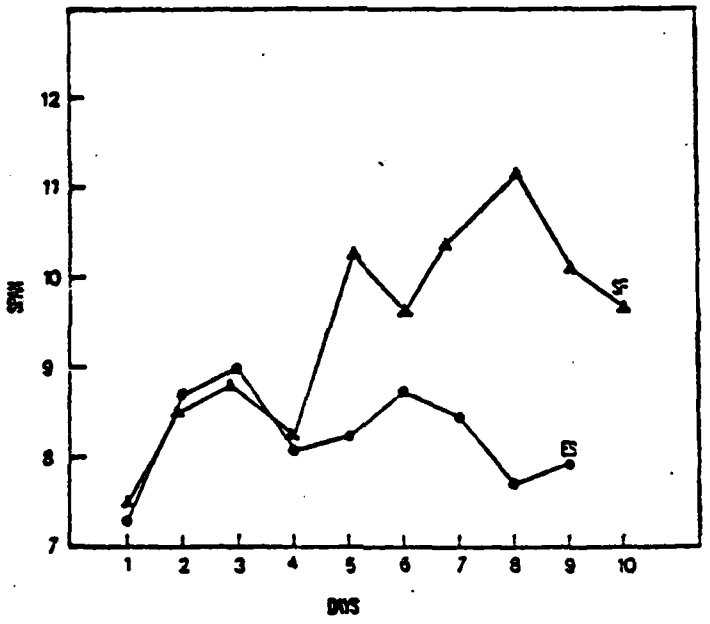


Figure 3: A comparison of SF with a subject who never developed a mnemonic. The jump in SF's performance from Day 4 to Day 5 is accompanied by the first report of mnemonic encodings on Day 5.

Figure 3 compares SF with an unmotivated subject who quit after a couple of weeks. In contrast to SF, this subject never developed a mnemonic system and consequently was never able to improve very much. Notice that the performance of both subjects is very comparable through the first four days of the experiment. In fact, on Day 4, SF gave us a fairly lengthy verbal report about how he had reached his limit and no further improvement was possible.

And then, on Day 5, something very interesting happened. There was a large improvement in SF's digit span (a jump of 4 standard deviations from the day before), and, for the first time, SF began to

report the use of a mnemonic aid. From this point on, SF showed a steady increase in his digit span as he developed his mnemonic system and the accompanying control structure.

To give an idea of the kind of protocols we obtained from SF, Table 1 shows a protocol from a fairly early session (Day 39). This is a trial on which SF achieved a new high of 22 digits. On this trial, the experimenter read the digits at a 1-sec rate, and there was a 20-sec delay followed by recall, and then the experimenter requested a retrospective report. (The experimenter's comments are indicated by parentheses in the protocol.)

The most interesting thing to notice about the protocol is the mnemonic: SF is coding the digits as running times. It turned out that SF is a very good long-distance runner,[3] and he uses his knowledge of various times for events as a mnemonic aid.

From an analysis of SF's protocols, we were able to determine the coding rules used by SF to categorize groups of digits as running times. Table 2 shows the early development of SF's mnemonic coding scheme. This table shows, for each coding rule, the session number when it first appeared in the verbal protocols. The significant part of this coding scheme is the invention of the running-time mnemonic on Day 5, and its extension to 4-digit running times on Day 20 and decimal times on Day 26. Additions to this basic code didn't occur until much later (around Day 60), when SF invented additional mnemonic rules to handle digit groups that cannot be converted to running times. For example, 896 can't be a time because the second digit is too big, and under these circumstances, SF codes this group as "eighty- nine point six years old, very old man." To take another example, 1943 is coded as "near the end of World War II." These extra rules include AGE + DECIMAL for 3-digit groups and, for 4-digit groups, YEARS, AGE + AGE, or DIGIT + TIME. By the end of 6 months--100 sessions--SF had essentially completed his mnemonic scheme and he was coding 95% of the digit sequences, of which the majority were running times (65%), a substantial minority were ages (25%), and the rest of the coded sequences were years or numerical patterns (5%). After 200 hours of practice, SF was coding virtually everything.

The next table (Table 3) shows the systematic nature of SF's running-time mnemonic system in semantic memory. After each session, SF is asked to recall as many groups of digits as he can from that session. (This table is a transcription of the recall on Day 39.)[4] First, notice that SF has 11 major categories of running times, ranging from half-mile times to marathon times, plus a few nontimes at the end. From SF's protocols we know that he also has many subcategories within each category. For example, 3492 is coded as "Three forty-nine point two, near-world-record mile time." And there are many other types of mile times, such as "very poor mile time," "average mile time for the marathon," "average work-out mile time," and so on. Another thing to notice is the very systematic nature of SF's recall (left-to-right and top-to-bottom in the table). He begins with the shortest race and

TABLE 1

Protocol of SF reaching a new high of 32 digits
Session #39
July 11, 1978

[Digits Presented 1 per sec.] (4 1 3 1 7 7 8 4 0 6 0 3 4 9 4 8 7 0 9 4 6 2)

[20 second delay] ["nine-four-six-two" rehearsed about 15 times rapidly in a whisper]

[Signal to recall] Time (sec)

0 All right. All right. All right. All right. All right. All right. All Right.

5 Oh geez!

Ok. Ok. Ok.

10 All right now...now this one is ...um

it it...uh...oh.

15 ok.ok.ok.ok.

20 Ok!

Four thirteen point one

25 Seventy-seven eighty-four

Oh six oh three

30 Four nine four, eight seven oh,

35 Nine forty-six

Oh no!

Nine forty-six point...

40 Ok!

Nine forty-six point...

45 two!

50 (Can I please have it again once more please?)

Oh no. Oh no. Oh no. Oh no.

55 What?

(Can you take it once more, please?)

Oh....Oh.

60 All right. All right. All right.

1:05 It's four thirteen point one nine.

Then seventy-seven eighty-four.

1:10 Then oh six oh three.

Then four nine four.

Eight seven oh.

1:15 Nine...forty-six.

What'd you run it?

1:20 I ran it in nine forty-six point...two!

1:25 (Thank you. Please tell me everything you can remember.)

All right. All right. All right. All right. All right.

1:30 Starting from the beginning.

I made the four thirteen point one a mile time.

I just remembered the seventy-seven eighty-four.

1:35 Ok? Ok? Right. Seventy-seven eighty-four.

1:40 Then...then...then I...

(Any pattern?)

What?

(Any pattern?)

No. No. Nothing. Just like seventy-seven eighty-four.

1:45 Oh. Then I made the oh six oh three, I made that a mile time.

1:50 Then I remembered the four nine four

and the eight seven oh.

I just had to remember these.

Then, I remembered the nine forty-six point...two!

1:55 It's definitely point two, two-mile.

2:00 I said, so I said to myself "what did you run it in?"

I ran it in nine forty-six point two. Nine forty-six point two. Right.

2:05

2:10 (Uh...Could you uh...tell me about the last three groups of digits. I'm, I'm not sure that I...)

Um. It was, it was four nine four. Nothing. Eight seven oh. Nothing.

2:15 Then nine forty-six point two two-mile.

2:20 (Did you rehearse anything?)

Yes. Nine forty-six point two

keeping in mind the first two sets of three.

2:25 (Uh. Were you unsure of any of the digits?)

2:30 (Sigh) No...No. No.

2:35

systematically works his way up, category by category, with very few reversals. Within each category, he uses the same procedure of systematically recalling from the shortest to the longest subcategory, with pauses separating subcategories. At the lowest level within each subcategory, SF still generally recalls times in an orderly way from smallest to largest times. On rare occasions, a running time will trigger episodic recall of other times from the same trial, such as a pair of mile times occurring together. In general, however, SF is unable to recall order information from the session.

We characterize SF's after-session recall as directed search through his semantic memory categories at the highest levels and at the lowest level, we characterize the mechanism as a generate-and-test procedure, in which the number line is used as a retrieval device. We think this is an important property of skilled memory--the ability to search systematically and efficiently through the knowledge base.

TABLE 2

MAJOR CODING STRUCTURES

	CODING STRUCTURE	EXAMPLE	FIRST REPORTED (SESSION NO.)
3-DIGIT GROUPS	TIME	8:05	5
	AGE + DECIMAL	49.7	70
4-DIGIT GROUPS	TIME (3,4,5,10 MI)	13:20	20
	TIME + DECIMAL	4:10.6	26
	DIGIT + TIME	9-7:05	60
	YEAR	1955	64
	AGE + AGE	46 76	64

TABLE 3

CATEGORY	After-Session Recall: Day 39									
1/2 mile	233.6	(257)								
3/4 mile	(312)									
1 mile	343	354	413.1	418	432.1	507	(516)	529	601	641
2 miles	723	826	820	946.2	935					
3 miles	---									
4 miles	2252									
5 miles	2966									
10 km	3215									
15 km	—									
10 miles	5614	5649	6610							
Marathon	---									
Misc.	000	494	870	(057)	7784					

A quantitative analysis of SF's after-session report shows a steady increase in the amount recalled (Figure 4), until at the present time, virtually everything from an hour's session is in retrievable long-term memory. With about four months of practice, SF was able to recall about 65% of the material in a session. There were also some slight variations in recall, depending on the learning conditions. For example, SF was able to recall about 10% more from the second half of the session than from the first half, he was able to recall about 20% more from those trials on which he gave a retrospective verbal report, and there are also some slight variations in serial position. After two years of practice,

however, these effects have disappeared, as virtually everything from a session can be recalled.[5]

There are several other lines of evidence that show that these codes are stored in long-term memory. In one experiment (after about four months of practice), we tested SF's memory after the session with a recognition test because recognition is a much more sensitive measure of retention than recall. On that occasion, SF not only recognized perfectly 3- and 4-digit sequences from the same day, he also showed substantial recognition of sequences from the same week.[6] In another experiment (after about 4 months of practice), after an hour's session, we presented SF with 3-and 4-digit probes, but with the last digit missing, and he had to name the missing digit. SF was able to recall the last digit 67% of the time after 4 months of practice; after 250 hours of practice, SF was virtually perfect at this task.

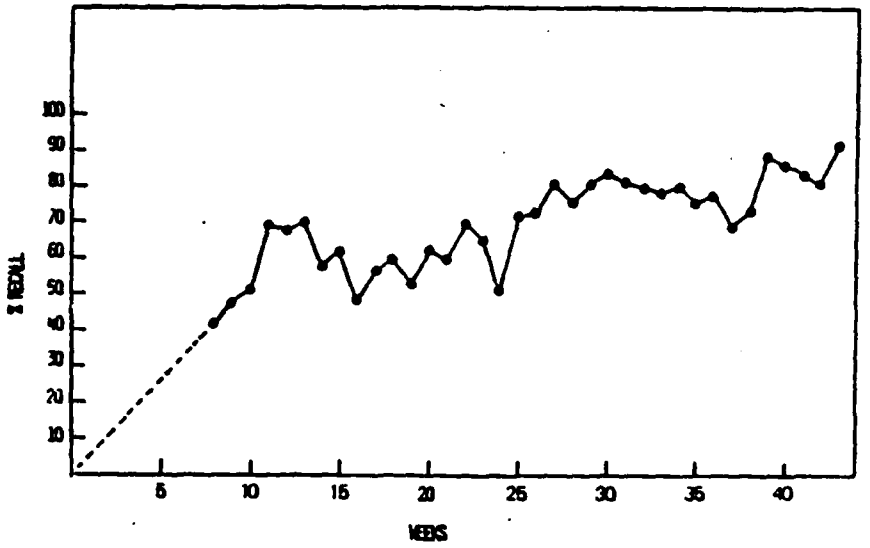


Figure 4: SF's average after-session percent recall in 5-day blocks. We first started taking systematic measurements on this task around the 8th week. The dotted line represents an extrapolation back to when SF was a normal subject; normal subjects remember virtually nothing from an hour's session.

Finally, we report an interesting variation on the after-session recall task, in which we asked for an extended recall (Williams, 1976). We first asked SF for an extended recall on Day 125. At this time, SF was normally recalling about 80% of the material from each session, and he typically took no more than 5 minutes for his after-session recall. In this experiment, after SF had recalled about 80% of the digits from a session, we asked him to try harder and to keep trying until he could recall all the digit sequences. After about an hour of extended recall, SF had recalled all but one of the missing digit sequences. We have asked for extended recall several times since then, and each time, SF has

shown virtually perfect recall. Also, as SF became more practiced, extended recall became progressively easier until, after 250 hours of practice, SF recalls over 90% in his normal after-session recall.

Our analysis so far has shown that SF has invented a mnemonic system that relies on already-existing long-term memory knowledge of running times. We need, however, to establish that this knowledge system is *necessary* for SF's skilled memory performance. That is, would SF's memory performance return to normal without the use of his mnemonic system? We further need to specify the mnemonic system in more precise theoretical terms, and further, we need to subject our theory to more rigorous experimental verification.

The Theory and The Experiments

When we first started the study, we intended to run SF for a couple of weeks to see if it was possible to increase one's memory span with practice, and if so, could we discover how it was done by analyzing the verbal protocols. To our great surprise, SF revealed a steadily increasing skill in the memory span task, and his verbal protocols were very rich and revealing about his mnemonic system. It took us about 40 sessions to analyze the protocols and develop a theoretical account of what SF was doing. At this point, we were ready to test our theory. From the protocols, we were able to simulate SF's mnemonic coding scheme with a few simple rules in the form of a production system, and our simulation was able to predict how SF would code digit sequences between 85% and 95% of the time. In fact, we have simulated SF's mnemonic coding scheme at several levels of practice, and we have discovered that the major advances in his mnemonic system occurred very early--within the first 100 hours of practice. Although there are occasional minor adjustments, the mnemonic system itself was essentially completed within a few months.

Since our theoretical analysis is based mainly on the verbal protocols, this evidence can be characterized as descriptive. A stronger test of our theory requires more direct experimental control. To this end, our first two experiments (Days 42 and 47) were designed to test our theory of the mnemonic system. We reasoned that if the mnemonic system were critical, then SF should perform poorly when the digit sequences were uncodable (Exp. I) and, conversely, if all the digit sequences could be coded as running times, SF's performance should improve (Exp. II).

In our first experiment, on the basis of our analysis of the verbal protocols, we constructed digit sequences that could not be coded as running times (this was before SF started to use ages to supplement his running times). We also eliminated other easy sequences, such as patterns of ascending or descending sequences, repetitions, triplets of odd or even digits, and the like.

When SF was faced with these uncodable sequences, his performance dropped back almost to his

beginning level. Figure 5 compares the experimental session to the weekly averages preceding the experiment. The bottom curve (circles) is the initial ascending sequence until an error occurs,[7] and the top curve (triangles) is the average of the up-and-down procedure. The bottom curve shows an almost complete return to baseline, and the top curve shows a 20% drop from SF's normal performance.

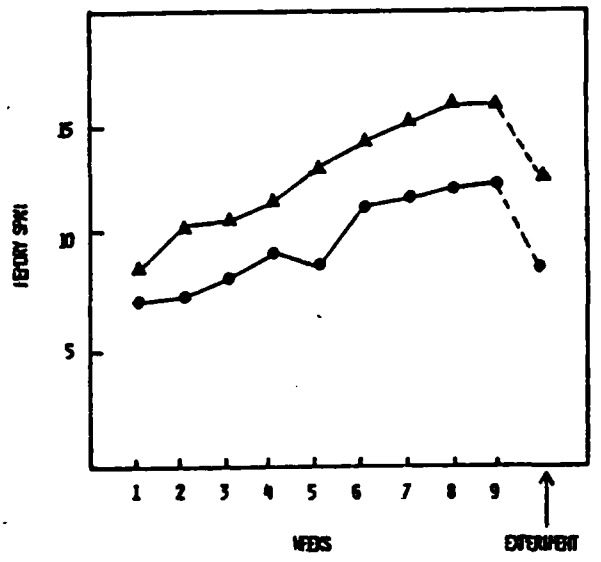


Figure 5: SF's average digit span for Experiment I versus the 8 preceding weeks. The top curve [triangles] shows SF's average digit-span with the up-and-down method. The lower curve [circles] shows SF's digit-span on the initial ascending sequence. Each session was started with an ascending sequence, starting with 5 digits, until SF made an error [circles]; the rest of the session was conducted with the more reliable up-and-down procedure [triangles].

Table 4 shows a more detailed analysis of performance on the experimental day (Friday) compared with the four preceding days. The first two columns are the digit span and the percentage of groups that were coded as running times. The means and standard deviations are shown at the bottom for the four prior days. Both the digit span and the number of mnemonic codes show substantial drops on the experimental day. The last three columns are the number of times, nontimes, and total digits recalled in the after-session report, and again, there are substantial drops on the experimental day.

TABLE 4

EXPERIMENT I - NON-TIME SEQUENCES

	DIGIT SPAN	% TIMES IN RETROSPECTIVE REPORTS	AFTER-SESSION REPORT: NUMBER OF TIMES	AFTER-SESSION REPORT: NUMBER OF NON-TIMES	AFTER-SESSION REPORT: NUMBER OF DIGITS
• MONDAY	13.1	65	26	7	110
TUESDAY	18.8	62	24	5	98
WEDNESDAY	16.2	70	31	4	123
THURSDAY	15.6	75	43	3	165
	15.9	68	31	4.75	124
	2.34	5.72	8.52	1.71	29.2
FRIDAY	12.7	41	12	10	79
		18 REGULAR	23 CONVERTED		

It is worth noting at this point that SF was still able to use his mnemonic system in a clever way to avoid a complete regression in performance. SF was able to change his strategy in two ways. First, he was able to augment his coding scheme by converting nontimes to times. For example, the 3-digit group 564 isn't a running time because the second digit exceeds 5. However, SF converted this group in the following way: 564-->6:04 mile time, and he remembered the additional fact that it is a converted time.[8] The second strategy change occured about half way through the session when SF hit on the idea of changing his grouping structure. For example, we expected SF to code 13 digits as 3-3-3-4, but SF very cleverly learned to group 13 as 1-3-3-3-3, which allowed him to find some running times.

In our second experiment, conducted a few days later, we did just the opposite. We reasoned that if the running time mnemonic is important, then SF's performance should improve if we gave him all running times. We therefore constructed sequences of digits that, according to our theory, should all be coded as running times.

Table 5 compares the results of this experiment with the four preceding days of the week. With these good sequences, SF's memory span performance jumped by 27% (from 15.3 to 19.5), all his codes were running times (as expected), and there was a substantial jump in his after-session recall. In short, the results of this experiment support our theory of the importance of SF's mnemonic coding system.

TABLE 5

EXPERIMENT II - GOOD SEQUENCES

			AFTER-SESSION REPORT		
	DIGIT SPAN	% TIMES IN RETROSPECTIVE REPORTS	NUMBER OF TIMES	NUMBER OF NON-TIMES	NUMBER OF DIGITS
MONDAY	15.1	91.4	32	3	117
TUESDAY	14.3	93.3	42	3	147
WEDNESDAY	15.6	75.0	42	14	211
THURSDAY	16.3	87.2	34	5	145
	15.3	86.7	37.5	6.25	155
	.84	8.22	5.26	5.25	39.8
FRIDAY	19.5	100.0	54	—	192

In a third experiment, we were interested in establishing the reliability of SF's mnemonic coding rules. We presented SF with the same sequence on Day 103 that he had been presented with a month earlier (Day 85), and we compared the verbal protocols on these two days. SF used the same mnemonic code on 81% of the sequences (38 of 47). In addition, 3 of the 9 discrepancies could be traced to changes in the mnemonic coding rules between Day 85 and Day 103, and 4 discrepancies were due to coding failures (i.e., no code) on one day or the other. In other words, in only two instances (4%) was there an unexplained discrepancy in the mnemonic rule system. Thus, there is good agreement from one occasion to the next in SF's mnemonic codes.

To summarize our analysis thus far, we have established that SF's performance is based on a mnemonic coding scheme in semantic memory, and we have modeled this coding scheme and

experimentally verified it to our satisfaction. We next address the question of whether or not these semantic codes are stored in short-term memory. That is, do these semantic codes have to be held in short-term memory in order to be recalled?

The Rehearsal Suppression Experiments

Exactly what is the role of short-term memory in SF's memory span performance? The standard procedure for studying short-term memory in a given task is to prevent rehearsal and see how task performance deteriorates; any loss in performance is attributed to the absence of information in short-term memory. We initiated a series of rehearsal-suppression experiments to explore SF's use of short-term memory, and the results are summarized in Table 6. This table shows the experimental manipulation and the day of the experiment on the left, and on the right, the current memory span level (the weekly average preceding the experiment) is compared with the experimental result.

TABLE 6

REHEARSAL SUPPRESSION EXPERIMENTS

Recite Alphabet	(Day 62)	20.6 → 16.3
Visual Suppression - Copy	(Day 73)	25.7 → 26.5
Visual Suppression - Rotate	(Day 73)	25.7 → 24.5
Hya - Hya	(Day 75)	25.7 → 23.9
Shadowing	(Day 99)	31.6 → 20.5

In the first experiment, immediately after the list was presented, SF recited the alphabet repeatedly as quickly as he could for 20 sec, and then he recalled the list. The drop in performance corresponds almost exclusively to loss of the last group of digits at the end. This result makes perfect sense because, according to SF's verbal reports, he normally holds this last group in a rehearsal buffer. Again, about half way through the session, SF changed his grouping strategy to produce a smaller rehearsal group at the end, and this strategy change reduced the interference considerably.

The next two experiments were visual suppression experiments which we conducted because we thought that SF might be using some visual-spatial coding.[9] The interfering tasks in these two experiments were copying geometric shapes in the first case, and rotate-and-copy in the second case. In this latter task, SF had to mentally rotate a geometric shape ninety degrees and then draw the rotated shape. These tasks had been previously designed by Charness (1976) to interfere with short-term visual retention. In these experiments, immediately after a list of digits was presented, SF was instructed to copy or rotate-and-copy a list of geometric shapes as quickly as he could for 20 sec before recalling the list of digits. The results were straightforward: These visual suppression procedures had no effect at all on SF's performance.

The last two experiments were an attempt to occupy short-term memory during presentation of the digits because we believe that the phonemic buffer is used during the coding process. That is, there must be some temporary storage of digits while a group is formed and semantic memory is searched for a mnemonic code, and we believe that SF initially codes digits phonemically for just such a purpose.[10] In the first experiment, we introduced a concurrent chanting task ("Hya-Hya") that has been used by Baddeley and his associates to suppress short-term memory (cf. Baddeley & Hitch, 1974). In this task, SF was required to say "Hya" after each digit during presentation. To our great surprise, SF was able to say "Hya" between presentation of the digits without any trouble at all. In his verbal reports, SF said that he could organize this verbal chanting independently and somehow "hear" it in a different spatial location than where he was listening to and coding the incoming digits.

In the final rehearsal-suppression experiment, we imposed an attention-demanding shadowing task at the end of each group. From SF's protocols (and our model), we could predict how SF would group the digits, and the shadowing task was inserted in the 1-sec intervals between the last digit of one group and the first digit of the next group. One experimenter read digits to SF at a 1-sec rate and the other experimenter read a letter of the alphabet (randomly selected) to SF at the end of each group. SF's task was to listen to the digits, repeat back each letter as quickly as possible, and recall the digits at the end.

This experiment produced a very substantial decrement in performance (35%). It is interesting to compare this task with the concurrent chanting task which requires between three and four times as much verbalization, yet the concurrent chanting task did not produce any measurable interference. We interpret these results as follows. We think that concurrent chanting does not disrupt the phonemic buffer (as SF's introspections suggest). This is consistent with Levy's (1975) experiments on comprehension in reading and listening in which she found that concurrent chanting disrupted reading but not listening. She suggested that concurrent chanting does not interfere with the phonemic buffer, but it does inhibit generation of phonemic codes.

We suggest that in the shadowing task, unlike the concurrent chanting task, SF was forced to retrieve a spoken letter from the phonemic buffer immediately after the last digit in each group was presented. This phonemic buffer operation eliminated SF's normal strategy of lagging behind the input and using the phonemic buffer as a temporary storage for the incoming group while processing semantically the previous group. In the following, we present evidence of SF's normal lagging strategy.

We conducted this experiment at about the same time as the rehearsal suppression experiments. Although this experiment does not involve rehearsal suppression, it has direct bearing on the role of short-term memory in SF's performance. In this task, we interrupted SF at some random point during a trial and asked for an immediate verbal protocol. Among other things, we were interested in how far behind the spoken sequence SF's coding lagged. That is, how many uncoded digits are kept in short-term memory; what is the running short-term memory load? Basically, we found that SF was actively coding the previous group of 3 or 4 digits while the digits for the current group were still coming in, a lag of about 4 to 7 sec in time. The contents of short-term memory were: (1) the most recent one, two or three ungrouped digits in a phonemic code, (2) the previous group of three or four digits (it is not clear how these grouped items are coded), and (3) all the semantic information associated with the active mnemonic coding of the previous group.

From this experiment, and the rehearsal-suppression experiments, we draw the conclusion that at any moment in time, the contents of short-term memory represent a very narrow window of the digit sequence. At recall, it appears that nothing except the rehearsal group is retrieved directly from short-term memory, and there is some evidence that with further practice, even the rehearsal group was no longer stored exclusively in short-term memory.[11]

This concludes our experimental analysis of the role of short-term memory in SF's performance. Before moving on to a consideration of the theoretical mechanisms underlying SF's mnemonics, we briefly consider whether or not SF has increased his short-term memory capacity.

Short-Term Memory Capacity

After more than 250 hours of practice, has SF increased his short-term memory capacity? There are several reasons for thinking not. First, SF's mnemonically coded groups were almost always 3 and 4 digits, and he never generated a mnemonic code greater than five digits. Second, SF's phonemically coded rehearsal group never exceeded 6 digits, and a rehearsal group of 6 digits was always segmented into two groups of 3 digits. Thus, SF never kept a group larger than 5 digits *unattended* (coded but not rehearsed) in short-term memory, and even when attended (rehearsed), SF still only kept 6 or fewer digits in a phonemic code. We later show that SF almost never was able to keep the *order* straight for more than 3 or 4 coded groups, and he thus resorted to a hierarchical

organization of groups (to be described later). After some initial difficulty in trying to keep the order straight for 5 groups, SF never allowed more than 4 groups to be clustered together. Third, after 3 months of practice on the digit span task, we tested SF's memory span for consonants, and he showed no transfer at all from the digit-span task and his consonant span was around 6. Finally, in the literature, expert mental calculators and other memory experts seem to group digits into units of this size. Rückle's numerical codes are 6-digit groups with a 3-3 substructure (Müller, 1911), and Aitkin's memory for digits is organized in 5-digit groups (Hunter, 1962). There does not seem to be a single exception to this generalization in the mental calculation literature (Mitchell, 1907). For normal subjects, it appears that an optimum group size is 3 or 4 digits (Wickelgren 1964).

These data suggest that the reliable working capacity of short-term memory is around 3 or 4 units, as Broadbent (1975) has recently argued. It is useful to distinguish the working capacity from the span. This latter term is defined as the size of the list that can be reported correctly 50% of the time. But the reliable capacity of short-term memory--the amount of material that is available almost all the time--is closer to three or four symbols. When we talk about skilled performance, this latter number is a more realistic estimate of the working capacity.

Meaning in Skilled Memory

At this point, we emphasize the first characteristic of skilled memory: *Experts use their knowledge structures in semantic memory to store information during skilled performance of some task.* The idea that mnemonic or other meaningful associations are necessary for skilled memory is consistent with the literature. The literature on memory performance of mental calculation experts suggests that these people invariably use their knowledge about mathematics to make extensive meaningful associations with numbers (Hunter, 1962, 1968; Mitchell, 1907; Müller, 1911). The literature on chess experts (Chase & Simon, 1973; de Groot, 1966) as well as a variety of other types of knowledge-based experts (Chase & Chi, 1980), suggests that meaningful patterns in long-term memory underlie superior memory. In short, expert memory performance in various semantically rich domains seems to involve coding and organized access to knowledge structures in long-term memory.

In the present study, we have presented a great deal of evidence that, in the memory span task, SF invented a mnemonic system to take advantage of his knowledge of running times. However, we have not considered some of the broader issues, such as, what is a mnemonic and precisely how does it work? What accounts for the precision of mnemonic associations? How, for example, is it possible to recover the exact digit sequence 3492 from an abstract retrieval cue like "near world-record mile-time?"

We should make it clear that a comprehensive coverage of these general issues is beyond the scope of this paper. However, we do have some ideas about how mnemonics and other meaningful

associations work, particularly in the context of skilled memory, and it is useful at this point to explore these ideas.

In general, a mnemonic is some mechanism for associating unknown material with something familiar; the advantage is that it relieves the burden on short-term memory because recall can be achieved via a single association with an already-existing code in long-term memory. To understand *how* mnemonic associations work, however, requires an answer to the more general question of how meaningful associations work, and there is no definitive answer to that question in the literature, although the literature is filled with good ideas (see Bower, 1972, for a good review).

Early theoretical accounts tended to emphasize the encoding process, and most attention was focused on the power of contexts and interactive codes. For example, the most important principle to follow when using visual imagery mnemonics is to make the images *interactive*. If you want to remember COW and BALL, it is important to imagine them interacting in some way, viz., "The cow kicked the ball." When COW is presented at recall, it serves as a retrieval cue for the context, and BALL is derived from the context.

This idea is closest to the theoretical explanation we favor, namely that items to be remembered must be embedded within a hierarchical knowledge structure in semantic memory. To take another example, the three digits 325 are much easier to remember if they are interpreted as "Our meeting time this afternoon." Most people could confidently commit these digits to long-term memory without writing them down (unless there are competing times) and then have little trouble recalling them, given the retrieval cue "What time were we meeting this afternoon?"

Another way to think about this example is that the concept of a meeting time exists as a set of procedures in semantic memory for activating various semantic features that interpret this time. These procedures are used to build a semantic structure that is bound to the memory trace. In Figure 6, we have depicted the meeting-time mnemonic in the form of a link-node structure. There are two parts to the structure: the time of day and the time during the hour. At encoding, it is assumed that something like a mid-afternoon feature is activated. It is assumed that the feature only responds to a small range of hours (say 2,3, or 4), and the stimulus trace "three" activates this feature and the stimulus trace is then bound to the MID-AFTERNOON node. Further, the stimulus trace for minutes is assumed to activate the nearest reference point feature (say HOUR, QUARTER-HOUR, HALF-HOUR, THREE-QUARTERS HOUR), whether the time is BEFORE or AFTER the reference point, and further, since meeting times are often stated in 5- or 10-minute units, it is assumed that when a meeting time falls on one of these units, a further semantic feature is activated. In this case these units are sufficient to uniquely specify the meeting time to the exact minute.

This example captures what we believe is the essential characteristic of meaningful associations:

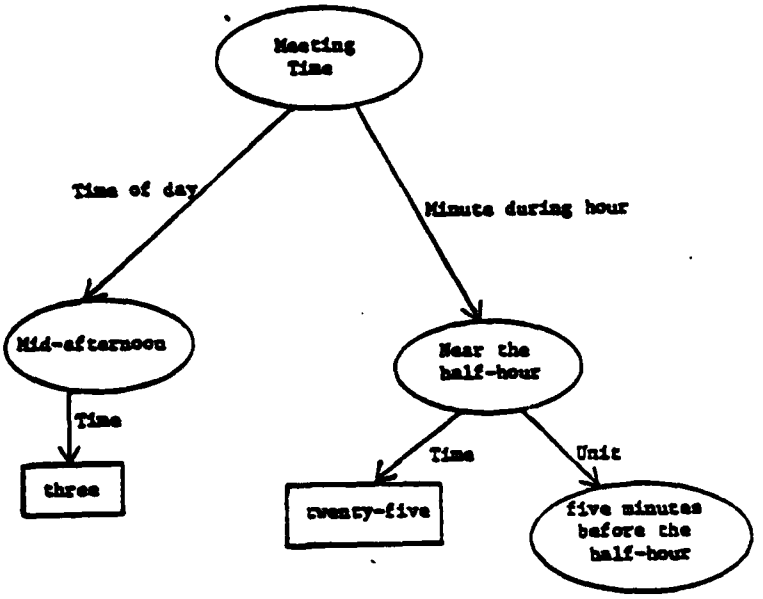


Figure 6: A link node structural representation of a mnemonic encoding of a meeting time.

The stimulus trace is bound to a hierarchical semantic structure. The meaningful association or mnemonic provides a retrieval cue to the semantic structure, and once the semantic structure is activated, the trace is retrieved through the structure. Without such a structure, how is recall to be achieved? Unless the items are in short-term memory, about the only retrieval cue one can use is "What numbers have I heard recently?", and this retrieval cue is not very specific, nor does it help to specify the order of the numbers in the unlikely event that a retrieval does occur.

Why are some mnemonics better than others? Why is "The cow kicked the ball" easier to remember than "Truth is good?" Besides the interactive principle, the next important principle about mnemonics is that they should be *concrete* (Paivio, 1971). Various theoretical explanations of this fact have emphasized the distinctiveness, uniqueness, redundancy, or elaboration of memory traces (cf. Anderson & Reder, 1979). We illustrate this principle with a link-node structure representation of "The cow kicked the ball." It is assumed that when people generate a mental image of a cow kicking a ball (or comprehend the sentence), a set of procedures in semantic memory is activated which builds a hierarchical link-node structure something like the one depicted in Figure 7. The traces of COW and BALL are bound to the central node KICKING in this structure by *agent* and *object* links.

Notice how much extra information is needed in this structure to fully specify the concept. Compared to this structure, the semantic structure for "Truth is good" is very impoverished, with

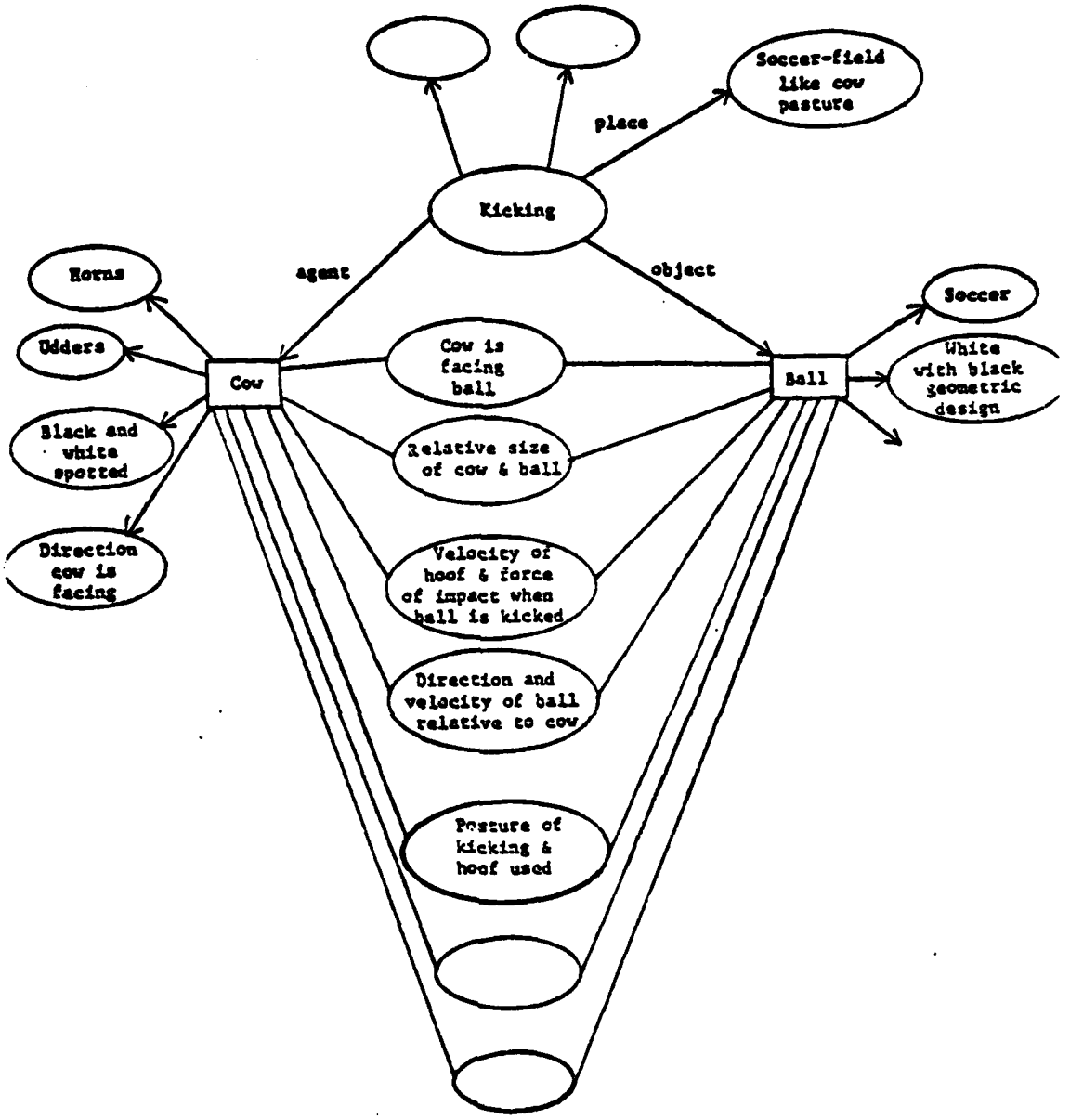


Figure 7: A schematic link node representation of a mnemonic encoding of "A cow kicking a ball." The central node in this structure is the action node [KICKING], connecting COW and BALL by *agent* and *object* links, respectively.

nothing more than a *subject-predicate* relation, and perhaps a single semantic feature of GOODNESS, to link the traces. We have divided the features in Figure 7 into two types: interactive and free. Interactive features are those needed to specify the relationship between COW and BALL in the context of kicking, and free features are those that aren't essential to the interaction.

There is a theoretical (and empirical) issue here as to why an elaborated memory trace is more memorable. If one believes that the memory trace in Figure 7 is more memorable because it is more distinct or unique (Bower, 1972) then the non-interactive features are important. However, if one believes that the elaborations serve as redundant retrieval links between the trace items (Anderson & Reder, 1979; Bower, 1972; Stein & Bransford, 1979), then only the interactive features are important. We agree with Anderson and Reder (1979) that it is the interactive features that are important.

We should point out that according to our theory, an elaborated memory trace is important but not essential. We deliberately choose the meeting-time and COW-BALL examples to demonstrate this point. Both these associations work as mnemonics. The COW-BALL example is a better mnemonic because of the elaborated interactive links, but the meeting-time mnemonic works because, according to our theory, the trace is bound to a semantic structure in long-term memory. It is the semantic structure that is essential.

How are meaningful associations retrieved in the particular context of paired-associate learning? Following a recent proposal by Norman and Bobrow (1979), we suggest that at the time of retrieval, the subject can rely on very much the same mechanism he used to generate the meaningful association. Norman and Bobrow (1979) labeled this the *constructability mechanism*. The skilled mnemonist has a set of well-practiced procedures for generating mental images, and given the retrieval cue (COW), he can use his procedural knowledge to retrieve the context (KICKING). The elaborated image provides many redundant retrieval cues to facilitate this retrieval. In our example, body parts, postures, and other interactive features serve to retrieve BALL from COW. We think that the ability to regenerate encoding features at the time of recall is a crucial characteristic of skilled memory.

SF's Mnemonic System

Now that we have introduced the appropriate theoretical context, we next take up the representation of SF's mnemonic system. It is traditional to describe memory in terms of the three logical phases: Encoding, Storage, and Retrieval. However, we postpone our discussion of retrieval until we have presented our analysis of SF's retrieval structure in the next section. In this section we outline our theory of SF's encoding and storage processes.

Basically we assume that SF has an elaborate mechanism for recognizing running times, and we have modeled this mechanism as a production system. It is easier, however, to illustrate the encoding operation as a discrimination net (Chase & Simon, 1973; Simon & Gilmartin, 1973), and we claim without proof that discrimination net and production system models of pattern recognition are isomorphic.

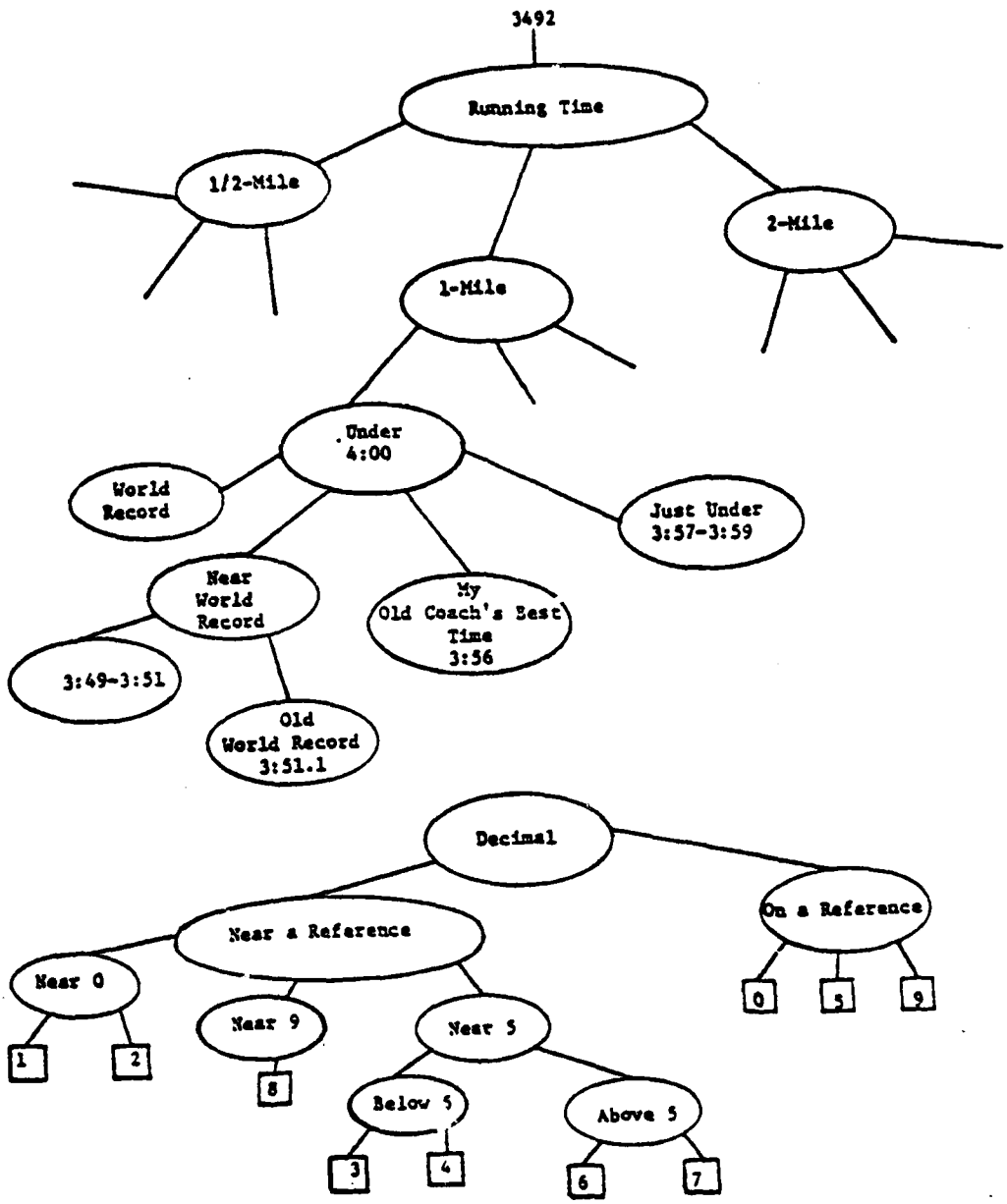


Figure 8: The relevant part of the discrimination net for accessing the mnemonic encoding for 3492. The net shown at the top contains procedures for encoding mile times under 4 minutes, and the separate net shown at the bottom contains procedures for encoding the decimal point.

In Figure 8, we illustrate how SF's semantic memory might encode 3492. Each node in the discrimination tree corresponds to a production rule in our production system. An interesting

property of this discrimination tree is that SF can take advantage of the sequential presentation by conducting tests higher in the tree on the first digits. In most cases, categorization can take place with the first two digits regardless of the following digits. In this case, when SF has heard 3 and 4, he can categorize this group as a RUNNING TIME, and it is either a 1-MILE TIME, a 3/4-MILE TIME, or a 10,000- meter time. After hearing the third digit, 9, he can then recognize this sequence as a NEAR-WORLD RECORD, and we assume that there is further discrimination around the reference node 351.1. At this node, there are only three potential 1-mile times to choose from (3:49, 3:50, and 3:51). We assume that the first three digits are sorted separately from the decimal digit, and we assume that some structural representation based on reference points is needed for the decimal digit because of some remarks to that effect in the verbal protocols. The power of SF's mnemonic system, as we have characterized it here, is in its ability to derive a unique code.

What happens when another group activates the same category? What happens, for example, when SF hears another near-world-record mile time? That category is no longer unique. We suggest that when a final node in the discrimination net is accessed, previously associated groups are *automatically* activated. In order to keep these similar groups distinct at recall, SF encodes the current group in relation to the old group. For example, 3492 is 1/10 sec *faster* than, say, 3493. By this discrimination process, SF generates a unique code even though the abstract code is not unique. In his verbal protocols, SF often reports that some digit groups are encoded in relationship to previous groups. Further, in his after-session recall, these similar groups are reported together without pauses between them.

At this point it is worth mentioning that many normal subjects use some rudimentary mnemonics in the digit-span task. These mnemonics are typically such things, as "ascending sequence," "odd digits down," "the first two digits sum to the third one," and so on. When normal subjects are able to recall anything at the end of a session, it is invariably these kinds of patterns.[12] Compared to these numerical relation codes, SF's codes are unique. Because these numerical codes are imprecise, they have the additional disadvantage that they are susceptible to interference. They may work once or twice, but with repeated use, they quickly become overworked (i.e. associated with too many digit sequences). In contrast, the probability of getting more than one "near world-record mile time" during a session is very small, and when this does happen, there is evidence that SF automatically differentiates them.

It is instructive at this point to consider numerical codes that do work. Müller (1911, 1913, 1917) studied extensively the skills of Rückle, a mathematics professor, who was skilled at mental calculation and could commit many numbers to memory at a very rapid rate.[13] Rückle had extensive knowledge of numerical properties and he used these properties (mostly factorizations) to code digits into 5- or 6-digit units. Müller reports the following four examples of Rückle's mnemonics (Müller,

1911, p.216):

```
 26169 ------------>  26 =  2 x 13; 169 = 13 x 13
451697 ------------> 451 = 11 x 41; 697 = 17 x 41
893047 ------------> 893 = 19 x 47; 047 = 47
286219 ------------> 219 =  3 x 73; log(73) = 1.86
```

Notice how unique these relations are. Hunter (1962) gives an almost identical picture of Professor Aitkin, the Edinburgh mathematics professor. In both these cases, and in many others in the literature, experts derive unique numerical relations very quickly to serve as mnemonic aids in their mental calculation skill. We point to uniqueness as the critical factor.

Having described the encoding process as a discrimination net, we next describe our *storage* assumptions. We assume that every time a production rule fires, a semantic feature is activated (i.e., stored in short-term memory). In this example, 3492 has activated semantic features corresponding to RUNNING TIME, 1-MILE TIME, NEAR WORLD RECORD, BELOW 3:50, and there are further structural features describing the decimal as NEAR ZERO. We assume that the trace 3492 (not the phonetic features, but the numerical features corresponding to their magnitude) is bound to a semantic structure like that depicted in Figure 9.

Another way to say this is that all these features are stored together in one chunk by virtue of the fact that they are all active in short-term memory and attended to together as a unit. That is, in our model, the binding process is a chunking operation in short-term memory. This chunk can then be recalled by a retrieval process with the structure depicted by Figure 9. This is another theoretical issue: whether mnemonics derive their advantage from storage or retrieval operations. We argue later that it is the interaction of storage and retrieval that is critical.

At this point we mention one experimental result that is particularly relevant for our model of the structure of these memory traces. In this experiment, after an hour's session, we presented SF with 3- and 4-digit probes from the session, but with one digit missing, and he had to name the missing digit. The latency data are shown in Figure 10 as a function of the location of the missing digit. The mean latency and the variance are both monotonically decreasing functions of the depth of the missing semantic features in the discrimination tree.

We interpret these results as evidence that SF uses an ordered set of rules to successively narrow down the search. As we showed in the discrimination net model, the mnemonic category is determined primarily on the basis of tests on the first two digits. However, for 4-digit groups, the third digit will sometimes be critical in determining the mnemonic category. For example, 5782 is coded as

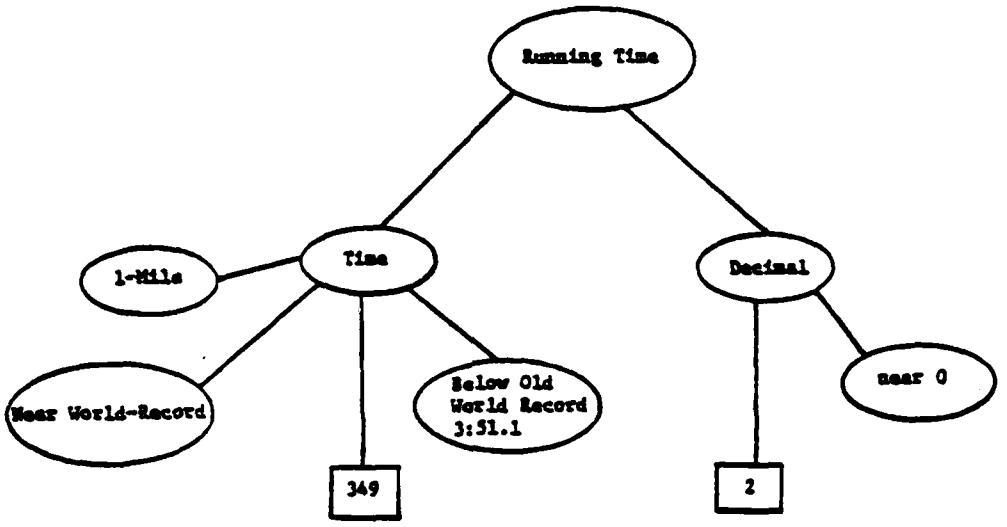


Figure 9: The memory trace for 3492 is bound to a running time semantic structure containing semantic features derived from the discrimination net shown in the previous figure.

two ages whereas 5732 is a 10-mile time. The latency differences in Figure 10 seem to reflect the amount of active search through SF's mnemonic categories.

The retrospective reports showed that the correct mnemonic category was retrieved before the missing digit could be accessed. These reports also showed systematic search through possible mnemonic categories when the correct category could not be determined from the available digits, which was the case for probes with one of the first two digits missing.

This completes our analysis of SF's mnemonic coding system. The next issue we address is how SF retrieves these mnemonic codes. It would be wrong to adopt a simple model in which SF holds a set of retrieval cues in short-term memory. To take a concrete example, we will claim that SF does not hold "near world-record mile time" (or the equivalent semantic feature) in short-term memory and then use this feature as a retrieval cue at recall. His memory system is much more sophisticated than this, as we hope to show.

There are two problems with this simple short-term memory retrieval model. First, the rehearsal suppression experiments have proven to our satisfaction that SF's coded digit groups are not in short-term memory. Our analysis of SF's running short-term memory load indicates that only the most recent one or two groups occupy short-term memory momentarily while being coded into long-term memory.

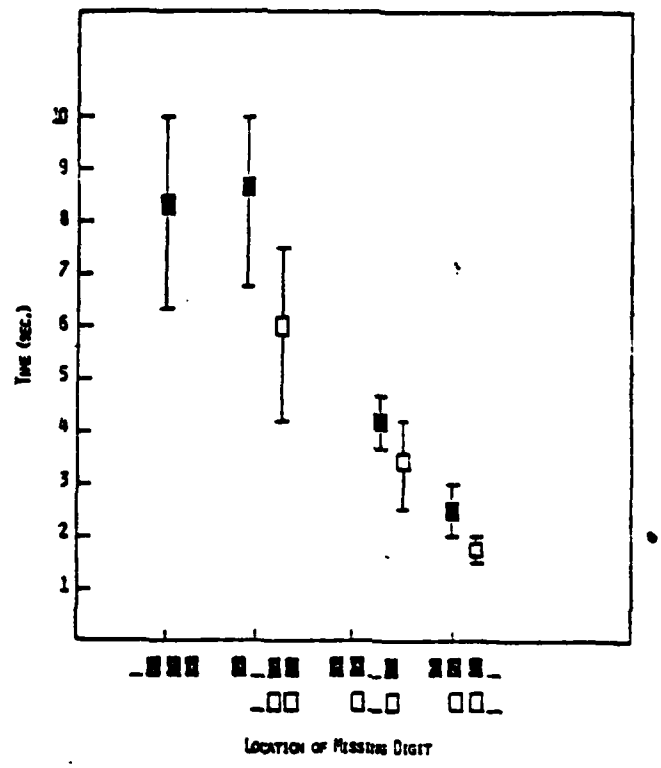


Figure 10: Time to retrieve a missing digit as a function of the location of the missing digit in the probe. [The location of the missing digit is indicated at the bottom of the figure. Open squares represent 3-digit probes, and darkened squares represent 4-digit probes.] Brackets in the figure represent ± 1 standard deviation, based on 10 or fewer observations.

The second problem with the simple short-term memory model of retrieval is that SF recalls too much. If we assume that SF's original memory span for symbols is around 7, and he learns to recode single digits into groups of 3 or 4 digits, then his memory span should be around 7 groups, or a maximum of 28 digits. In fact, since there is additional memory overhead associated with groups, the real memory span limit is around 3 or 4 groups, or 16 digits. But SF's memory span performance has increased steadily to over 80 digits (22 groups) and there is no sign of a limit. There must be some other mechanism besides the mnemonic coding. In the next section, we describe SF's retrieval structure.

The Retrieval Structure

A retrieval structure is a long-term memory structure that is used to make associations with material to be remembered. In effect, it serves the function of storing retrieval cues in addressable locations without having to use short-term memory. The retrieval structure can preserve the order of items to be remembered, although it is more versatile than that because it allows direct retrieval of any identifiable location.

The best example of a retrieval structure is the set of locations used in the method of loci. The way the method of loci works is to associate a list of concrete items with a predetermined set of locations (say the rooms in your house). An interactive mental image is generated successively for each item on the list with some known object in each corresponding location. Then, at recall, the object in each location is used as a retrieval cue to activate the mental image and recall the item to be remembered. The method of loci can be used for ordered recall, for reverse recall, for recall of the n^{th} item, or for recall of any specified set of locations. All that is necessary is to know the locations of the items to be recalled. We assume that the recall mechanism is activation of the interactive links (illustrated earlier for the COW-BALL example), and that the same principle operates for any mnemonic system, such as the peg-word method and the chaining method.

The Verbal Protocols

Most of the details of SF's retrieval structure are revealed in his verbal protocols; Figure 11 illustrates the development of the retrieval structure. In the beginning, like most people, SF simply tried to hold everything in a phonemically coded rehearsal buffer (R). By the second day of practice, however, SF demonstrated the first rudimentary use of a retrieval structure. Instead of holding everything in a rehearsal buffer, he tried to separate one or two groups of three digits each from the rehearsal group, and recall these groups while rehearsing the last 4-6 digits. This rudimentary grouping strategy is also typical of normal subjects. The difference between SF and normal subjects is that SF invented a mnemonic (Day 5) and used the retrieval structure to store the mnemonic codes.

After SF invented his mnemonics, this grouping strategy worked well, and he gradually perfected it over the course of the first 30 sessions to the point where he could recall up to 18 digits by coding three groups of four digits each as running times and holding the last six digits in his rehearsal buffer. At this point, SF began to experience real difficulties in keeping the order straight for more than 3 or 4 running times. These difficulties are associated with the first plateau in his performance curve (Fig. 1, Blocks 8 and 9).

The next important advance came after SF introduced hierarchical organization (Day 32): he used two 4-digit groups followed by two 3-digit groups, and the rehearsal group. SF's performance

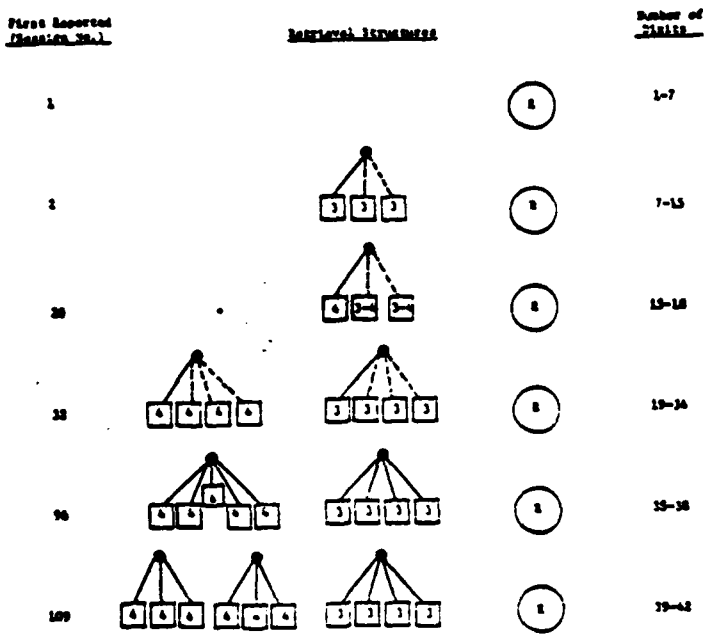


Figure 11: This graph illustrates the development of SF's retrieval organization. Shown on the left is the session number on which SF first reported the corresponding retrieval structure shown in the center. On the right is shown the range of digits for which the retrieval structure is designed. Each square corresponds to a digit-group with number of digits given inside of it. Groups connected by lines to the same node [filled circles] belong to the same supergroup. The circle with R corresponds to the rehearsal group, which consists of 4 to 6 digits depending on the sequence length.

improved rapidly as he perfected the use of this hierarchical retrieval structure, in parallel with improvements in his mnemonic system, until he began to experience the same difficulties as before. The second plateau in his performance curve (around Block 22, Fig. 1) is associated with difficulties in remembering the order of more than 4 groups of 4 digits followed by more than 4 groups of 3 digits. At this point (Day 96), SF tried unsuccessfully to tag the middle item of 5 groups as a "hitching post" or "peg." Then he finally introduced another level in the hierarchy by breaking these groups up into subgroups (Day 109), and his performance has improved rapidly ever since. SF is now using at least a 3-level hierarchy: (1) digits ----> groups, (2) groups ----> supergroups, and (3) supergroups ----> clusters of supergroups. That is, it takes at least three features to locate a group within the hierarchy.

SF is currently averaging around 80 digits, and his grouping structure for 80 digits is illustrated in Figure 12 for a typical trial. This figure represents our best guess about the hierarchical grouping structure, based on several sources of evidence.

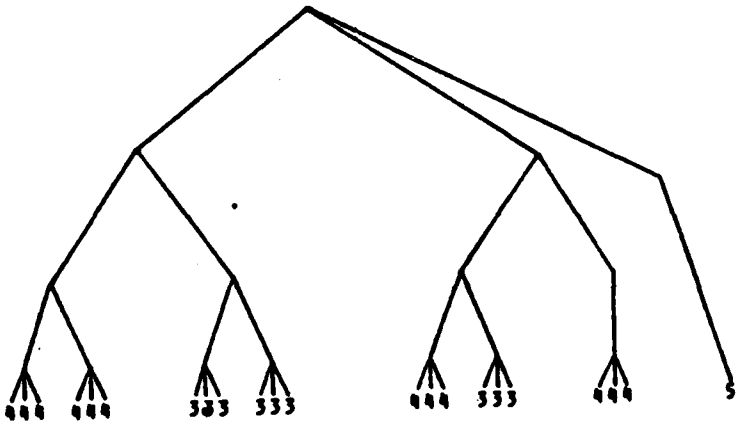


Figure 12: This figure shows our best hypothesis about the hierarchical organization of SF's retrieval structure for 80 digits.

The Experimental Evidence

Besides the verbal protocols, there is a great deal of additional evidence that SF uses hierarchical retrieval structures. Probably the most straightforward evidence comes from SF's speech patterns during recall, which almost invariably follow the same pattern. Digit groups are recalled rapidly at a normal rate of speech (about 3 digits per sec) with pauses between groups (about 2 sec between groups, on average, with longer pauses when he has difficulty remembering). At the end of a hierarchical group, however, there is a falling intonation, generally followed by a longer pause.

Pauses, intonation, and stress patterns are well-known indicators of linguistic structures (Halliday, 1967; Pike, 1945). We carried out one study specifically designed to determine how reliably the prosodic features could predict the grouping patterns. This study was carried out before SF invented his mnemonic (Day 3), because after the first few sessions, the grouping patterns were so obvious from the speech patterns. In this study, one experimenter coded only the group boundaries as indicated by the prosodic features in SF's recall without listening to the verbal protocol, and the other experimenter coded the grouping patterns reported by SF in his verbal protocols without listening to recall, and there was virtually perfect agreement.

In another study, after an hour's session we presented SF with 3-and 4-digit groups from that session and asked him to recall as much as he could about that group. SF invariably recalled the mnemonic code he had used, and he often recalled a great deal about the hierarchy, such as which supergroup and where the group was located within the supergroup (first, middle, last). After an hour, SF was almost never able to recall which group preceded or followed the presented group. On rare

occasions, SF was able to recall a preceding or following group, but this recall was invariably associated with some specific feature, such as two adjacent 1-mile times.

When SF recalls digits, he generally waits between 30 sec and 2 min after the digits have been presented before he begins to recall. In one study, we asked SF to indicate which digit groups he was thinking about during this interval. We found that SF rehearsed the digit sequence in reverse, supergroup by supergroup. That is, he rehearses the last supergroup, then the next-to-last supergroup, and so on. Within supergroups, he sometimes rehearses in reverse order, but generally he rehearses in forward order. The interesting thing about this experiment is that rehearsal is organized into supergroups.

We ran two experiments to determine if the group size was important for maintaining supergroups. We instructed SF to group all by 4's or all by 3's, and we found no decrement in performance, although SF did complain about having too much interference. We think this is an important result because it suggests that the retrieval structure is associated with abstract mnemonic codes and not with some specific size-dependent digit patterns.

We have run several memory search experiments that reveal, in a quantitative way, the nature of SF's retrieval operations. All these experiments were run between Day 98 and Day 116 on 30-digit lists with the following retrieval structure: 4-4-4-4-3-3-3-5. Three of these experiments were analogous to Sternberg's (1969) scanning-for-location experiment, and we asked SF to locate probes within the retrieval structure. The fourth experiment was to name the last digit in the group, given the first digits in the group as a probe. In all experiments, instead of asking for recall after presenting SF with a list of digits, SF was presented with a probe and we measured his latency. The three scanning-for-location experiments were as follows:

1. Given a 3-or 4-digit probe from the list, SF had to name the preceding or following group in the list,

2. Given a 3-, 4-, or 5-digit (the rehearsal group) probe from the list, SF had to indicate the location of the probe in the list by pointing to the location within a graphic representation of the retrieval structure, and

3. Given a graphic representation of the retrieval structure, the experimenter pointed to a location and SF had to name the corresponding group.

In two of these experiments, the latencies are very fast, and we claim that in these cases, SF uses the probe to directly access the memory trace in long-term memory. Given all but the last digit in a group, SF can very quickly name the last digit (1.8 sec), and given a probe, SF can quickly point to its location in the retrieval structure (1.2 sec). In both cases, we claim that SF activates the memory trace in long-term memory and, in the one case, retrieves the missing digit, and in the other case, retrieves the location of the probe in the retrieval structure.

In contrast to the fast times associated with direct access, search through the retrieval structure is relatively slow, and further, search times depend on the location of the probe within the retrieval structure. Given a location, it took SF almost 7 sec to name the associated group, and he was considerably slower for groups in the middle of the retrieval structure. Further, when SF had to name the preceding or following group, it took him more than twice as long if the search crossed a hierarchical boundary (10.1 vs 4.4 sec).

Table 7 compares the latencies of these various experiments as a function of the serial position of the probe. The top two rows give the results of the two direct-access experiments and the bottom two rows give the results of the search experiments. The bottom row shows the average latencies within each supergroup and average latencies to cross the supergroup boundary. Notice that, compared to the search experiments, the direct-access latencies are fast and independent of the serial position within the retrieval structure.

TABLE 7

MEMORY SEARCH EXPERIMENTS

	GROUPING STRUCTURE							
EXPERIMENT	4	4	4	4	3	3	3	5
Name the last digit in the probe	1.6	1.5	1.7	1.8	2.3	2.2	1.7	2.1
Point to the location of the probe	1.2	1.4	2.0	1.2	1.0	.7	.9	
Name the group pointed to	5.0	9.3	8.9	11.7	8.1	5.1	4.3	2.9
Name the group preceding or following the probe		5.4			⟷ 10.1		3.3	

Up to this point, we have presented evidence that groups are accessed through the hierarchical retrieval structures rather than through direct associations between groups. We next present an essential piece of evidence that these retrieval structures are necessary for SF's memory performance.

Figure 13 compares SF's performance with that of two other subjects that we have run for an extended period of time. One subject (triangles) is also a long-distance runner, and we have explicitly trained him to use SF's system. After about 75 hours of practice, he is performing slightly above SF's performance curve,[14] and from all indications he is doing essentially the same thing as SF.

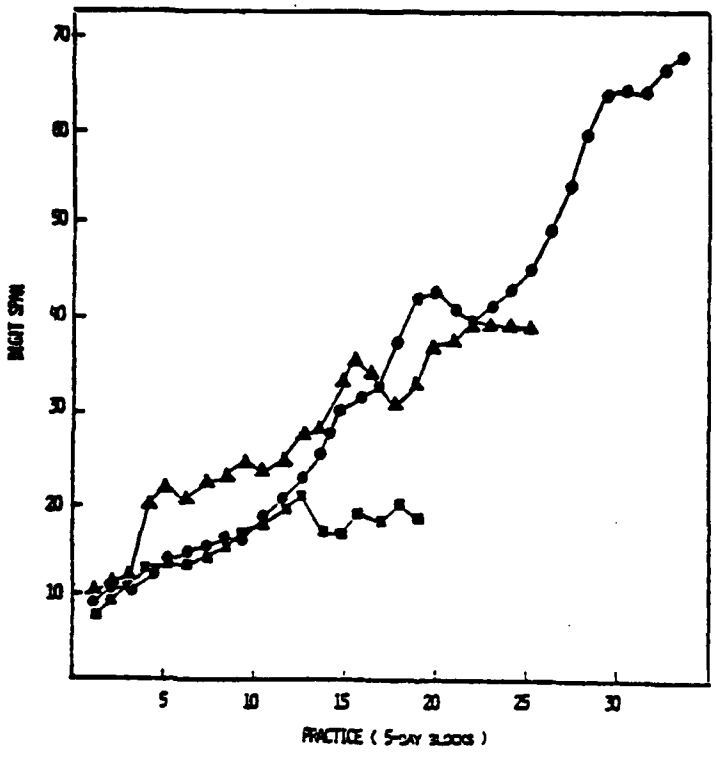


Figure 13: This graph compares SF's learning curve [circles] with two other subjects. One subject [triangles] was explicitly trained to use SF's system, and the other subject [squares] was allowed to develop her own mnemonic.

The other subject (squares) was run independently for about a hundred hours, and in that time she invented a very elaborate set of mnemonic associations based mainly on days, dates, and times of day. For example, 9365342 = "September third, 1965, at 3:42 P.M." However, this subject never invented a retrieval structure.

The difference in performance between this subject and the other two subjects is readily apparent in Figure 13. Her mnemonic associations worked very well, and her performance curve was very similar to SF's until she reached about 18 digits. At that point, she showed no further improvements,

and she stayed at that asymptote for several weeks and eventually quit due to loss of motivation.

The difference between this subject and SF is quite apparent from their protocols. Basically, this subject codes digit groups into mnemonics according to how they occur to her during presentation, on the basis of how the digits fall into good groups. In contrast, SF always decides beforehand how he will group the digits and he tries never to deviate from his grouping structure. It seems apparent from the protocols that this subject's mnemonics are as good (i.e., uniquely determined) as SF's mnemonics, as well as Rückle's numerical-relation mnemonics.[15] But because she has not associated her mnemonic codes with a retrieval structure, her mnemonic codes are stored in long-term memory without a means of retrieving them in their proper order. Without a retrieval structure, she has to rely on short-term memory to remember the order, and she can only remember the order of about four independent groups. Hence, we take this study as evidence that a retrieval structure is necessary if memory span performance is to exceed the limited ability of short-term memory to store the order of retrieval cues.

Retrieval in Skilled Memory

At this point, we emphasize the second characteristic of skilled memory: *Expert memory involves organized and direct retrieval from long-term memory.* There are two parts to this principle. First, experts seem invariably to know when to apply knowledge in a given task, whereas it is characteristic of novices that they often fail to apply what they know. In the literature, this characteristic has been demonstrated by de Groot (1966) for expert and novice chess players, and by Jeffries, Turner, Polson and Atwood (in press) for expert and novice programmers. In SF's case, we note that he can rapidly generate his mnemonic codes, and quickly and systematically search his semantic memory for his after-session recall.[16]

The second part of the principle is that, during the performance of some skilled task, experts store intermediate knowledge states for future reference in directly accessible locations in long-term memory. Chiesi, Spilich and Voss (1979) have found that baseball fans are better able to remember sequences of baseball events because they understand the game better, which is to say that they relate the events to the game's goal structure. In SF's case, he invented a structure, that we have called the *retrieval structure*, for storing retrieval cues for his mnemonic codes, and this allowed him to bypass the limits of short-term memory.

It is this idea of a retrieval structure which we believe has important implications for a theory of skilled memory. Up until very recently, cognitive theories have generally assumed that short-term memory is the primary storage system for intermediate results in many mental tasks, and that everything else is stored in long-term memory. However, cognitive theorists are beginning to question this assumption. Both Baddeley (1976) and Shiffrin (1976) have questioned the role of short-term

memory in complex tasks. Shiffrin, for example, makes the point that short-term memory simply does not have the capacity to store enough information to do anything useful in a complex task. Rather, intermediate knowledge states in long-term memory are tagged with the current context, which can then serve as a retrieval cue. Shiffrin has labeled this knowledge *temporal-contextual information.*

We agree with Shiffrin that directly retrievable knowledge states operate all the time in normal memory, and they allow people to build up sufficient context to do things like comprehend connected discourse, read text, solve problems, etc. The build-up of intermediate knowledge states undoubtedly underlies the phenomenon of warmup in cognitive tasks. That is, it simply takes time to search out knowledge states in semantic memory and build up enough *directly accessible* information to perform efficiently.

This problem is especially critical in skilled memory, where there is a premium on rapid access to large numbers of intermediate knowledge states. One of the intriguing aspects of our work is that it suggests that skilled memory involves rapid generation and direct retrieval of intermediate knowledge states. Later, we discuss more fully the importance of rapid access to intermediate knowledge states in skill.

There are several cases in the cognitive skills literature where our theory is relevant. First, current explanations of mental calculation experts in the literature stress that these people avoid the heavy memory overhead involved in mental computation in two ways: (1) by acquisition of special procedures that reduce memory load, and (2) by relying on recoding of digits into larger groups of meaningful numbers. For example, Bidder, the famous British mental calculation expert of the last century, was said to have recognized all 4-digit combinations as "old friends." A 3-digit number for a mental calculation expert is supposedly as familiar to him as single digits and familiar numbers, such as addresses and phone numbers, are to normal people.

In our preliminary analysis of a mental calculation expert, we have verified that these findings are true. However, these mechanisms are not sufficient. There is still a substantial memory overhead involved in storing and retrieving the results of intermediate computations. During a complex problem, intermediate computations must be temporarily stored, and then, at the right moment, they must be retrieved rapidly when needed. There is not enough time to recompute these intermediate products or to search for them because these processes are too costly both in time and in the interference that they generate. Intermediate computations must be directly accessible--retrieval structures are necessary.

Second, in the chess literature, it has been a puzzle as to why chess masters have such good memories for chess positions. It has been known for some time that chess masters can remember almost an entire chess position after a brief (5 sec) glance at the chess board (de Groot,1966), and

Chase and Simon (1973) found that when they counted familiar, chunked patterns rather than single pieces, the master's span still exceeded his short-term memory capacity.

Finally, in a series of interference studies, Charness (1976) demonstrated that all these chess patterns, except perhaps for the last one, are not in short-term memory. It seems clear that these chess patterns are stored in a retrieval structure.

We might speculate that retrieval structures for intermediate knowledge states are particularly useful in problem solving. Current views of skill in chess, for example, place emphasis on the pattern-recognition system--our first principle. That is, the central mechanism that leads search through the problem space is the recognition of patterns in long-term memory because they are associated with evaluations and procedural knowledge about good moves.

We suggest that a critical aspect of search in problem solving is the ability to store these intermediate knowledge states in a direct and rapid-access retrieval structure. As search proceeds through the problem space, we suggest that an important component of skill is the ability to reactivate these intermediate states directly. This ability is particularly useful when search involves backtracking to previous knowledge states. It is also apparent in another interesting way: when experts demonstrate their reconstructive abilities, and when they demonstrate their ability to generate extensive retrospective reports.

To summarize thus far, we have claimed that short-term memory does not have the capacity to store enough temporary knowledge to be useful in the performance of complex cognitive tasks. Rather, intermediate knowledge states are stored in directly addressable locations in a long-term memory structure that we have called a retrieval structure. Further, we have claimed that direct and rapid access to these intermediate knowledge states is characteristic of skilled performance in cognitive tasks. In short, there are good theoretical reasons for postulating the usefulness of retrieval structures.

We have not, however, discussed the mechanisms underlying retrieval. How is it possible to have direct access to long-term knowledge structures? This problem has been the central issue in recent reevaluations of the levels-of-processing literature (Jacoby & Craik, 1979; Nelson, 1979; Tulving, 1979). The original levels-of-processing claim was that meaningful codes are more memorable because they are processed at a deeper level, and most of the endeavor was an attempt to define what is meant by deeper. However conceived, most of the original emphasis was on encoding operations. But it has gradually become apparent that retrieval operations are critical, and the current consensus is that meaningful associations and mnemonics are memorable because they can generate retrieval cues that reinstate the encoding operations. This is what is meant by the encoding-retrieval interaction, that retrieval cues should match or reactivate the original encoding operations as

closely as possible.

There is still debate over whether it is necessary to postulate good vs. poor encoding operations. It is consistent with our theory that encoding operations are critical, that the memory trace must be bound to a semantic structure, and that redundant interactive contextual features are important. However, we agree with the current levels-of-processing literature that retrieval operations that reactivate the original encoding operations are also critical.

At this point, let us raise a theoretical problem. How is it possible to use the same retrieval structure over and over? What happens to previous groups bound to the same structure? If we assume that the retrieval cues derived from the retrieval structure are sufficient to access the current digit group, it is not clear from traditional theories of long-term memory how the same retrieval cue can reliably discriminate earlier memory traces bound to the same cue. Our analysis of our subjects' encodings shows no sensitivity to the current context that would allow it to serve as a discriminating retrieval cue. Without any hard evidence of how the current group is discriminated, we can only speculate. We believe that the most recent memory trace associated with the retrieval structure overwrites the previous group, is tagged as most recent, or is discriminated by a strength cue. Our subjects report that they actively seek to speed up their retrieval as this information appears to decay fairly rapidly within a few minutes, and intrusion errors from the same location on a previous trial are not uncommon.

Although we have not yet specified retrieval assumptions in our computer simulation model, we conceive of them in the following way. Recall that during encoding, we assumed that SF activates a set of semantic features that specify, say, a "near world-record 1-mile time" (cf. Figure 9). In short-term memory, SF attends simultaneously to these semantic features and the grouped set of digits (3492), and this chunking operation is the mechanism that serves to bind the memory trace to these semantic features.

Our retrieval assumption is that the current location in the retrieval structure is used to activate traces in long-term memory that are associated with the current location. Notice in Figure 12 that the retrieval structure is in the form of a hierarchical tree, which is a very efficient sorting structure. We assume that every branch in the tree is specified by a feature. Thus, in the tree structure in Figure 12, it takes a maximum of four features to uniquely specify one of twenty-two groups. It is this set of features that we assume is activated during encoding and bound to the memory trace. In Figure 14 we have illustrated the memory trace with the retrieval structure bound to it. The location is specified by a set of features (f_i) linked to the LOCATION node.

Notice that we have created links primarily between the running time structure and the location in the retrieval structure. Although there is virtually nothing in the verbal protocols about how memory

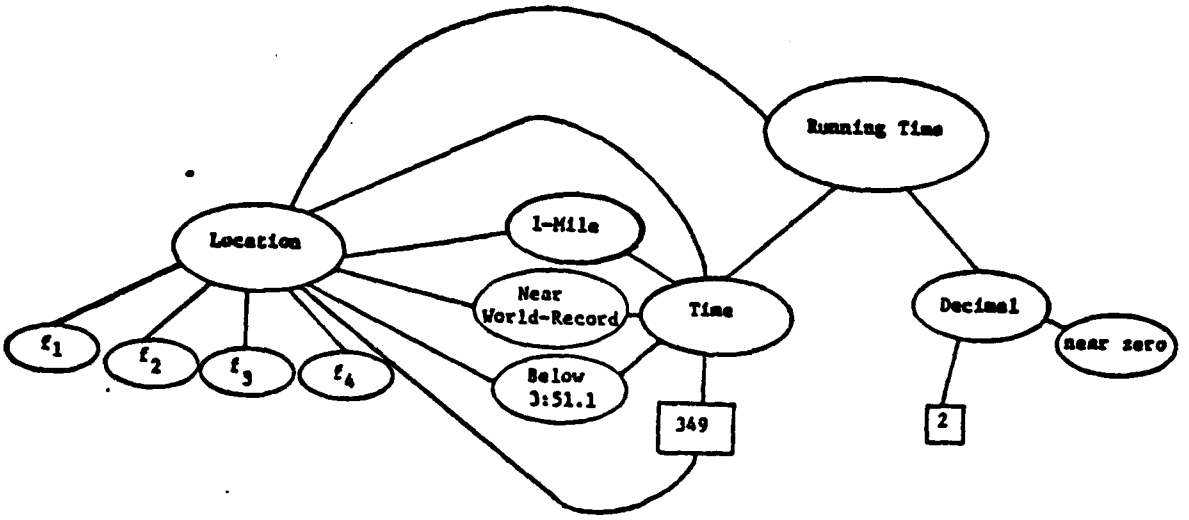


Figure 14: A link-node structural representation of the full memory trace for 3492. The memory trace is bound to the hierarchical semantic structure for a running time [shown previously in Figure 9] and the featural representation for the location in the retrieval structure is linked to the running-time structure.

traces are associated with the retrieval structure, we must account for the major results, namely that SF remembers mnemonic codes; and his retrieval structure seems to work well only for the particular mnemonic codes that he has practiced (running times, ages, years, patterns). We have created a direct link from the retrieval structure node to the memory trace because SF very occasionally remembers uncoded sequences. The power of the retrieval structure, however, must derive from the nature of the interactive links between the mnemonic codes and the locational features of the retrieval structure. As yet, however, we do not have any evidence about the nature of these links.

The featural representation of the retrieval structure accounts for the major types of transposition errors that occur during recall, namely transposition of groups within a supergroup, transposition of the same position across two adjacent supergroups, and intrusion errors of a group from a previous trial (usually the prior trial) in the same location.

There is evidence that SF stores more information than simply the association between the group and the retrieval features. Most commonly, SF reports noticing relationships between adjacent groups, such as a pair of 1-mile times even though they may be given very different mnemonic codes, e.g., "near-world-record mile time" and "fair mile time for a warmup." (For the case of identical mnemonic codes, see our earlier discussion.) Sf almost invariably notes the relationship of order, such as, the first mile time was faster than the second in the pair. Another common report is that,

given a mile time followed by a 2-mile time, the mile time is thought of as the time for the first half of the 2-mile time. These facts are stored as part of the memory trace and can serve as redundant retrieval cues as well as serve to determine the order.

We account for these reports as follows. First, because we have found that SF's short-term memory span includes the current group plus the previous group, we suppose that he automatically notices matches and other relations in short-term memory (e.g., two identical 1-MILE TIME features), and this noticing operation in effect binds the previous group to the current group. This noticing operation also sets up expectations for noticing strings of categories (e.g., all 1-mile times).

Up to this point, we have described the two most important mechanisms underlying SF's memory skill: the mnemonic associations and the retrieval structure. These, however, are still not sufficient to fully explain SF's performance. The problem is that both of these systems were essentially complete within the first 100 hours of practice. There have been minor improvements, but all major revisions took place within the first 100 hours. Yet SF continues to show steady improvement through 250 hours of practice and there is no sign of an asymptote. Something else must be happening.

On the Speedup of Encoding and Retrieval Operations

We have reached the point where SF's verbal reports are of little direct help. Following Ericsson and Simon's (1980) theory of verbal reports, we suppose that SF is able to report the contents of short-term memory. Thus, SF is able to report semantic features and other knowledge states that become activated, but he cannot tell us where these came from or how they were activated. That is, mental structures and processes themselves are not directly observable, but only their results that appear as knowledge states in short-term memory.

We are at the point, we believe, where we need to know something about the details of SF's mental structures. We know from SF's verbal reports that very few new rules were added to the mnemonic system or the retrieval structure after 100 hours of practice. We need to know how these existing rules change with practice.

We have several lines of evidence that SF's coding operations have speeded up with practice. In one experiment, we were interested in obtaining some detailed timing data, so instead of reading digits to SF, we presented him with a computer-controlled video display. In this experiment, SF controlled the rate at which he received the digits by pressing a button each time he wanted a digit, and we measured the time between button pushes.

We have taken these timing data on SF several times over a 2-year period. As one might expect, SF pressed buttons very rapidly (200-300 msec/digit) until the end of a group was reached, and all the

pauses occurred between groups. In Figure 15, we show the pause time between groups as a function of the size of the list. These data are shown for Days 69, 160, and 200, and SF's span on those days was 26, 69 and 79 digits, respectively.

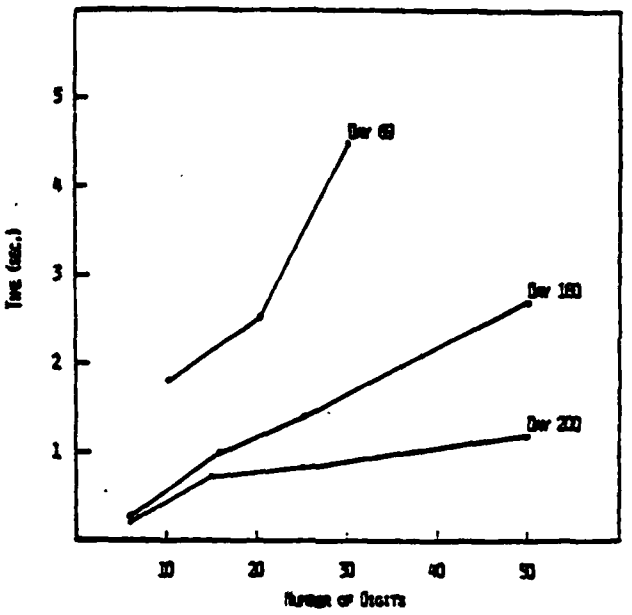


Figure 15: The average time that SF takes between groups as a function of the length of the digit sequences. The parameter is the level of practice, which is spaced over almost a 2-year period. The measure plotted is the average time SF paused between visually presented digit groups when he controlled the presentation of digits. This time is virtually identical to the average time interval between the presentation of the first digit in one group and the first digit in the next group with the minimal time to press keys for intermediate digits subtracted.

First, pause time increases with the size of the list. This result confirms what has been known for many years, namely that longer lists take more time per item to learn (Woodworth, 1938, p.21). That is, there is more learning overhead with larger lists.

Notice that over a 2-year period, SF's coding time has shown a very substantial decrease. Further, the last set of data (Day 200) shows much less of an increase in pause time for larger lists. It is as if there is almost no overhead in learning time for larger lists. We speculate that with practice, possibly the hierarchical retrieval structure is being displaced by a flat retrieval structure, analogous to the method of loci, with more distinctive location cues.

Finally, notice that with practice the absolute encoding times are falling below 1 sec, a time that we believe approaches the range of short-term memory operations.

In another experiment, we have a direct comparison of SF'S encoding and retrieval times, spaced 1 year apart, with those of several other mnemonists on the 50-digit matrix mentioned earlier. In this task, SF studies a 50-digit matrix of 13 rows and 4 columns until he has learned it, and then he is asked to recall the matrix and then to report various parts of the matrix, such as a given row, column, a zig-zag diagonal, etc.

TABLE 8

STUDY AND RECALL TIME (SEC)
SF, TWO MNEMONISTS, SUBJECT WITH MNEMONICS TRAINING,
AND THREE NORMAL SUBJECTS ON LURIA'S 50-DIGIT MATRIX

			Mnemonists		Subject with Mnemonics Training	Normal Subjects		
	SF	SF (1 year later)	Luria's S	Hunt & Love's VP	AB	S1	S2	S3
Study time	187	81	180	390	222	1240	685	715
Recall time								
Entire matrix	43	57	40	42	51	95	42	51
Third column	41	58	80	58	56	117	42	78
Second column	41	46	25	39	40	110	31	40
Second column up	47	30	30	40	54	83	46	63
Zig zag diagonal	64	38	35		52	107	78	94

In Table 8 we compare SF's learning and retrieval times for Days 111 and 211 with several other subjects. These data on the two famous mnemonists S (Luria, 1968) and VP (Hunt & Love, 1972) are reported in the literature. We have also run this experiment on a subject who has had mnemonics training,[17] and we ran three normal subjects for comparative purposes.

Note that all the subjects who use mnemonics are comparable, both in their encoding times and their retrieval times, despite wide differences in their reported mnemonics. We note in passing that Luria's S claimed to be scanning a visual image, but his retrieval times seem inconsistent with such a

strategy. His times are comparable to the other subjects who are retrieving mnemonic codes.

Mnemonics training markedly decreased encoding time (relative to normals), and in SF's case, a year's worth of practice has produced a large improvement in his encoding times, which are now substantially faster than all the other subjects. There does not, however, seem to be nearly as much variation in the retrieval times with practice.

In the next figure (Figure 16), we compare data on SF's learning time with Rückle's data, reported by Müller (1911). As far as we know, Rückle's data are by far the fastest learning times ever reported in the literature for digits (cf. Woodworth, 1938, p.21), and after 2 years of practice, SF's learning times seem comparable. As we noted earlier, Rückle's times are for simultaneous visual presentation, and SF's performance is far superior to Rückle's for fast auditory presentations.

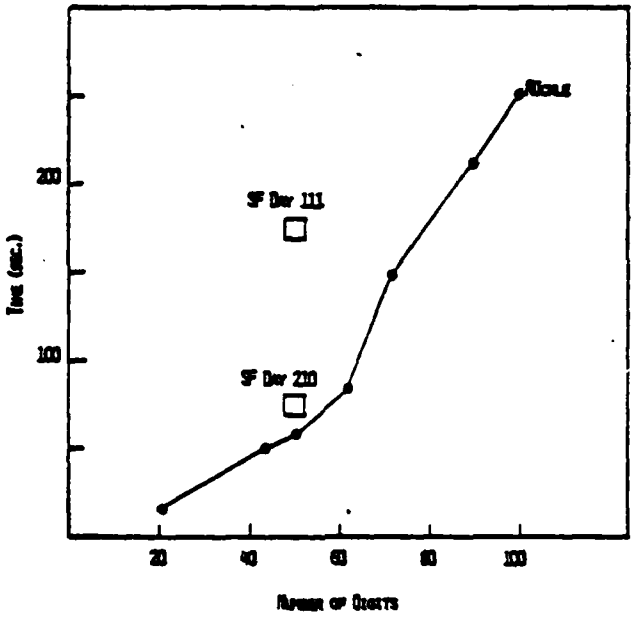


Figure 16: A comparison between SF [open squares] and Professor Rückle [circles]. Shown is the time required to memorize visually presented digits as a function of number of digits. SF's data are taken from the experiment on the Luria-matrices [Table 8], and Rückle's data are derived from Müller [1911].

We mention one final experiment on SF's coding times. In one of our early experiments, we presented SF with digits at a rapid rate (3 digits/sec), and we found that SF was unable to code at this rate and his span dropped back to 8 or 9 digits, and for over a year and a half, SF was unable to code at these fast rates. However, we have found recently that SF is able to code one or two groups of 3

digits each at the fastest rates (about 5 digits/sec) and hold about 5 digits in a rehearsal buffer, for a total span of about 11 digits.

This set of experiments, taken together, provides good evidence that SF's encoding operations have speeded up considerably over the course of two years of practice. Although we have no data to confirm it as yet, we believe that SF's retrieval processes have also speeded up. In terms of absolute magnitudes, we think it is important that SF's encoding times and recognition times (cf. experiment on missing digit) are falling below 1 sec, which brings them into the range of short-term memory operations.

This brings us to our third principle of skilled memory: *Skilled memory involves rapid storage and retrieval of intermediate knowledge states in long-term memory.*

Implications for a Theory of Skilled Memory

During the course of our analysis of SF, we have outlined three principles of skilled memory. The first principle--that skilled memory involves knowledge structures in semantic memory--is already well-documented in the literature. It is the second and third principles that we believe are important additional contributions to our understanding of skilled memory. These principles say that experts store and retrieve intermediate knowledge structures, and that they do it fast.

The key to skilled memory performance, we believe, is in the ability to rapidly store and re-access intermediate knowledge states. This property is very useful because it relieves the burden on short-term memory, which normally serves the purpose of holding knowledge structures in an active (i.e., directly accessible) state for ready access. Practice causes these storage and retrieval operations to speed up to the point where, on an absolute scale, access times are less than a second, bringing skilled memory operations within the range of useful speeded skills.

The advantage of short-term memory is that a small set of information is directly accessible without search. Intermediate knowledge structures require skill in the sense that future situations, in which this information is relevant and should be retrieved, are anticipated at the time of encoding and associations are formed with relevant retrieval cues for those future situations. Skilled memory is thus only possible in situations where future retrieval can be anticipated. Short-term memory, on the other hand, does not require such anticipation of future use and is therefore a characteristic of novice performance. By extensive practice, coordination is developed between encoding processes and retrieval processes. This constitutes skilled memory.

This rapidly accessible intermediate knowledge structure in effect provides the expert with a large memory system that has the properties of short-term memory. The advantages are enormous. It frees up short-term memory for other processes. Direct accessibility reduces search, which costs time,

takes up processing capacity, and dredges up interfering knowledge states. Finally, it allows the expert to organize and execute more complex mental operations than would otherwise be impossible with the small capacity of short-term memory. No wonder the reported feats of memory-based experts seem so astounding to the average person.

So far, we have described what we believe accounts for SF's continuing practice effects: a gradual speedup in his encoding and retrieval operations. But we have not said how this is possible. Although we have virtually no data on this problem, we speculate that SF is gradually learning a distinctive set of interactive links between his retrieval locations and his mnemonic codes (Figure 14). These links are unique to each retrieval location, and their interactions with the mnemonic codes uniquely determine which mnemonic code is associated with the location.

We are reasoning by analogy with the method of loci, although there is a big difference: There are rich introspections about interactive features with visual imagery whereas SF can report nothing about these numerical codes. The method of loci is also a much more time-consuming mnemonic (we estimate a minimum of 3 sec per image). Nevertheless, we believe that the principle is the same. As one learns to use the method of loci, one learns a set of distinctive locations, and one learns to use a set of distinctive interactive links between locations and objects to be remembered. At recall, when a practiced expert thinks of a location, he knows how to regenerate an image. In effect, at retrieval, he has learned how to reproduce as good a match as possible with the encoding operations. This is the encoding-retrieval interaction principle derived from the levels-of-processing literature, and the constructability principle discussed by Norman and Bobrow (1979).

In principle. our learning assumption is fairly simple. With practice, SF's encoding processes become faster and more reliable, and the links between his mnemonic codes and his retrieval structure are strengthened, resulting in more direct, reliable and faster retrieval.

Although we have no evidence about the nature of the learning mechanism, the consequences of such a mechanism seem clear. During encoding, more time is left for other processes, such as noticing additional relationships among mnemonic groups. During recall, there is a smaller probability of a retrieval failure, and faster and more direct retrieval produces less retrieval interference. There is some evidence in the protocols that this might be the case, and this is one area where some experimental effort is needed.

Concluding Remarks

There are two aspects of this study that we think are important. First, the sheer magnitude of the memory feat is something that has never been accomplished before. As far as we know, SF's memory span is by far the largest ever reported in the literature. We were able to observe the development of

this skill in a subject without any special memory abilities, and we were further able to train SF's system in another subject. Thus, we take this result as clear evidence that no special abilities are necessary for the development of memory skill. Practice, in conjunction with an appropriate mnemonic system and retrieval structure, is all that is necessary for the development of memory skill, and there is apparently no limit to improvements in memory skill with practice.

The second aspect of this study that we want to comment on is the implications of our results for a cognitive theory of skilled memory. Because we were able to observe the acquisition of SF's memory skill, we could analyze the underlying cognitive mechanisms, and we outlined what we thought were the three most essential components of that skill.

The most interesting implication of our results is that skilled memory seems to require rapid access to a large number of intermediate knowledge states, allowing the memory expert to bypass the limits of short-term memory. We propose that the traditional view by current cognitive theory that short-term memory is the storage mechanism for intermediate knowledge states must be reconceptualized. Short-term memory simply does not have the necessary capacity to handle the large number of intermediate knowledge states that are needed for skilled memory performance in some domain.

We have tried to sketch out the properties of a memory system that holds these intermediate knowledge states:[18] (1)Intermediate knowledge states are semantic structures in long-term memory, (2) they are stored in directly accessible locations in a retrieval structure, which is also in long-term memory, and (3) storage and retrieval operations in the retrieval structure are fast enough to bypass (or at least augment) short-term memory. Rapid access to such a large, versatile memory system allows the cognitive system of the expert to use complex operations that would not be possible using only a limited-capacity short-term memory. This is one reason why expert performance in semantically rich domains appears to be qualitatively superior to that of the novice.

Acknowledgments

This research was supported by Contract N00014-79-C-0215 with the Advanced Research Projects Agency of the Office of the Secretary of Defense, which is monitored by the Office of Naval Research. We are grateful to J. R. Anderson, S. Faloon, and M. W. Schustack for comments on an earlier draft.

References

Anderson, J. R., & Reder, L. M. An elaborative processing explanation of depth of processing. In L. S. Cermak and F. I. M. Craik (Eds.), *Levels of processing in human memory*. Hillsdale, N. J.: Lawrence Earlbaum Associates. 1979, 385-403.

Bachelder, B. L.,& Denny, M. R. A theory of intelligence: I Span and the complexity of stimulus control. *Intelligence*, 1977(a),*1*, 127-150.

Bachelder, B. L., & Denny, M. R. A theory of intelligence: II. The role of span in a variety of intellectual tasks. *Intelligence*, 1977(b), *1*, 237-256.

Baddeley, A. D. *The psychology of memory*. New York: Basic Books, 1976.

Baddeley, A. D., & Hitch, G. Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation, Vol. 8*,1974, 47-90.

Bower, G. H. Mental imagery and associative learning. In L. W. Gregg (Ed.), *Cognition in learning and memory*. New York: Wiley, 1972.

Broadbent, D. A. The magical number seven after fifteen years. In A. kennedy and A. Wilkes (Eds.), *Studies in long-term memory*. New York: Wiley, 1975.

Brown, J. Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental psychology*, 1958, *10*, 12-21.

Bryan, W. L., & Harter N. *psychological Review*, 1899, *6*, 345-375.

Charness, N. Memory for chess positions: Resistence to interference. *Journal of Experimental Psychology: Human Learning and Memory*, 1976, *2*, 641-653.

Chase, W. G., & Chi, M. T. H. Cognitive skill: Implications for spatial skill in large-scale environments. In J. Harvey (Ed.), *Cognition, social Behavior, and the environment*. Potomac, Maryland: Lawrence Erlbaum Associates, 1980.

Chase, W. G., & Simon, H. A. Perception in chess. *Cognitive Psychology*, 1973, *4*, 55-81.

Chiesi, H. L., Spilich, G. J., & Voss, J.F. Acquisition of domain-related information in relation to high and low domain knowledge. *Journal of Verbal Learning and Verbal Behavior*, 1979, *18*, 257-273.

de Groot, A. D. Perception and memory versus thought: Some old ideas and recent findings. In B. Kleinmuntz (Ed.), *Problem solving: Research, method, and theory*. New York: Wiley, 1966.

Ericsson, K. A., & Simon, H. A. Verbal reports as data. *Psychological Review*, 1980, *87*, 215-251.

Gates, A. I., & Taylor, G. A. An experimental study of the nature of improvement resulting from practice in a mental function. *Journal of Educational Psychology*, 1925, *16*, 583-592.

Halliday, M. A. K. *Intonation and grammar in British english*. The Hague: Mouton, 1967.

Hatano, G., & Osawa, K. Digit span of grand experts in abacus-derived mental computation. Paper presented at the Third Noda conference on cognitive science, 1980.

Hunt, E., & Love, T. How good can memory be? In A. W. Melton and E. Martin (Eds.), *Coding processes in human memory*. Washington, D. C.: Winston, 1972.

Hunter, I. M. L. An exceptional talent for calculative thinking. *British Journal of Psychology*, 1962, 53, 243-258.

Hunter, I. M. L. Mental calculation. In P. C. Wason and P. N. Johnson-Laird (Eds.) *Thinking and Reasoning*. Baltimore: Penguin, 1968.

Jacoby, L. L., & Craik, F. I. M. Effects of elaboration of processing at encoding and retrieval: Trace distinctiveness and recovery of initial context. In L. S. Cermak and F. I. M. Craik (Eds.), *Levels of processing and human memory*. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1979.

Jeffries, R., Turner, A. A., Polson, P. G., & Atwood, M. E. The processes involved in designing software. In J. A. Anderson (Ed.), *Cognitive Skills and their Acquisition*. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1981.

Klatzky, R. L. *Human memory: Structures and processes, Second ed.*, San Francisco: W. H. Freeman and Co., 1980.

Levy, B. A. Vocalization and suppression effects in sentence memory. *Journal of Verbal Learning and Verbal Behavior*, 1975, *14*, 304-316.

Lorayne, H., & Lucas, J. *The memory book*, New York: Ballantine books, 1974.

Luria, A. R. *The mind of a mneumonist*, New York: Avon, 1968.

Martin, P. R., & Fernberger, S. W. Improvement in memory span. *American Journal of Psychology*, 1929, *41*, 91-94.

Miller, G. A. The magical number seven, plus or minus two. *Psychological Review*, 1956, 63, 81-97.

Mitchell, F. D. Mathematical prodigies.*American Journal of Psychology*, 1907, *18*, 61-143.

Müller, G. E. Zur Analyse der Gedachtnistatigkeit und des Vorstellungsverlaufes: Teil I. *Zeitschrift fur Psychologie, Erganzungsband 5*, 1911.

Müller, G. E. Zur Analyse der Gedachtnistatigkeit und des Vorstellungsverlaufes: Teil III. *Zeitschrift fur Psychologie, Erganzungsband 8*, 1913.

Müller, G. E. Zur Analyse der Gedachtnistatigkeit und des Vorstellungsverlaufes: Teil II. *Zeitschrift fur Psychologie, Erganzungsband 9*, 1917.

Nelson, D. L. Remembering pictures and words: Appearence, significance, and name. In L. S. Cermak and F. I. M. Craik (Eds.), *Levels of processing in human memory*. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1979, 45-76.

Newell, A., & Simon, H. A. *Human problem solving*. Englewood Cliffs, N. J.: Prentice-Hall, 1972.

Norman, D. A., & Bobrow, D. G. An intermediate stage in memory retrieval. *Cognitive Psychology*, 1979, *11*, 107-123.

Oberly, H. S. A comparison of the spans of 'attention' and memory. *American Journal of Psychology*,

1928, *40*, 295-302.

Paivio, A. *Imagery and verbal processes*. New York: Holt, Reinhart and Winston, Inc., 1971.

Peterson, L. R., & Peterson, M. J. Short-term retention of individual items. *Journal of Experimental Psychology*, 1959, *58*, 193-198.

Pike, K. *The intonation of American english*. Ann Harbor: Univ. of Michigan Press, 1945.

Shiffrin, R. M. Capacity limitations in information processing, attention and memory. In W. K. Estes (Ed.) *Handbook of learning and cognitive processes, Vol. 4*. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1976, 177-236.

Simon, H. A., & Gilmartin, K. A simulation of memory for chess positions. *Cognitive Psychology*, 1973, 5, 29-46.

Stein, B. S., & Bransford, J. D. Constraints on effective elaborations: Effect of precision and subject generation. *Journal of Verbal Learning and Verbal Behavior*, 1979, *18*, 769-778.

Sternberg, S. Memory scanning: Mental processes revealed by reaction time experiments. *American Scientist*, 1969, 57, 421-457.

Tulving, E. Relation between encoding specificity and levels of processing. In L. S. Cermak and F. I. M. Craik (Eds.), *Levels of processing in human memory*. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1979, 405-428.

Wickelgren, W. A. Size of rehearsal group and short-term memory. *Journal of Experimental Psychology*, 1964, *68*, 413-419.

Williams, M. D. Retrieval from very long-term memory. Unpublished doctoral dissertation. University of California, San Diego, 1976.

Woodworth, R. S. *Experimental Psychology*. New York: Henry Holt and Co., 1938.

Yates, F. A. *The art of memory*. London: Rutledge and Kegan Paul, 1966.

Footnotes

1. There have been many changes in procedure over the two years of this study. For example, we used to ask for a verbal report after 1/2 the trials, randomly selected. Further, in the beginning we had some conditions with immediate recall and some conditions with 20-sec delays because we were interested in various verbalization conditions in relation to verbal protocols. We eventually dropped all these delay conditions when it became apparent that they had no effect on the data.

2. We find it surprising that subjects would not report using meaningful associations in that study, because we want to claim that improvements in memory span must necessarily involve mnemonic aids. Martin and Fernberger (1929) only discuss organization and the number of digits in the apprehended group, and do not comment on whether or not subjects used meaningful associations. In another early study, Oberly (1928) discusses retrospective reports from normal subjects in the memory-span task, and he found that subjects with larger memory-span scores invariably reported using meaningful associations.

3. To give some indication of SF's skill, he was a member of the university track and cross-country team, a member of a junior college national championship marathon team, and a member of the Human Energy Running Club. SF is now 22 years old, he trains 10-13 miles a day, and he has competed in numerous long-distance events in the eastern region of the U. S. for the past 9 years. SF's best events are the 3-mile, 5-mile and marathon, and his best times in these events are 14:39, 25:40 and 2:39:36, respectively. SF rates himself in the top 2% of runners for events over 10 miles. In other respects, SF seems to have average memory abilities and average intelligence test scores (SAT = 990, GRE = 1140), although he has a high grade-point average (3.80).

4. Times in parentheses are ones that could not be found in the digits presented that day. Although there were a few of these false alarms in the early sessions (before Session 100), they are virtually non-existent in his later sessions.

5. The after-session report is susceptible to motivational changes. For example, when SF has a bad session, he doesn't try as hard in the after-session report, and his performance drops off.

6. There is an interesting anecdote worth mentioning here. Near the end of the recognition session, we deliberately presented SF with a few probes that he had been shown earlier in the session. For both old and new probes, SF would respond immediately (within a second or two) and with some irritation "I already told you that one," or something to that effect. The ability to retain this kind of information for at least an hour is a clear demonstration that these codes are stored in long-term memory.

7. In the beginning, we started every session with an initial ascending sequence until SF made an error (as in the memory span procedure on IQ tests), after which we used the more efficient up-and-down procedure. We eventually dropped this initial procedure because it became too time-consuming as SF's memory span increased.

8. It is this experiment that apparently caused SF to induce this rule, which became a standard, albeit small, part of the mnemonic system.

9. In some of SF's early protocols, he would occasionally point to different spatial locations with his hand, in left-to-right order, when he recalled groups of digits. This behavior is

also typical of normal subjects when recalling groups.

10. This is the most commonly accepted view of short-term memory for verbal materials--that they are buffered in a phonemic code for several seconds (cf. Baddeley, 1976, ch. 7; Klatzky, 1980, ch. 5).

11. When these rehearsal suppression experiments were conducted, the rehearsal group was often not coded, but eventually (after about 150 hours of practice) SF invariably coded every digit group, including the rehearsal group.

12. Fewer than half of the college students we have tested can recall anything from a 20-minute session, and those who do, recall only one or two groups.

13. Most of Müller's stimuli were visually presented lists of digits. For example, Rückle could memorize a matrix of 25 digits in about 12 sec, although his auditory digit span at the 1-sec rate was only about 18 digits.

14. Part of this subject's initial jump in performance is due to a change in the up-and-down procedure, and part of it is due to the fact that because we explicitly trained him to use SF's system, he avoided the initial trial-and-error associated with SF's learning.

15. Müller (1911) also reports evidence of hierarchical grouping by Rückle when he memorized long lists of digits.

16. When SF has trouble recalling a group, he usually invokes the strategy of systematically searching semantic memory with the generate-and-test procedure.

17. This subject uses a standard mnemonic device, picked up from the Lorayne and Lucas book (1974), for converting digits to phonemes, phonemes to concrete words, and concrete words to visual images, which he then links up via interactive images.

18. A good name for such a memory system is "working memory," but this term has traditionally been used to describe the temporary knowledge states that have the properties of short-term memory (cf. Baddeley, 1976, ch. 8; Klatzky, 1980, ch. 5). This term is derived from the prevailing view that the intermediate knowledge states needed to perform cognitive tasks are stored in short-term memory.

Navy

1 Dr. Robert Preaux
Code N-711
NAVTRAEQUIPCEN
Orlando, FL 32813

1 Chief of Naval Education and Training
Liason Office
Air Force Human Resource Laboratory
Flying Training Division
WILLIAMS AFB, AZ 85224

1 Dr. Richard Elster
Department of Administrative Sciences
Naval Postgraduate School
Monterey, CA 93940

1 DR. PAT FEDERICO
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

1 Dr. John Ford
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Henry M. Halff
Department of Psychology,C-009
University of California at San Diego
La Jolla, CA 92093

1 LT Steven D. Harris, MSC, USN
Code 6021
Naval Air Development Center
Warminster, Pennsylvania 18974

1 Dr. Patrick R. Harrison
Psychology Course Director
LEADERSHIP & LAW DEPT. (7b)
DIV. OF PROFESSIONAL DEVELOPMENT
U.S. NAVAL ACADEMY
ANNAPOLIS, MD 21402

1 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

Navy

1 Dr. William L. Maloy
Principal Civilian Advisor for
Education and Training
Naval Training Command, Code 00A
Pensacola, FL 32508

1 Dr. Kneale Marshall
Scientific Advisor to DCNO(MPT)
OP01T
Washington DC 20370

1 CAPT Richard L. Martin, USN
Prospective Commanding Officer
USS Carl Vinson (CVN-70)
Newport News Shipbuilding and Drydock Co
Newport News, VA 23607

1 Dr William Montague
Navy Personnel R&D Center
San Diego, CA 92152

1 Library
Naval Health Research Center
P. O. Box 85122
San Diego, CA 92138

1 Naval Medical R&D Command
Code 44
National Naval Medical Center
Bethesda, MD 20014

1 Ted M. I. Yellen
Technical Information Office, Code 201
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

1 Library, Code P201L
Navy Personnel R&D Center
San Diego, CA 92152

1 Technical Director
Navy Personnel R&D Center
San Diego, CA 92152

6 Commanding Officer
Naval Research Laboratory
Code 2627
Washington, DC 20390

Navy

1 Psychologist
ONR Branch Office
Bldg 114, Section D
666 Summer Street
Boston, MA 02210

1 Psychologist
ONR Branch Office
536 S. Clark Street
Chicago, IL 60605

1 Office of Naval Research
Code 437
800 N. Quincy SStreet
Arlington, VA 22217

5 Personnel & Training Research Programs
(Code 458)
Office of Naval Research
Arlington, VA 22217

1 Psychologist
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101

1 Office of the Chief of Naval Operations
Research Development & Studies Branch
(OP-115)
Washington, DC 20350

1 Captain Donald F. Parker, USN
Commanding Officer
Navy Personnel R&D Center
San Diego, CA 92152

1 LT Frank C. Petho, MSC, USN (Ph.D)
Code L51
Naval Aerospace Medical Research Laborat
Pensacola, FL 32508

1 Dr. Gary Poock
Operations Research Department
Code 55PK
Naval Postgraduate School
Monterey, CA 93940

Navy

1 Roger W. Remington, Ph.D
Code L52
NAMRL
Pensacola, FL 32508

1 Dr. Bernard Rimland (03B)
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Worth Scanland
Chief of Naval Education and Training
Code N-5
NAS, Pensacola, FL 32508

1 Dr. Robert G. Smith
Office of Chief of Naval Operations
OP-987H
Washington, DC 20350

1 Dr. Alfred F. Smode
Training Analysis & Evaluation Group
(TAEG)
Dept. of the Navy
Orlando, FL 32813

1 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

1 Roger Weissinger-Baylon
Department of Administrative Sciences
Naval Postgraduate School
Monterey, CA 93940

1 Dr. Robert Wisher
Code 309
Navy Personnel R&D Center
San Diego, CA 92152

Army

1 Technical Director
U. S. Army Research Institute for the Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 HQ USAREUE & 7th Army
ODCSOPS
USAAREUE Director of GED
APO New York 09403

1 Dr. Michael Kaplan
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Dr. Milton S. Katz
Training Technical Area
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Director
U.S. Army Human Engineering Labs
Attn: DRXHE-DB
Aberdeen Proving Ground, MD 21005

1 Dr. Harold F. O'Neil, Jr.
Attn: PERI-OK
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Robert Sasmor
U. S. Army Research Institute for the Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Joseph Ward
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Air Force

1 Air University Library
AUL/LSE 76/443
Maxwell AFB, AL 36112

1 Dr. Earl A. Alluisi
HQ, AFHRL (AFSC)
Brooks AFB, TX 78235

1 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AFOSR
Bolling AFB, DC 20332

1 Dr. Ronald G. Hughes
AFHRL/OTR
Williams AFB, AZ 85224

1 Dr. Marty Rockway
Technical Director
AFHRL(OT)
Williams AFB, AZ 58224

1 Dr. Frank Schufletowski
U.S. Air Force
ATC/XPTD
Randolph AFB, TX 78148

2 3700 TCHTW/TTGH Stop 32
Sheppard AFB, TX 76311

1 Jack A. Thorp, Maj., USAF
Life Sciences Directorate
AFOSR
Bolling AFB, DC 20332

Marines

1 H. William Greenup
Education Advisor (E031)
Education Center, MCDEC
Quantico, VA 22134

1 Headquarters, U. S. Marine Corps
Code MPI-20
Washington, DC 20380

1 Special Assistant for Marine Corps Matters
Code 100M
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

1 DR. A.L. SLAFKOSKY
SCIENTIFIC ADVISOR (CODE RD-1)
HQ, U.S. MARINE CORPS
WASHINGTON, DC 20380

Other DoD

12 Defense Technical Information Center
Cameron Station, Bldg 5
Alexandria, VA 22314
Attn: TC

1 Dr. Dexter Fletcher
ADVANCED RESEARCH PROJECTS AGENCY
1400 WILSON BLVD.
ARLINGTON, VA 22209

1 Military Assistant for Training and Personnel Technology
Office of the Under Secretary of Defense for Research & Engineering
Room 3D129, The Pentagon
Washington, DC 20301

1 HEAD, SECTION ON MEDICAL EDUCATION
UNIFORMED SERVICES UNIV. OF THE HEALTH SCIENCES
6917 ARLINGTON ROAD
BETHESDA, MD 20014

Civil Govt

1 Dr. Susan Chipman
Learning and Development
National Institute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Joseph I. Lipson
SEDR W-638
National Science Foundation
Washington, DC 20550

1 Dr. Arthur Melmed
National Intitute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Andrew R. Molnar
Science Education Dev.
and Research
National Science Foundation
Washington, DC 20550

1 Dr. H. Wallace Sinaiko
Program Director
Manpower Research and Advisory Services
Smithsonian Institution
801 North Pitt Street
Alexandria, VA 22314

1 Dr. Frank Withrow
U. S. Office of Education
400 Maryland Ave. SW
Washington, DC 20202

1 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, DC 20550

Non Govt

1 Dr. John R. Anderson
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Anderson, Thomas H., Ph.D.
Center for the Study of Reading
174 Children's Research Center
51 Gerty Drive
Champiagn, IL 61820

1 Dr. John Annett
Department of Psychology
University of Warwick
Coventry CV4 7AL
ENGLAND

1 DR. MICHAEL ATWOOD
SCIENCE APPLICATIONS INSTITUTE
40 DENVER TECH. CENTER WEST
7935 E. PRENTICE AVENUE
ENGLEWOOD, CO 80110

1 1 psychological research unit
Dept. of Defense (Army Office)
Campbell Park Offices
Canberra ACT 2600, Australia

1 Dr. Alan Baddeley
Medical Research Council
Applied Psychology Unit
15 Chaucer Road
Cambridge CB2 2EF
ENGLAND

1 Dr. Patricia Baggett
Department of Psychology
University of Denver
University Park
Denver, CO 80208

1 Mr Avron Barr
Department of Computer Science
Stanford University
Stanford, CA 94305

Non Govt

1 Dr. Nicholas A. Bond
Dept. of Psychology
Sacramento State College
600 Jay Street
Sacramento, CA 95819

1 Dr. Lyle Bourne
Department of Psychology
University of Colorado
Boulder, CO 80309

1 Dr. Kenneth Bowles
Institute for Information Sciences
University of California at San Diego
La Jolla, CA 92037

1 Dr. John S. Brown
XEROX Palo Alto Research Center
3333 Coyote Road
Palo Alto, CA 94304

1 Dr. Bruce Buchanan
Department of Computer Science
Stanford University
Stanford, CA 94305

1 DR. C. VICTOR BUNDERSON
WICAT INC.
UNIVERSITY PLAZA, SUITE 10
1160 SO. STATE ST.
OREM, UT 84057

1 Dr. John B. Carroll
Psychometric Lab
Univ. of No. Carolina
Davie Hall 013A
Chapel Hill, NC 27514

1 Charles Myers Library
Livingstone House
Livingstone Road
Stratford
London E15 2LJ
ENGLAND

1 Dr. William Chase
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

Non Govt

1 Dr. William Clancey
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, Ma 02138

1 Dr. Lynn A. Cooper
LRDC
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. Meredith P. Crawford
American Psychological Association
1200 17th Street, N.W.
Washington, DC 20036

1 Dr. Kenneth B. Cross
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

1 Dr. Hubert Dreyfus
Department of Philosophy
University of California
Berkely, CA 94720

1 LCOL J. C. Eggenberger
DIRECTORATE OF PERSONNEL APPLIED RESEARC
NATIONAL DEFENCE HQ
101 COLONEL BY DRIVE
OTTAWA, CANADA K1A 0K2

1 Dr. Ed Feigenbaum
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Mr. Wallace Feurzeig
Bolt Beranek & Newman, Inc.
50 Moulton St.
Cambridge, MA 02138

Non Govt

1 Dr. Edwin A. Fleishman
Advanced Research Resources Organ.
Suite 900
4330 East West Highway
Washington, DC 20014

1 DR. JOHN D. FOLLEY JR.
APPLIED SCIENCES ASSOCIATES INC
VALENCIA, PA 16059

1 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

1 Dr. Alinda Friedman
Department of Psychology
University of Alberta
Edmonton, Alberta
CANADA T6G 2E9

1 Dr. R. Edward Geiselman
Department of Psychology
University of California
Los Angeles, CA 90024

1 DR. ROBERT GLASER
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 Dr. Marvin D. Glock
217 Stone Hall
Cornell University
Ithaca, NY 14853

1 Dr. Daniel Gopher
Industrial & Management Engineering
Technion-Israel Institute of Technology
Haifa
ISRAEL

1 DR. JAMES G. GREENO
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

Non Govt

1 Dr. Ron Hambleton
School of Education
University of Massechusetts
Amherst, MA 01002

1 Dr. Harold Hawkins
Department of Psychology
University of Oregon
Eugene OR 97403

1 Dr. Barbara Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. Frederick Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. James R. Hoffman
Department of Psychology
University of Delaware
Newark, DE 19711

1 Glenda Greenwald, Ed.
"Human Intelligence Newsletter"
P. O. Box 1163
Birmingham, MI 48012

1 Dr. Earl Hunt
Dept. of Psychology
University of Washington
Seattle, WA 98105

1 Dr. Steven W. Keele
Dept. of Psychology
University of Oregon
Eugene, OR 97403

1 Dr. Walter Kintsch
Department of Psychology
University of Colorado
Boulder, CO 80302

1 Dr. David Kieras
Department of Psychology
University of Arizona
Tuscon, AZ 85721

Non Govt

1 Dr. Stephen Kosslyn
Harvard University
Department of Psychology
33 Kirkland Street
Cambridge, MA 02138

1 Mr. Marlin Kroger
1117 Via Goleta
Palos Verdes Estates, CA 90274

1 Dr. Jill Larkin
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Alan Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

1 Dr. Michael Levine
Department of Educational Psychology
210 Education Bldg.
University of Illinois
Champaign, IL 61801

1 Dr. Robert A. Levit
Director, Behavioral Sciences
The BDM Corporation
7915 Jones Branch Drive
McClean, VA 22101

1 Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat
Groningen
NETHERLANDS

1 Dr. Mark Miller
Computer Science Laboratory
Texas Instruments, Inc.
Mail Station 371, P.O. Box 225936
Dallas, TX 75265

1 Dr. Allen Munro
Behavioral Technology Laboratories
1845 Elena Ave., Fourth Floor
Redondo Beach, CA 90277

Non Govt

1 Dr. Donald A Norman
Dept. of Psychology C-009
Univ. of California, San Diego
La Jolla, CA 92093

1 Dr. Jesse Orlansky
Institute for Defense Analyses
400 Army Navy Drive
Arlington, VA 22202

1 Dr. Seymour A. Papert
Massachusetts Institute of Technology
Artificial Intelligence Lab
545 Technology Square
Cambridge, MA 02139

1 Dr. James A. Paulson
Portland State University
P.O. Box 751
Portland, OR 97207

1 MR. LUIGI PETRULLO
2431 N. EDGEWOOD STREET
ARLINGTON, VA 22207

1 DR. PETER POLSON
DEPT. OF PSYCHOLOGY
UNIVERSITY OF COLORADO
BOULDER, CO 80309

1 Dr. Fred Reif
SESAME
c/o Physics Department
University of California
Berkely, CA 94720

1 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson St. NW
Washington, DC 20007

1 Dr. Ernst Z. Rothkopf
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

Non Govt

1 DR. WALTER SCHNEIDER
DEPT. OF PSYCHOLOGY
UNIVERSITY OF ILLINOIS
CHAMPAIGN, IL 61820

1 Dr. Alan Schoenfeld
Department of Mathematics
Hamilton College
Clinton, NY 13323

1 Committee on Cognitive Research
% Dr. Lonnie R. Sherrod
Social Science Research Council
605 Third Avenue
New York, NY 10016

1 Robert S. Siegler
Associate Professor
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

1 Dr. Robert Smith
Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

1 Dr. Richard Snow
School of Education
Stanford University
Stanford, CA 94305

1 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 DR. ALBERT STEVENS
BOLT BERANEK & NEWMAN, INC.
50 MOULTON STREET
CAMBRIDGE, MA 02138

1 Dr. Thomas G. Sticht
Director, Basic Skills Division
HUMRRO
300 N. Washington Street
Alexandria,VA 22314

Non Govt

1 Dr. David Stone
ED 236
SUNY, Albany
Albany, NY 12222

1 DR. PATRICK SUPPES
INSTITUTE FOR MATHEMATICAL STUDIES IN THE SOCIAL SCIENCES
STANFORD UNIVERSITY
STANFORD, CA 94305

1 Dr. Kikumi Tatsuoka
Computer Based Education Research Laboratory
252 Engineering Research Laboratory
University of Illinois
Urbana, IL 61801

1 Dr. John Thomas
IBM Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

1 DR. PERRY THORNDYKE
THE RAND CORPORATION
1700 MAIN STREET
SANTA MONICA, CA 90406

1 Dr. Douglas Towne
Univ. of So. California
Behavioral Technology Labs
1845 S. Elena Ave.
Redondo Beach, CA 90277

1 Dr. J. Uhlaner
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

1 Dr. Benton J. Underwood
Dept. of Psychology
Northwestern University
Evanston, IL 60201

1 Dr. Phyllis Weaver
Graduate School of Education
Harvard University
200 Larsen Hall, Appian Way
Cambridge, MA 02138

Non Govt

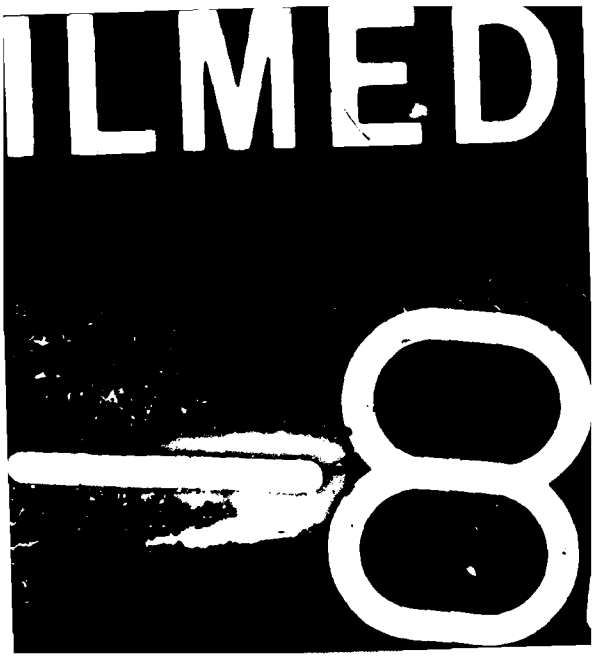
1 Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

1 DR. GERSHOM WELTMAN
PERCEPTRONICS INC.
6271 VARIEL AVE.
WOODLAND HILLS, CA 91367

1 Dr. Keith T. Wescourt
Information Sciences Dept.
The Rand Corporation
1700 Main St.
Santa Monica, CA 90406

1 DR. SUSAN E. WHITELY
PSYCHOLOGY DEPARTMENT
UNIVERSITY OF KANSAS
LAWRENCE, KANSAS 66044

1 Dr. Christopher Wickens
Department of Psychology
University of Illinois


ILMED
8