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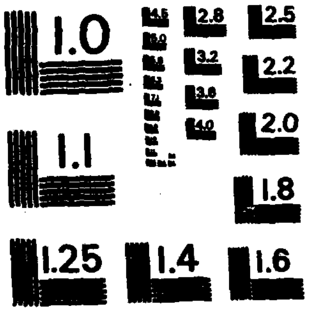

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Exceptional Memory

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K. Anders Ericsson
William G. Chase

Exceptional Memory

Extraordinary feats of memory can be matched or surpassed by people with average memories that have been improved by training

There are scientific records of memory feats that deviate so markedly from the normal that they are called exceptional and are assumed to reflect a memory system structurally different from that of most people. Some recent research involving memory training of normal people has led us to question this distinction. We will first describe the empirical evidence reported in support of the idea that exceptional memory is different from normal memory. Then we will present our research in support of the assertion that normal memory structure is sufficient to explain exceptional memory feats, if we take into account differences in practice and prior experience.

Let us first describe some laws and general characteristics of normal human memory and then specify how exceptional memory deviates from and contradicts them. The contemporary view of the memory system in normal adults is that information can be held primarily in two different storage systems: short-term and long-term memory. When new information is perceived and attended to, it is kept available for a short time but then is irrevocably lost unless it is attended to again, or rehearsed. This temporary storage system is called short-term memory (STM). The amount of information that can be held at one time in STM is severely limited for normal people. To be stored permanently, information has to be placed in long-term memory (LTM), which consists of an essentially unlimited and permanent base for storing information. Information in LTM can be retrieved only by precise retrieval cues, and failure in retrieval is the major cause of loss of information in LTM. For normal people it requires conscious effort and considerable time to commit unrelated information to LTM in a form that makes it available for retrieval.

Fairly early in psychology, attempts were made to measure the capacity of STM. The most common procedure was the memory-span task, in which an experimenter presents a number of items to be recalled in order. The items are presented at a fairly rapid rate (1 item per second) to minimize the amount of information converted to LTM. The interesting conclusion was that the memory span is limited and is approximately the same for many types of symbols: around 7 different digits or consonants and slightly fewer (5 or 6) colors, visually presented geometrical designs, and words. Miller (1956) summarized this research by saying that STM has the capacity to retain 7 plus or minus 2 symbols or chunks. A chunk is a collection of symbols, such as a phone number, that acts as a memory unit: all the symbols of the chunk are forgotten or retrieved together, and there is a single retrieval cue for the chunk.

There have been many reports of individuals whose exceptional feats of memory appear to violate the limitation of STM and other characteristics of normal memory. Most of these memory feats have used numbers and other kinds of meaningless material, similar to those used to test STM in normal people. Around the turn of the century Binet (1894) published a study of the exceptional memory of mental calculators and chess masters. The calculators were able to multiply two 5-digit numbers mentally without external memory aids, and were also able to commit large matrices of digits to memory after a brief presentation. According to the verbal reports of these mental calculators, they stored the presented digits as either auditory or visual images, thus suggesting some primitive copying process and leading to the term "photographic memory."

In the most cited and extensive study of exceptional memory, Luria (1968) examined the memory of a newspaper reporter named S. V. Shereshevskii (S) for over 20 years. S showed an exceptional ability to memorize meaningless information such as nonsense syllables, mathematical formulas, and poems in foreign languages. Although Luria unfortunately provided little actual documentation of S's memory feats, he did publish a detailed description of S's memorization of a matrix containing 50 digits. S looked at the matrix for 3 minutes and then, after the matrix was taken away, was able to describe all the information on the matrix as if it were available to him in a mental picture. Luria argued that S's exceptional memory was structurally different from normal and was based on noncognitive, sensory processes.

A few recent studies have used modern experimental methods to analyze and document the performance of people with exceptional

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memory. The most notable of these studies is Hunt and Love's (1972) analysis of VP, an excellent chess player who displayed the best memory of recent subjects although he is not up to the same level as Luria's S.

Several types of evidence have been cited in support of the idea that exceptional memory is qualitatively different from normal memory. First, there is a marked difference in performance, a difference so large that the exceptional feat is judged to be outside the range of normal subjects. For example, after having had their memory span for digits measured, most people find it inconceivable that they could ever double or triple their performance, regardless of the amount of practice. A second difference concerns the processes and structures involved in the transfer of information to LTM. Subject S reported forming a visual image by simply looking at the digit matrix. Most people form a verbal string by using rote rehearsal, as they do for other types of memorized information such as the names of the months and the national anthem. Furthermore, most people require extensive effort and concentration over prolonged periods of time to memorize meaningless information. If the information is almost photographically copied, it appears unlikely that skill or other cognitive processes are involved. The implicit assumption is that, even with practice, normal people's memory processes are simply not powerful enough to generate the performance exhibited by people with exceptional memories. However, most normal people are simply unaware of the existence of techniques that can be used to improve the memory.

A type of superior memory related to exceptional memory has been observed in experts for their domain of expertise. If a chessboard is shown for 5 seconds, a beginner at chess can reproduce the location of only 4 or 5 pieces. This is exactly what the limits for normal STM would predict. However, a chess master can, after the same short exposure, recall all the pieces on the chessboard virtually perfectly. Experienced chess players at intermediate levels of skill show better memory than the beginner, but worse than the expert. There is thus a clear relation between level of skill and ability to recall. Investigators have demonstrated this relation for a large number of skills, using bridge hands (Charness 1979), circuit diagrams (Egan and Schwartz 1979), and architectural drawings (Akin, in press).

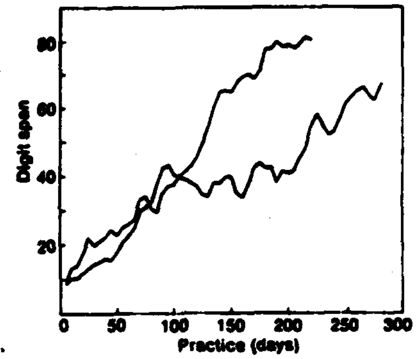


Figure 1. Most normal people can remember a sequence of random numbers only as long as 7 digits, and even people with exceptional memories cannot remember as many as 20 digits. Yet SF, a college student who ran long-distance races, developed a set of mnemonic associations based on running times that enabled him to remember sequences of about 80 digits. His memory span over 20 months of practice is shown in black. DD, another subject who was a long-distance runner, was trained to use SF's system, and his memory span is shown in color.

In his original studies Binet (1894) sent out questionnaires to chess masters, inquiring about their mental representation of chess games. The chess masters almost invariably reported having the chessboard stored as a visual image, like a mental photograph. However, Binet found some differences between regular photographs and these mental visual images: the images did not include the exact color and detailed features of chess pieces or the shadows cast by the pieces, and, in general, the images seemed to take on an abstract or schematic character.

Some more recent research has definitely refuted the notion that chess masters are able to make a visual mental copy of chessboards (Chase and Simon 1973a, b; de Groot 1966). When investigators briefly showed the chess masters completely random arrangements of chess pieces on a chessboard, the masters could recall the locations of only 4 or 5 pieces, which was no better than the novice chess players did with such random boards. Thus, the superior performance of chess masters was closely linked to the presence of meaningful chess patterns, patterns that have become familiar with years of practice.

In the rest of this article, we will argue that both exceptional and expert memory are consistent with the laws and limitations of normal memory, and that all adults can develop these forms of memory through extensive practice. In theory, extensive practice creates a large knowledge base in LTM and new information can be stored efficiently in a retrievable form by associating it with familiar material in the knowledge base.

Our argument is based on three sources of data. First, we will demonstrate that normal adults with modest amounts of practice can achieve memory performance that equals the recorded performance of people with exceptional memories. By closely examining the development of such a memory skill we will show its relation to the limits of normal memory. Second, we will show that the cognitive structures and processes acquired through practice can account for exceptional and expert memory. In particular, we will compare in some detail the performance of our trained subjects with that of people with allegedly exceptional memory. Finally, we will demonstrate that all normal adults exhibit skilled and exceptional memory in a domain where they are experts.

Acquisition of exceptional memory

We decided that it would be particularly interesting to study the effects of practice on the digit-span task, which is generally used to assess the capacity of a person's STM. In this task, a subject is read a sequence of random digits at a rate of about 1 digit per second. If the subject repeats the sequence correctly, then the next sequence is increased by 1 digit; otherwise, the next sequence is decreased by 1 digit. The estimated span of a subject equals the length of a digit sequence that the subject can repeat correctly half the time.

We administered the digit-span task to an undergraduate, SF, for about 1 hour a day, 3 to 5 days a week, for 20 months, or for more than 230 hours of laboratory testing. Although

Table 1. Digit spans of memory experts

Investigator	*Memory expert*	*Digit span*
Binet (1894)	Inaudi	< 12
	Diamondi	< 12
	Arnould	< 12
Müller (1911)	Rückle	18
Luria (1968)	S	< 20
Hunt and Love (1972)	VP	17
Hunter (1977)	Aitken	15

SF had only average memory abilities and average intelligence for a college student, his digit span steadily improved from 7 to around 80 digits, a truly exceptional memory performance (Fig. 1). Normal subjects have spans of around 7 digits and only rarely are spans of over 10 digits observed. Even individuals with allegedly exceptional memory do not come close to this level of performance (Table 1). The highest digit span ever recorded previously is 18 digits, the span of the German mathematics professor Rückle (Müller 1911).

It is important to note that during this entire study SF was in no way coached or instructed in how to improve. However, he was highly motivated and constantly tried different methods to improve his span. His skill was thus self-taught.

In the first 4 sessions of the experiment, SF either rehearsed the entire digit sequence or broke the sequence into two groups and rehearsed the second group. He also occasionally reported noticing numerical patterns, such as 654 and 424. This is exactly what we observe with other normal subjects. During this initial period, SF's memory span stayed within a normal range of 7 to 9 digits.

In the fifth session, SF noticed that some digit groups reminded him of running times for different races. (SF was a good long-distance runner who competed in races throughout the eastern United States.) As soon as he started thinking of some digit groups as running times, his digit span increased markedly. What SF did was begin mentally to encode 3- and 4-digit groups as running times for various races. For example, he remembered 3492 as "3 minutes and 49.2 seconds, near world-record time for running a mile." In the early phases of SF's practice, he discovered only a small number of running-time categories, which meant that he had to remember many digit sequences without mnemonic associations. But during the first 4 months he gradually constructed an elaborate set of mnemonic associations based initially on running times and then supplemented with ages (893 was "89.3 years old, a very old person") and dates (1944 was "near the end of World War II") for those sequences not categorized as running times. Running times account for 62%, and ages 25%, of SF's mnemonic associations.

As soon as we discovered SF's successful technique of associating digit sequences with running times, we attempted to construct a model of his cognitive processes. We simulated the processes involved in receiving and encoding a digit sequence by constructing a computer program that would transform digit sequences into running times. We used our computer model to generate digit sequences that SF would not associate with running times. When he was faced with these uncodable sequences, SF's performance dropped almost to his beginning level. In another experimental session, we presented him with sequences that could all be associated with running times. His performance jumped by 22%, from an average of 16 to an average of 19.5 digits.

This last experiment also demonstrates that SF's memory span for digits was not unlimited even when all the groups of 3 and 4 digits were meaningful. SF was at that time able to remember only three or four such groups in addition to the 5 or 6 digits at the end of a sequence that he rehearsed to himself. It was only after he introduced a new level of encoding, in which the digit groups were combined into "super groups," that SF was able reliably to recall more than four groups. For example, to remember 25 digits, SF normally grouped the digits into three groups of 4 digits each, three groups of 3 digits each, and a 4-digit rehearsal group at the end. One indication of this grouping structure is that when a subject repeats the digits, there is a falling intonation in his voice on the last group of 4 digits and there is a long pause before he repeats the 3-digit group. With further practice, SF continued to introduce further levels into his hierarchical storage of digit groups until he reached his highest memory span of 82 digits. His organization of 80 digits is shown in Figure 2.

In another series of experiments, we demonstrated that SF stored these digits in a retrievable form in LTM, as shown by his ability to recall over 90% of the 200–300 digits presented during an entire session. When SF could regulate the speed of presentation of digits, after about 100 hours of practice he was able to reduce by half the time he needed to memorize 50 digits.

On the basis of these and other experiments, we concluded that SF's memory skill consisted of efficient and rapid storage and retrieval of information in LTM. SF did not achieve his extraordinary performance by simply improving his ability to rehearse digits mentally. In fact, he relied on rehearsal only to remember the last few digits presented in each sequence. He gave the

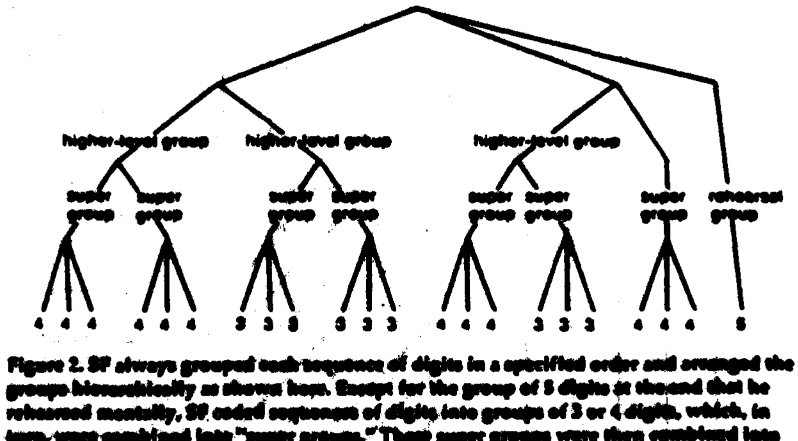


Figure 2. SF always grouped each sequence of digits in a specified order and arranged the groups hierarchically as shown here. Except for the group of 5 digits at the end that he rehearsed mentally, SF coded sequences of digits into groups of 3 or 4 digits, which, in turn, were combined into "super groups." These super groups were then combined into higher-level groups.

other inherently meaningless digits meaningful interpretations as running times, ages, dates, and so on. Throughout his development of the memory skill there is no evidence that SF extended the limits of STM. The largest number of digits for which he generated mnemonic associations was four, and the number of encoded digit groups in a single "super group" was never more than four. Even after 20 months of practice, he almost never rehearsed more than six digits to himself. We also tested his memory span for another kind of symbol—i.e., consonants—and found that it remained at six consonants.

We have elsewhere reported the results of experiments analyzing errors in recall and temporal patterns of recall that strongly support the description we have given here of SF's skill (Chase and Ericsson 1981, 1982; Ericsson et al. 1980). We have also shown that other subjects can acquire the same skill with practice and initial coaching. Using SF's techniques, another long-distance runner, DD, has been able to improve his digit span, which is currently at about 75 digits (see Fig. 1).

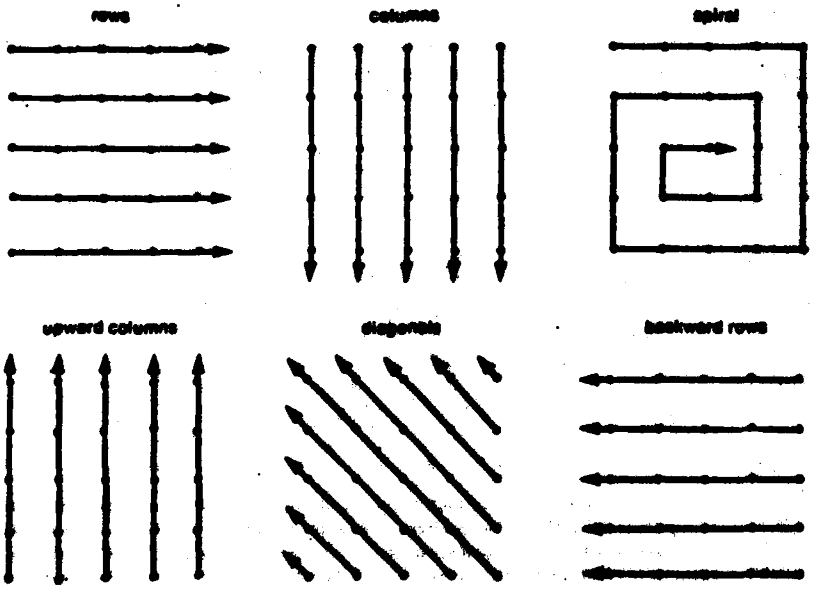
In this series of studies, we have demonstrated that normal adults can perform outstanding feats of memory without extending any of the basic limitations of normal memory. In memory tasks in which normal subjects rely on rehearsal in STM, our trained subjects rapidly encoded the information meaningfully and were able to store it in permanent and retrievable form in LTM.

LTM storage processes

Are the cognitive processes of meaningful encoding and storage in LTM sufficient to account for performances of expert and exceptional memory? Relatively little information is available on the cognitive processes used by exceptional subjects to commit information to memory. However, Müller (1911) analyzed in detail how Rückle, who had the highest observed digit span reported in the literature, memorized digit sequences. Rückle reported dividing 18 digits into three groups of 6 digits and meaningfully encoding each of these groups by using his extensive knowledge of numbers. For example, 893047 was encoded as 893 = 19 × 47; 047 = 47.

Figure 3. At the right is a 25-digit matrix of the type used by Alfred Binet to test his memory experts. Binet asked his subjects to repeat the whole matrix in the various orders shown, or to repeat an individual row as a 5-digit number. If the matrix is memorized as a visual image, retrieving the numbers in any order should be equally fast. However, if the matrix is memorized as a sequence, retrieving it in the order in which it was memorized should be much faster than retrieving it in any other order.

4	7	1	0	2
3	0	4	3	6
2	1	1	4	8
8	7	4	2	9
1	5	2	7	9



From Luria's (1968) analysis of S, we know that S committed information to LTM, as evidenced by his ability to recall the information days, weeks, and years later. S reported that he generated meaningful associations for many types of nonsense materials, such as foreign poems, to aid memorization. (S denied using such associations for numbers. We will return to this fact later.)

Mnemonic associations like those described by S have been known since the time of the ancient Greek orators, who developed techniques to aid them in memorizing lists of items and names. An example of these techniques, which have been refined and extended over the centuries (Lorayne and Lucas 1974; Yates 1966), is the generation of a mental image to connect otherwise unrelated words. The word pair "cow, ball" can be effectively remembered if one forms an image of a cow kicking a ball.

It has been shown fairly recently that even without practice normal people can use these techniques to improve their memory significantly (Bower 1972). In fact, people do not normally commit nonsense information to memory simply by rote rehearsal. Psychological experiments have demonstrated that normal subjects almost invariably generate meaningful associations when they memorize nonsense words (Montague et al. 1966; Prytulak 1971). For example, the nonsense syllable "cts" can be remembered as "cats without an a." Mnemonic techniques appear to be simply more effective versions of methods that people normally use to memorize information, and people can easily learn to use mnemonic techniques to improve their performance. Thus, the techniques used by individuals with exceptional memory are not qualitatively different from the methods used by normal people.

We have tried to show that feats of exceptional memory exhibit the same characteristics as the feats of our trained subjects. We will now compare one subject's performance on a certain task with the performance of the exceptional people. We have selected memorization of matrices of digits as the task, because S regarded numbers as "the simplest type of material" (Luria 1968, p. 60) and because numbers were the only kind of material for which S did not report generating mnemonic associations.

Process and structure of exceptional memory

In comparing people with allegedly exceptional memory to our trained normal subjects, we are interested in showing not only that the performance of the two groups is comparable, but also that their cognitive processes and subsequent memory structures—the ways in which they store information—are similar. The first problem is to evaluate the memory structure.

Fortunately, there are data that have been used to infer the structure of exceptional memory. Suppose that a subject is asked to memorize a matrix of digits like the ones shown in Figures 3 and 4. Binet (1894) used such a procedure to study the memory of mental calculators, and Luria used a similar procedure to assess S's memory structures. The underlying idea is quite simple and straightforward: once a subject has memorized the matrix we can examine the memory structure by seeing how the information is retrieved.

According to the theories that came to be accepted around the turn of the century, there are basically two ways that a matrix can be stored in memory. It can be stored as a list of auditory symbols, the way most people store the alphabet or the national anthem. Alternatively a matrix can be stored visually, which preserves its spatial structure. If the matrix is stored auditorily, then the information can be rapidly retrieved only in the same order in which it was committed to memory. Retrieving the matrix in any other way, such as backward or by columns, would be much harder and would take longer. On the other hand, if the matrix is stored visually, it should be possible to retrieve the information in almost any way with about the same speed. The implicit assumption is that retrieval from a visual image is analogous to scanning a visual display.

To assess how the information was stored, the subjects were instructed to recall the digits in many different ways, several of which are illustrated in Figure 3. The time needed by several mental calculators and other subjects to study and then to retrieve the 25-digit matrix are given in Table 2; Table 3 gives similar results for Luria's 50-digit matrix.

Before we turn to a detailed discussion of these results, let us briefly report how they were originally interpreted. Binet (1894) argued that the data shown in Table 2 supported the reports of the mental calculators Inaudi, who claimed to encode the digits as auditory symbols, and Diamondi, who claimed to encode them visually, as Diamondi was much faster than Inaudi in retrieving the digits. Luria (1968) argued that the data shown in Table 3 upheld S's reports of generating a visual image of the digit matrix, as his retrieval times were about the same regardless of the order in which the digits were recalled. These data are the only objective evidence supporting Luria's claim that S had a structurally unique memory. The rest of S's memory performance is based on standard mnemonic techniques.

We had our trained subject, SF, and a few other undergraduates perform the same tasks (see Tables 2 and 3). Furthermore, we found that Müller (1917) had collected data on normal subjects and on the mathematics professor Rückle for Binet's 25-digit matrix (see Table 2). We can see that the normal subjects took much longer than our trained subject and the exceptional subjects to study the matrices. However, there is no

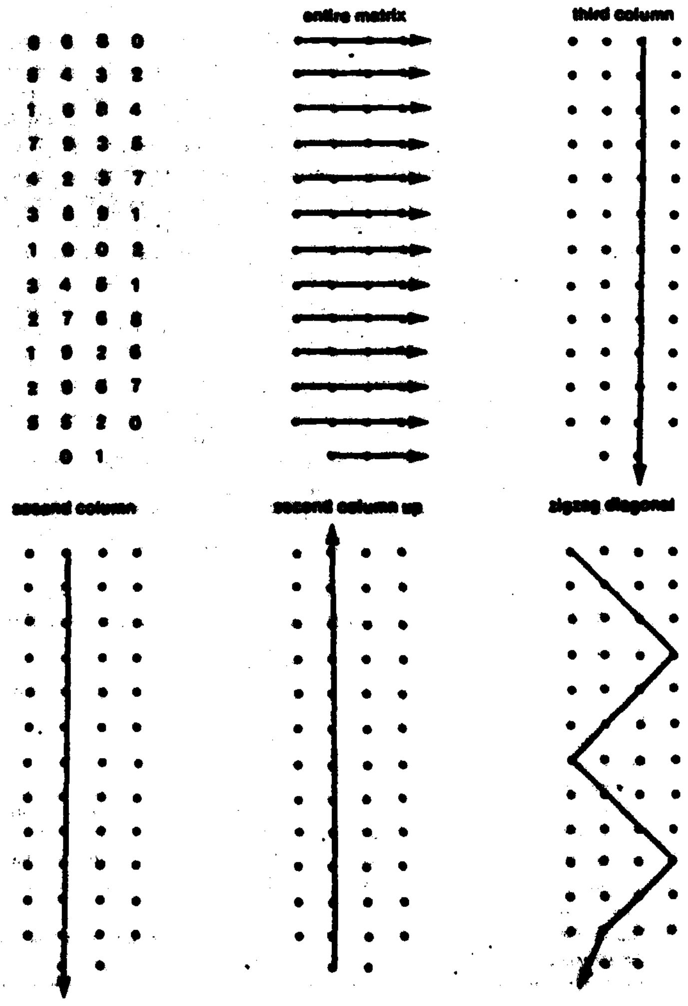


Figure 4. Aleksandr Luria used a 50-digit matrix to test the memory of his subject, S. According to Luria, S's memory was structurally unique because S could retrieve digits in the matrix in any of the orders shown with equal speed.

Table 2. Time (in seconds) needed to study and retrieve Binet's matrix

	Inaudi[a]	*Diamondi*[a]	*Rückle*[b]	*Rückle (more than one year later)*[b]	*SF*	*Normal subjects*[c]	*Number of retrievals*
Study time	45	180	20.2	12.7	26.8	229.6	
Retrieval time							
Rows	19	9	7.2	8.7	41.8	24	5
Individual row as 5-digit number	7	9	7.8	8.3	28.7	31.2	5
Backward rows	—	—	9.0	7.0	22.9	33.9	5
Columns	60	35	23.9	19.1	64.0	71.6	25
Upward columns	96	36	24.6	18.5	58.5	—	25
Spiral	80	36	29.7	8.5	43.3	73.8	11
Diagonals	168	53	58.7	18.4	92.6	124.0	25

[a] Binet 1894

[b] Müller 1917

[c] An average based on the times of eight subjects reported by Müller (1917)

evidence that the mental calculators and S were faster than SF and Rückle. Rather, there is a clear indication to the contrary.

Let us now proceed to the times required to retrieve the memorized digits in different orders. A visual inspection of the retrieval times reveals no clear, systematic differences between the exceptional, trained, and normal subjects. Although it took the normal subjects many times longer than the experts to memorize the matrices, they were able to retrieve parts of the matrices almost as fast as the experts. From experimental studies, we know that the speed of retrieval is closely related to the extra study time spent beyond that required for memorization alone (see, for example, Newell and Rosenbloom 1981). Thus, it will be the relations between different retrieval times of a subject that will give us information about the memory structure, rather than the absolute retrieval times. To take a simple example, are the experts able to retrieve a matrix by columns as fast as by rows? Such a result would support the idea that the experts are retrieving information from an uncoded visual image.

We can measure the similarity of the pattern of retrieval times for any two subjects by calculating the correlation coefficient. A high positive correlation shows a very similar pattern of retrieval times for the subjects and suggests that they have similar memory structures. For the 25-digit matrix shown in Figure 3, the correlations between all subjects are very high and positive; in Table 4 we have given the correlations between the average retrieval time of normal subjects and that of each exceptional subject in Table 2.

When we calculate the corresponding correlations for the 50-digit matrix shown in Figure 4 and the subjects in Table 3, we find them to be low and within chance variation (Table 5). The retrieval times for this matrix appear to be about the same regardless of the retrieval instruction, and this same pattern of uniform times is indicated by all subjects—which would lead to the low correlations in Table 5. The interesting result to notice is that subjects are able to retrieve the entire matrix row by row as fast as they can retrieve a single column.

Given our knowledge of the cognitive processes used by trained subjects, can we account for the observed pattern of retrieval times? SF reported commiting the matrices to memory in a manner similar to the way in which he memorized digits in the digit-span task. Using his mnemonic associations, he coded each row of the matrix as a single digit group, and he stored each row in a memory structure similar to that shown in Figure 2. He retrieved the matrix row by row and extracted the required digit or digits from each row. The time-consuming phase was retrieving the next digit group; once a group was retrieved, finding the digits within a row was almost immediate. Similar verbal reports were obtained from our normal subjects and were given by Rückle (Müller 1911, 1917) as well as the mnemonist

Table 3. Time (in seconds) needed to study and retrieve Luria's matrix

	SF	*SF (one year later)*	*S*[a]	*VP*[b]	*AB*[c]	*S1*[d]	*S2*[d]	*S3*[d]	*S4*[d]	*Average*[d]	*Number of retrievals*
Study time	187	81	180	390	222	798	1,340	686	716	885	
Retrieval time											
Entire matrix	43	57	40	42	51	77	96	48	51	66	13
Third column	41	58	60	66	58	125	117	42	76	90	13
Second column	41	46	25	30	40	81	116	51	46	66	13
Second column up	47	30	30	40	54	112	85	46	63	76	13
Zigzag diagonal	64	58	36	—	62	183	107	96	94	101	12

[a] Luria 1968

[b] Hunt and Love 1972

[c] Subject with mnemonic training

[d] Normal subjects

VP (Hunt and Love 1972).

We have devised a simple model of retrieval, based on these reports, in which subjects store and retrieve these matrices row by row as digit groups in LTM. This model predicts that the time needed to recall a matrix in any order is a linear function of the number of times a new digit group or row is retrieved. In the last column of Tables 2 and 3 we have given, for each retrieval instruction, the number of times a new digit group has to be retrieved. The model does a remarkably good job of predicting retrieval times in Table 2 for the 25-digit matrix: retrieving the matrix by rows, which involves 5 digit groups, is faster than retrieving the matrix by columns, which involves 25 groups, and retrieving rows backward takes about the same time as retrieving them in the natural left-to-right direction. The correlations between the model's predictions and the observed retrieval times are very high for all retrieval instructions and even higher if the unusual instructions—i.e., the spiral and diagonal patterns in Figure 3—are omitted, as shown in the bottom two rows of Table 4. The model further accurately predicts that the retrieval times in Table 3 for the various instructions used with the 50-digit matrix should take approximately the same length of time: the entire matrix as well as single columns requires 13 retrievals.

Because we find considerable similarity and consistency in the pattern of the retrieval times for all subjects, we argue that the difference between normal and exceptional memory lies in the speed of encoding and successful storage in LTM. Amount of practice appears to be the major factor in the speed of storage. Both SF and Rückle showed a remarkable reduction in their study times when they were tested with matrices again after at least a year of intervening practice (see Tables 2 and 3). At the second testing they were clearly faster than the corresponding exceptional subjects.

Is exceptional memory really exceptional?

[illegible]

over 10,000 hours of practice (Chase and Simon 1973a, b). Although we lack data on the mental calculators Inaudi and Diamondi, we know from our studies of another mental calculator, AB, that similar estimates of the amount of practice are reasonable. Information on mathematicians Rückle and Aitken and other expert subjects also provides evidence of extensive practice. Corresponding data on amount of practice are not available for the mnemonists S and VP. However, Hunt and Love (1972) noted that both S and VP were educated in Latvia, whose school system relied primarily on rote memorization, and thus the mnemonists were given ample opportunities and motivation for developing their mnemonics. Further evidence of the importance of extensive practice comes from studies designed to identify the differences in basic cognitive processes between normal and exceptional subjects. Hunt and Love (1972) gave VP a large number of psychometric tests measuring basic cognitive processes. His performance was not outside the range of the best normal subjects on any of the tests except for those concerned with memory.

So far we have argued that superior or exceptional memory is not associated with any structural differences in memory but with practice in the efficient use of LTM. We also believe that such superior memory can be, and is, acquired by any normal adult in certain areas of expertise and skill. Because individuals develop skills in a variety of domains, it is difficult to find a set of skills that all normal adults have invariably acquired. However, all adults are experts in using their native language. Even after a hundred hours of practice and instruction in a new language, a person is still a beginner.

It is well known that normal people's memory for prose is many times better than that for nonsense material (Kintsch 1974; Kintsch and Van Dijk 1978). Although people's long-term retention of exact wording is poor, they virtually always recall sentences that are semantically consistent with the presented sentence. Most errors concern lexical substitutions without effect on meaning, such as exchanging definite and indefinite articles and altering prepositions. Sometimes modifiers, such as adjectives and adverbs, are omitted. In sum, people's long-term retention of prose is based on the semantic content.

What about short-term retention? Several investigators, using slightly different procedures than

Table 4. Correlation coefficients of retrieval time for Binet's matrix

	Inaudi	*Diamondi*	*Rückle*	*Rückle (more than one year later)*	*SF*	*Normal subjects*
Normal subjects	0.96^{a} (N = 5)	0.96^{a} (N = 5)	0.99^{b} (N = 6)	0.80^{a} (N = 6)	0.90^{a} (N = 6)	
Model						
All retrieval instructions	0.76^{c} (N = 6)	0.84^{c} (N = 6)	0.73^{c} (N = 7)	0.98^{b} (N = 7)	0.98^{a} (N = 7)	0.88^{a} (N = 6)
Familiar retrieval instructions	0.92^{c} (N = 4)	1.00^{b} (N = 4)	1.00^{b} (N = 5)	0.99^{b} (N = 5)	0.92^{c} (N = 5)	0.98^{a} (N = 4)

$^{a}p < 0.01$
$^{b}p < 0.001$
$^{c}p < 0.05$

Table 5. Correlation coefficients of retrieval time for Luria's matrix[a]

	[illegible]	[illegible] year later	S	VP	AB[b]
Normal subjects	[illegible]	[illegible]	[illegible]	[illegible]	0.95 (N = 8)

[illegible]

those in the regular memory-span test, have shown that normal subjects are in fact able to retain for a short time the exact wording of sentences, markedly surpassing the normal STM limit of only 6 or so unrelated words (Aaronson and Scarborough 1977; Jarvella 1971).

In order to compare memory for prose directly with the standard estimates of memory span, Ericsson and Karat (1981) used a procedure closely analogous to the digit-span task. They took meaningful sentences with different numbers of words from short stories and novels by Steinbeck. The longer sentences were used intact and were also scrambled to form meaningless sequences of the same words. These two types of stimuli correspond closely to the regular and scrambled chessboards studied by Chase and Simon (1973a, b). Both intact and scrambled sentences were read in the same monotone and at the same speed of one word per second. At the end of each sentence, the subjects wrote down as much of it as they could remember.

There was a striking difference in the amount remembered between the meaningful sentences and the scrambled words. The subjects had perfect recall half the time of scrambled sequences of only about 6 words, in complete agreement with the estimates we cited earlier of memory span for unrelated words. As predicted, the subjects' ability to recall the exact words of meaningful sentences was much better; sentences of 12 to 14 words were recalled perfectly about half the time. Although the average percent of perfectly recalled sentences decreased as the number of words in the sentences increased, several well-formed sentences with as many as 28 words were recalled perfectly by some subjects. To take one example, 2 of 20 subjects recalled the following 28-word sentence perfectly: "She brushed a cloud of hair out of her eyes with the back of her glove and left a smudge of earth on her cheek in doing it."

In terms of the amount recalled, these memory feats by normal subjects seem almost as impressive as those exhibited by the chess masters and digit experts. The question is whether we can account for normal subjects' superior memory for sentences with reference to the same mechanisms that underlie exceptional memory.

We designed an experiment to evaluate the hypothesis that LTM is responsible for the superior memory span for sentences. For scrambled words, little or no LTM would be expected. We presented intact and scrambled sentences alternately, and asked the subjects for immediate written recall after each sentence. The major difference from earlier experiments was that we also unexpectedly asked the subjects to recall all the presented information afterward, when they were cued by a unique word from each sentence.

The main result of this experiment was that the subjects' cued recall of the intact sentences was remarkably high, but their recall of the scrambled sentences was virtually nonexistent. In only 12% of the cases could the subjects recall anything from the scrambled sentences, and in only 4% were they able to recall more than a single word. In contrast, they recalled words from intact sentences 79% of the time, generally remembering more than half the presented words. This result clearly indicates the involvement of LTM in the superior memory for sentences.

In our experiments we have also consistently found systematic individual differences in the ability to recall sentences. Using traditional methods for calculating memory span, we found the span for words in sentences to range from 11.0 to 20.5 words for different subjects. When we analyzed our data in terms of the number of perfectly recalled sentences or the percent of recalled words we found reliable individual differences as well.

We conducted a final experiment to explore the relation between the subjects' language skill and their memory span for sentences. Language skill was assessed by a test of correct language use and verbal reasoning. To be able to refute the importance of general intelligence, we also gave the subjects a test of numeric reasoning. The number of correctly recalled words was very well predicted by both the language usage test ($r = 0.72, p < 0.001$) and the verbal reasoning test ($r = 0.74, p < 0.001$). For the number of correctly recalled whole sentences, the verbal reasoning test ($r = 0.66, p < 0.001$) was a slightly better predictor than the language usage test ($r = 0.50, p < 0.01$). The numeric reasoning test was only weakly related to these measures of accuracy and did not contribute any additional information. Similar results have been reported by Daneman and Carpenter (1980).

It appears that normal people's memory for prose involves the same mechanisms that underlie expert memory. People's memory for prose can exceed their STM capacity if they use their knowledge of semantics and syntax to store information in LTM. Further, one can interpret the large individual differences in prose memory as due primarily to differences in language skill. People who have spent many years building up their language skills have acquired an extensive verbal knowledge base in LTM that can be used more effectively to store the meaning and structure of sentences.

We noted earlier that feats of exceptional memory have been exhibited for information that is unfamiliar or meaningless to normal subjects. Normal subjects' memory for such information is severely limited and appears to reflect some fixed structural limits of the cognitive processing system for briefly presented information. However, we have shown that normal subjects can, through extensive practice, vastly improve their memory for certain types of information, even surpassing the performance of individuals with allegedly exceptional memory. The patterns of retrieval used by these trained normal subjects and by people with exceptional memories for large matrices of digits are similar to the processes used by untrained normal subjects to remember meaningful sentences.

In our analysis of large differences in memory performance, we have found that certain limits remain unchanged. We noted that the number of chunks of information that our subject SF kept in mind was limited to four, regardless of whether the chunks corresponded to digits rehearsed in STM, digits stored as a group, or groups of digits stored as a super group. In fact, we have not found a single exception to this limit in our analysis of the memory performance of normal subjects, experts, and mnemonists.

Exceptional memory is a skill based on learned cognitive processes, developed through extensive practice and experience, that allows for rapid and efficient use of LTM. Further, this skill is developed within the basic abilities and limits of the normal cognitive system. In every recorded feat of exceptional memory we have identified the same components: the importance of prior experience and practice, the availability of meaningful associations, storage in LTM, and efficient retrieval of information from LTM. A single model is adequate to describe all adult memory.

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