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Skilled Memory and Expertise: Mechanisms of Exceptional Performance

12. PERSONAL AUTHOR(S)
K. Anders Ericsson

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Two new studies tested Chase and Ericsson's (1982) three principles of skilled memory in the domain of exceptional digit span. One study showed that encoding a four-digit number as a unit (e.g. coding 3526 as a running time for a race) enables even expert runners to reliably retrieve only the first two digits of the number. The other study demonstrated that in addition to encoding numbers as running times, subjects encoded other patterns and relations between digits. This study also monitored in detail the emergence of a retrieval

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A review of studies of individuals with exceptional memory shows that skilled memory theory can account for all available evidence on exceptional memory. Furthermore, detailed analyses of the memory performance of an exceptional waiter and a chess master support the claim that skilled memory theory can account for the superior memory performance of experts in their domain of expertise. The paper also reports research on particular questions arising from the application of skilled memory theory to expertise. One study tested whether a subject lacking semantic knowledge about chess could achieve superior memory for briefly presented chess positions. A series of other studies concerned the accessibility of large bodies of information in long-term memory and investigated cued recall of large parts memorized by actors.

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The goal of the research reported here has been to extend our knowledge of exceptional memory performance and in particular to explore the generalizability of Chase and Ericsson's (1982) skilled memory theory. This report begins with a short description of skilled memory theory. The next section outlines some remaining issues pertaining to the mechanisms proposed to underly memory for lists of digits. The results of two recent studies on memory for digits are presented, and a recent review of memory skill is reported. The review clearly demonstrates the generalizability and validity of skilled memory theory as an account of memory skill and exceptional memory performance. The second half of this report describes research that investigated whether skilled memory theory can account for the superior memory performance of experts.

Skilled Memory Theory

Chase and Ericsson's (1981, 1982) approach to investigating skilled memory was to give subjects extensive practice on the digit-span task and to monitor the cognitive processes associated with any improvements by requesting retrospective verbal reports during some of the trials. During each session, the subjects were read random digits at the rate of one digit per second; they then recalled the sequence. If they reported the sequence correctly, the next sequence was increased by one digit; otherwise it was decreased by one digit.

In Figure 1, four subjects' average digit spans are shown as a function of practice. The subjects SF, DD, and RE were studied by Chase and Ericsson (1981, 1982; Ericsson, Chase, & Faloon, 1980). NB was studied recently by Ericsson, Fendrich, and Faivre (in preparation). That study will be described in more detail later.

Insert Figure 1 about here

Kliegl, Smith, and Baltes (1986) in West Berlin have trained groups of young and old subjects who have attained exceptional digit spans. Hence the dramatic improvement in digit span as a function of practice is a highly robust and generalizable empirical phenomenon.

In 1982 Chase and Ericsson proposed skilled memory theory to account for this phenomenon and other related characteristics of memory performance. Skilled memory theory assumes that the capacity of attention is limited and argues that exceptional digit span involves storage in long-term memory (LTM). Storage of presented digit lists in LTM is implicated by SF's ability to recall over 90% of the digits presented during a session, which totaled 200-300 digits. Chase and Ericsson (1981) performed a number of experiments with SF in which SF had to perform attention-demanding tasks assumed to totally interfere with any information in short-term memory (STM). These tasks were imposed just after the digits were presented but before SF had to recall them. That these tasks had essentially no effect supports the claim that the digits presented were stored in LTM.

Skilled memory theory acknowledges a constraint on the number of chunks and units that can be attended to or heeded at a single time. According to most authorities, that limit is around four. All four subjects segmented the list of digits presented to them into groups of three or four digits. On those occasions when digit groups consisted of five or six digits, the subjects invariably memorized them as a combination of two smaller groups of no more than four digits.

According to skilled memory theory, rapid storage in and retrieval from LTM is not available to all subjects for all types of information. Accessibility has certain preconditions and hence is consistent with the large body of evidence showing the effects of the limited capacity of STM on thinking and problem solving on unfamiliar tasks.

Chase and Ericsson (1982) identified three principles of skilled memory. First, according to the principle of meaningful encoding, it must be possible to encode information through meaningful associations in terms of knowledge structures in semantic memory. For example, three subjects on the digit-span task were experienced runners on the track teams of their respective universities. They relied on encodings of digit groups as running times, dates, and ages, as illustrated in Table 1.

Insert Table 1 about here

Second, the main constraint on LTM for efficient and accessible storage involves the retrieval of stored information. Skilled memory theory claims that at the time information is stored, special retrieval cues are associated with it and are subsequently used to retrieve it. Prior to the presentation of the digits, the subject must know exactly what sequence of retrieval cues is to be associated with the encoded digit groups. This organized set or sequence of retrieval cues Chase and Ericsson (1981, 1982) called a retrieval structure. At the time of recall, the subject can efficiently access or regenerate the corresponding retrieval cue, which in turn allows the corresponding digit group to be obtained from LTM. An example of a retrieval structure used by the digit-span experts is shown in Figure 2.

Insert Figure 2 about here

At the time of presentation, the subject segments digit groups and encodes the location of each group within the supergroup (e.g., "first," "middle," and "last"). At the time of recall the subject remembers how the list is encoded and can then recall the digit groups using these cues, namely, the first group with four digits, etc.

The best evidence for the use of retrieval structures comes from a number of experiments using cued recall. The subject was able to rapidly retrieve the target digit group with cues corresponding to its location or to the preceding or succeeding digit group (Chase & Ericsson, 1981). Consistent with the hypothesis that the subject uses the same vertical structure during a sequence of digit-span trials, accuracy of recall decreases with trials, which suggests a build-up of interference (Chase & Ericsson, 1982).

Third, according to skilled memory theory, encoding and retrieval operations can be dramatically accelerated by practice, so that memory encoding and retrieval can acquire the storage and access characteristics of STM and can be performed within a few seconds. The second finding was observed during SF's performance on a task involving self-paced memorization of sequentially presented digits. In this task, SF would memorize lists of up to 50 digits at his own pace. He regulated the presentation of individual digits on a CRT by pressing a button. An analysis of the times recorded between button presses showed that all major pauses (representing study time) occurred between digit groups. The average study time for each digit group is given in Figure 3 as a function of the length of the list and the time of testing.

Insert Figure 3 about here

With further practice, SF was able to memorize digit sequences below his current digit span at rates much faster than the rate of one digit per second used in the regular digit-span task. With further practice, the study times for a particular list length were further reduced. This is a particularly interesting finding for two reasons. First, the reduction of study time for a list of fixed length as a function of practice suggests that practice effects in memory skills are similar to the speed-up observed in most other skills with practice (Newell & Rosenbloom, 1981). Second, the fact that ability to memorize longer lists is associated with decreases in the necessary study time for shorter lists implies that with the fixed presentation rate of the regular digit-span procedure, more time is made available for additional processing necessary for encoding the digits in the longer lists.

The recent research has focused on two theoretical issues relevant to the three principles of skilled memory theory. One issue is whether encodings as running times are alone sufficient for meaningful encoding of digit groups. The other issue is whether the same retrieval structure can be used repeatedly on consecutive memory trials.

Encoding of Digit Groups

One issue arising from skilled memory theory is how encoding digits in a three- or four-digit group as a running time could possibly be sufficient for accurate encoding and retrieval of all digits. Chase and Ericsson (1981, 1982) tried to describe SF's meaningful distinctions between similar running times and found that he was able to distinguish between times differing in the first two digits. To explain how SF encoded and retrieved the last two digits at recall, Chase and Ericsson (1981, 1982) proposed additional encoding processes based on interviews with SF. Some recent research (Ericsson & Faivre, in preparation) clarifies the relation between knowledge about running times and memory for actual digit groups. Other research (Ericsson, Fendrich, & Faivre, in preparation) provides empirical evidence on the supplementary encoding processes, which in conjunction with running-time encoding allows for storage of all digits within the four-digit groups.

Encoding of digit groups as running times involves the selection of an appropriate race, for example, 2-mile time, before the quality of the running time for that race is assessed in more detail. This process could be automated by establishing a direct mapping between the first one or two digits and the various races; and in fact some new analyses of such mapping have recently been attempted (Ericsson, Fendrich, & Faivre, in preparation). Perhaps with extensive practice, three- and four-digit groups would become completely unitized and recognized directly even when one of the digits was missing. However, Ericsson and Chase (1981) showed that even after extensive practice, SF required the first two digits, which determine the mnemonic code (for example, type of race) in order to directly retrieve the corresponding digit group. Furthermore, his postsession recall of digit groups was always organized by the mnemonic code.

Encoding of Associations to the Retrieval Structure

According to skilled memory theory, SF was able to recall all digit groups in correct order by associating particular retrieval cues to each digit group at the time of presentation. The exact nature of the encoding processes corresponding to the associations of the digit groups with locations in the retrieval structure is still somewhat unclear. Chase and

Ericsson (1981) have already demonstrated that when a digit group was presented, SF had immediate access to its location within the retrieval structure. SF also had very accurate postsession recall of the location of the digit groups but was often unable to recall adjacent digit groups in the same list. Hence, it is clear that SF associated the location within a supergroup to the encoded digit group.

It is theoretically possible that SF's encoding of the sequential relations of a digit group was completely achieved by a single, direct association between the location within the entire retrieval structure and the encoded digit group. There are arguments both for and against this hypothesis. One argument against it copncerns the interference that is predicted to occur over repeated digit-span trials within a session. Chase and Ericsson (1982) analyzed memory performance as a function of trials within a session for SF and for DD, another subject with exceptional digit span, who is described in more detail later. For both subjects, the probability of perfect recall showed a clear decrease for later trials within the session. However, both subjects were able to recall entire digit lists with a very small number of errors.

Chase and Ericsson (1982) even designed an experiment to maximize interference based on a paradigm developed by Frey and Adesman (1976) to study memory for chess positions. Two digit sequences of equal length were successively presented to DD, who was required to recall the second sequence before he recalled the first. Recall under such maximally interfering conditions was quite high--ranging from almost no errors to 30% errors.

According to traditional views on interference, the decrement found in performance is surprisingly small if the same retrieval cues are assumed to have been used repeatedly. However, a recent study by Bellezza

(1982) shows that the same stimulus item in a paired associate can be used repeatedly for memorizing different associates. If the paired associate is memorized by means of mnemonic imagery, the most recent association can be reliably retrieved. In fact, even associations made for earlier lists were retrieved correctly in 60% to 70% of the cases. There is some question whether Bellezza's (1982) result can be generalized to the repeated use of the location cues in the retrieval structure. In Bellezza's (1982) study familiar words with high imagery value were used. The semantic associations available for these words appear qualitatively different from those for the location cues. Although Bellezza's (1982) subjects had 15 seconds to memorize each associate, similar effects might be attained with much shorter study times after practice. Hence the small interference effects do not completely rule out the sufficiency of direct associations between digit group and retrieval-structure location.

Potentially more damaging to the hypothesis is the assymetric retrieval in the cued-recall task discussed earlier. SF could immediately retrieve the location within the retrieval structure of a given digit group. However, when the location was given as a cue, retrieval of the corresponding digit group was slower, a finding that suggests mediating retrieval activity.

Some evidence suggests that encoding into the retrieval structure is not independent for each digit group and that encodings relating different digit groups are also generated. SF's verbal reports show that he explicitly related digit groups to each other. For example, when two or more digit groups were of the same mnemonic category, such as mile times, SF reported noting that the first occurrence was second place, that is, slower than the second occurrence (Chase & Ericsson, 1981).

Additional encoding of associative relations between digit groups would have empirically observable consequences. Such encoding is possible only when the second and later digit groups of the same supergroup are available in working memory. Hence the encoding time ought to increase as the number of encoded digit groups in the same supergroup increases, and it ought to be particularly long once the last digit group of the supergroup has been encoded. Evidence is presented later in this report for different types of encoding of associations between digit groups, such as alternating ages and mile times for a supergroup of 4 four-digit groups. If encodings at the presentation are made at even higher levels of the retrieval structure, recall should be hierarchically organized and additional processing should occur at each level.

Another line of evidence against direct associations of digit groups to the cues of the retrieval structure comes from results indicating that the retrieval structure is fairly flexible. In the process of improving his digit span, SF explored many different retrieval structures without any devastating decrements in performance (Chase & Ericsson, 1981). SF and other trained subjects memorized digit matrices with structures very different from the retrieval structures they regularly used. Studies of this task are reported below.

Knowledge about Running Times and Encoding of Digit Groups

Two recent studies furnish additional evidence about the encoding of digit groups and the nature of associations to the retrieval structure. Three of the subjects who acquired exceptional digit span reported using their knowledge about running times to form meaningful associations with groups of digits. All three subjects were runners on varsity track teams and had extensive knowledge of running times for different races. The first study (Ericsson & Faivre, in preparation) attempted to determine more directly how well a presented digit group could be encoded and remembered as a function of subjects' knowledge of running times. To test differential knowledge about running times, five elite runners, that is, members of the university track team or more advanced runners, and four recreational runners were used as subjects.

Ericsson and Faivre's study (in preparation) consisted of two sessions separated by a week. In the first session the subjects were interviewed, then presented with 40 random four-digit strings and asked to describe verbally how they would encode each one as a running time. They were told to make their descriptions distinctive so they would remember the four-digit string in a subsequent cued-recall task. The four-digit groups were presented one at a time, and the subjects were given 10 seconds to give their verbal description, which the experimenter wrote down. Shortly after completion of the encoding task, the experimenter read the verbal descriptions in a random order, and the subjects had to give their best guess as to the corresponding four-digit group. A week later the same cued-recall procedure was followed except that in addition to the subjects' own 40 verbal descriptions, 40 verbal descriptions by NB for a different set of four-digit groups were presented in a mixed order.

For each serial position in the four-digit group, immediate and delayed cued recall is given in Figure 4 for elite and recreational runners when their own encodings of digit groups were presented as cues.

Insert Figure 4 about here

The accuracy of recall shown in Figure 4 is reliably better for the elite runners for the first and second digits of a four-digit group after both immediate and delayed recall. The last two digits are recalled with an accuracy not significantly better than guessing.

To what extent can an elite runner use the verbal description of a different runner to reproduce a presented digit group? Elite and recreational runners' reproduction of four-digit combinations corresponding to an expert runner's (NB's) verbal descriptions was not significantly different for the first digit: 50.5% and 38.8% correct for elite and recreational runners respectively. Elite runners reproduced the second digit of one of NB's four-digit groups with reliably better accuracy than recreational runners did: elite runners had 16.5% correct, whereas the recreational runners were at the level of guessing, with 7.5% correct. Hence, the advantage of elite runners over recreational runners does not appear clearly when verbal descriptions by a different runner are presented.

Although elite runners were more accurate than recreational runners in recalling or inferring the individual digits of four-digit groups from verbal descriptions of them as running times, the verbal descriptions appeared to be effective for recall only of the first two digits of a four-digit group. The conclusion from this study is that reliable recall of four-digit groups requires additional encoding beyond the encoding as running times.

Self-Paced Memorization of 21 Digits as a Function of Practice

A regular digit-span trial provides little information about the subject's underlying cognitive processes. The self-paced memorization task provides more informaton about the time required for encoding and storing individual digit groups. Chase and Ericsson (1982, 1988) found a nice correspondence between digit-span performance and the speed of self-paced memorization of digit lists. Ericsson, Fendrich and Faivre (in preparation) decided to monitor the speed at which one subject, NB, memorized a list of 21 digits under self-paced conditions as a function of improvement in her digit span.

NB was a female short-distance runner on the track team at the University of Colorado. She spent the first half of each hour-long practice session on regular digit-span trials and the other half on self-paced memorization of 21 digits. In the latter task, when NB pressed a key on a computer terminal, a digit appeared briefly on the screen. The computer recorded the time interval between each keystroke. NB was instructed to form 4 four-digit groups, leaving five additional digits, which she encoded as a four-digit group and a single digit. After viewing the last digit, NB first recalled the digits and then gave a retrospective verbal report on her encoding of the digit groups. After the first five sessions there was nearly perfect agreement between the grouping NB used for regular digit span trials and the grouping she was instructed to use for the self-paced trials.

Only trials for which NB had perfect recall are reported here. From each of these trials study time for each of the 5 four-digit groups was calculated. The variables recorded for each study time for four-digit groups are listed with a brief description in Table 2.

Insert Table 2 about here

These variables were entered hierarchically in the order listed in a regression analysis to determine whether they significantly influenced study time. The details of these analyses are reported in Ericsson, Fendrich, and Faivre (in preparation).

General Results

From the initial practice session, NB was able to memorize the 21 digits under self-paced conditions. Her average study time for a four-digit group, 15.48 seconds for the first 10 sessions, corresponds to a presentation time of around 4 seconds per digit. Her average study time for a four-digit group towards the end of practice was 5.04 seconds, or 1.26 seconds per digit. As this study time includes the time required simply to press the keys to present the digits, the study time in the self-paced condition is comparable to that in the regular digit-span task, which allowed 1 second of presentation time per digit.

Ideally the reduction of study time for a four-digit group would be monotonic, but NB had considerable problems with tradeoffs between speed and accuracy. To deal with this problem, the analysis grouped the sessions in four consecutive blocks with similar accuracy levels. The average digit spans for these blocks were 11.91, 15.44, 18.39, and 21.28 digits, respectively. All analyses reported here have been aggregated and analyzed for these four blocks. The results are organized around two major themes, the encoding of individual digit groups and the encoding of retrieval structure cues.

Encoding of Individual Digit Groups

One issue remaining from the work with SF was to explain how subjects can rapidly determine what mnemonic category (i.e., type of race) to use for encoding a specific digit group. Furthermore, the running time encoding appears sufficient to determine only the first two digits in a four-digit group. Hence another issue is whether additional encoding processes are operating during the task.

To address the first issue, NB's verbal reports of mnemonic encodings were analyzed. NB relied on five distances of races: 100 meters, 200 meters, 300 meters, 400 meters, and 600 meters. All other running-time encodings, which NB infrequently used, were categorized as miscellaneous.

In Table 3 all digit groups encoded as running times are categorized by the distance of the race and by the first digit of the corresponding four-digit group.

Insert Table 3 about here

When the first digit is not zero, the relation between the first digit and the distance of the race is almost perfect. Excluding the miscellaneous running times, the first nonzero digit determines the corresponding distance in 98.1% of the cases. For the digit groups with a leading zero, the second, nonzero digit predicts the same distance of the race in 96.9% of the cases, and with miscellaneous running times excluded, in 99.2% of the cases. Most of the exceptions to this rule occurred early on in the practice. Hence, in well over 95% of the cases, a single digit could serve as a cue for retrieving the corresponding distance.

An analysis of errors in recalling individual digits in a four-digit group gave convincing evidence of the role of mnemonic encoding. The analysis was restricted to digit groups recalled with only one or two incorrect digits to exclude instances with guessing. For the first and second block, reliable differences in error rates were observed for the different positions within four-digit groups. The first digit had the lowest error rate followed by a somewhat higher error rate for the second digit but much higher error rates for the last two digits. This result replicates the pattern observed by Ericsson and Faivre (in preparation) for untrained subjects.

NB correctly recalled most of the digit groups she studied. This finding raises the issue of what additional encoding processes enabled NB to recall all four digits, especially the last two. From the beginning, NB would report noticing numerical relations within the digit group, such as repetitions of digits (2942) and sequential relations between digits (2398). In the regression analysis, objective variables related to patterns were entered before any of the variables derived from the verbal reports. For the first block, these objective variables did not make a significant contribution, but the verbal-reports variable corresponding to reported patterns did. This variable was significantly correlated with study time for the other blocks but did not have an independent contribution. Ericsson, Fendrich, and Faivre's (in preparation) interpretation of this result is that the numerical patterns were probably not reliably detected; but if they were, they reduced study time. In Blocks 3 and 4, considerable portions (over 10%) of variance in study time were accounted for by objective variables describing the repetitions of digits and the existence of zeros in the four-digit groups.

Associating Digit Groups with Retrieval Structure

All five 4-digit groups would require similar encoding processes for storage of the corresponding digits. If encoding of the individual digit group were sufficient to accomplish subsequent retrieval, no systematic differences in study time would be expected for the position of 4-digit groups within the 21-digit sequence. However, the regression showed highly systematic differences in study time for different positions (17-30% of variance) starting with the second block. In Figure 5 the average study time for different serial positions is shown for Blocks 2, 3, and 4.

Insert Figure 5 about here

NB reported making the first 3 four-digit groups into a unit. The increase of study time for the first three groups is consistent with some additional encoding process relating these groups to each other. Across the three blocks, the slope, or the difference in study time between adjacent digit groups, increases. This pattern is consistent with the proposition that the number of relational encodings is increased with further practice.

Additional evidence for relational encodings comes from the regression analyses. Once all predictor variables were entered in the regression model for a given block, the residuals were analyzed, and sequential correlations between adjacent residuals were computed. For the first three blocks, no reliable deviation from random residuals was found, although for the third block, this deviation was marginally significant. The fourth block had highly reliable correlations between residuals of adjacent study times. Correlations between residuals separated by more than a single step were not significant. To interpret this result, correlations between residuals for study times associated with four-digit groups with adjacent positions were computed. They are shown in Table 4.

Insert Table 4 about here

The negative correlations in Table 4 imply that a correspondingly short study time for a given four-digit group is associated with a longer compensatory study time for the following digit group and vice versa. The strongest association is between the study times of the third and middle digit group and the study times of the fourth digit group.

NB's retrospective reports suggest a possible mechanism for the relation observed between study times for adjacent digit groups within a sequence. Towards the latter half of the training sessions, NB increasingly reported noticing relations between adjacent digit groups. For example, the fourth and fifth digit groups 9023 and 9535 were encoded as running times for 660 yards; and in addition, the fifth group was encoded as the slower running time of the two. The method of encoding the relation between running times of the same subcategory is apparently a rather general comparison process. At one session NB encoded 2 four-digit groups (third and fourth positions) as dates: 1974 = "year" and 1854 = "year but *faster*." These relational encodings occur most reliably when the corresponding digit groups are adjacent in the digit sequence, but also quite often when the digit groups are separated by one or more digit groups. Later in training NB also started to report encoding relations between digits of two adjacent groups, for example 8507-8481, 8923-2383, 8117-6147, 1863-0630 (the corresponding digits in each pair are underlined). Although the frequency of such reports was relatively low—less than one report per list—it suggests that NB compared the digit groups in order to find such relations.

The postsession recall supports the conjecture that NB encoded digit groups as well as their sequential relations. NB perfectly recalled 60% and 75% of digit groups for comparable trials in Blocks 1 and 4 respectively. She also recalled 37% and 57% of the corresponding ordered pairs of digit groups for Blocks 1 and 4 respectively. Hence, NB's postsession recall also suggests that she explicitly encoded ordered relations between digit groups.

Summary

A short-distance runner, NB, attained a digit span of over 20 digits in approximately 100 half-hour sessions of practice. During the second half-hour of each session, NB memorized under self-paced conditions 21 digits organized as 5 four-digit groups. A comprehensive analysis of the data from the self-paced memory trials showed that the mnemonic category, that is, type of race, was almost completely determined by the first digit of each group. The pattern of errors in NB's recall of individual digits showed that most errors, especially early in practice, occurred for the last two digits, a finding consistent with estimates of the distinctiveness of running-time encodings. The regression analysis showed consistently shorter study times when digit groups contained repeating digits or zeros. This provides converging support for additional encoding processes using patterns. With respect to encoding of retrieval cues, the regression analysis showed marked differences in study time as a function of the serial position of the digit group. The pattern of results was consistent with cumulative encoding of relations between digit groups, as were verbal reports and postsession recall data.

Skilled Memory and Exceptional Memory for Digits

As a first step towards showing the generalizability of skilled memory theory as an account of memory in expert-level skills, I briefly review a number of studies documenting exceptional memory performance with digits. A more extensive and detailed description of these studies is available elsewhere (Ericsson, 1985).

For the digit-span task strictly defined as digits presented orally at the rate of 1 digit per second, the number of subjects with exceptional digit spans is quite small. Except for the 4 trained subjects described earlier, only 1 other subject, Professor Rueckle, has been recorded with a digit span over 20 digits. Mueller (1911, 1913) studied this subject's exceptional memory for digits for several years before testing his digit span. A number of subjects have attained digit spans between 12 and 18 digits (Ericsson, 1985), well outside the range for normal adults. These and other subjects have exhibited exceptional memory for digits under self-paced conditions. Most studies of these subjects provide rather detailed accounts of the cognitive processes mediating the memory performance. Some studies simply report the performance, but others attempt to empirically validate subjects' claims that they relied on basic, unmediated storage of the presented information.

The results of the studies assessing the detailed cognitive processes of subjects with exceptional memory performance are remarkably consistent with the three principles of skilled memory (Ericsson, 1985). All subjects in these studies showed evidence of having segmented the presented lists of digits into digit groups, and they verbally reported encoding these digit groups by drawing on preexisting knowledge and patterns. A couple of these exceptional subjects were skilled in mental calculation and had extensive experience in mathematics; they reported using their knowledge of mathematics to encode the digit groups (Bryan, Lindley, & Harter, 1941; Mueller, 1911, 1913). For example, Professor Rueckle reported encoding the following six-digit groups by identifying relations between prime factors of the 2 three-digit numbers. Thus 451697 became $451 = 11 \times \underline{41}$ & $697 = 17 \times \underline{41}$, and 893047 became $893 = 19 \times \underline{47}$ & $047 = \underline{47}$. The mathematicians also used other knowledge, such as dates and patterns, which nonmathematicians have used (Hunt & Love, 1972). The remaining subjects (Gordon, Valentine, & Wilding, 1984; Susukita, 1933, 1934) reported using mnemonic techniques with phonemic recoding, by which two to four digits can be recoded as concrete nouns.

Evidence for retrieval structures is limited and comes from subjects' memorization of lists of digits under self-paced conditions. The most systematic research was done by G. E. Mueller (1911, 1917) on Professor Rueckle. From the systematically longer pauses between certain digit groups during Rueckle's recall of the list, Mueller inferred that Rueckle used a hierarchical organization of long digit lists. One of the best pieces of evidence for Rueckle's retrieval structure comes from cued recall experiments in which Rueckle, when cued with the position of digit groups within the retrieval structure, rapidly recalled them (Mueller, 1917).

Susukita (1933, 1934) described Isahara's retrieval structure, which consisted of a fixed sequence of about 400 physical locations, such as a brook near his house. In memorizing digits Isahara would recode a group of digits into a concrete word and then form a visual image of the word and the first physical location. The next word would be imagined in the second location and so on. At the time of recall, Isahara would use his knowledge about the fixed series of locations to retrieve the images stored there and would then recode the word to identify the presented digits. The mnemonically trained subject studied by Gordon, Valentine, and Wilding (1984) used a similar method relying on a prelearned sequence of concrete objects, like pegs.

The third principle of skilled memory states that with extensive practice, the speed of encoding and storage as well as retrieval is increased and that with sufficient practice these operations can be performed in a matter of seconds, comparable to the time required for STM. Figure 6 shows the study times for a number of subjects differing in expertise and practice.

Insert Figure 6 about here

At the far left of Figure 6 the study times of untrained students are given; at the far right, the study times of the professional mnemonist, Isahara. Of particular interest is the retesting of Professor Rueckle's speed of memorization, which was found to increase considerably after 5 years of further memory testing (Mueller, 1913).

This summary should convey that in one group of studies, memory experts showed wide variability in the details of their cognitive processes but a remarkable consistency at the general level of the three principles of skilled memory.

Another group of the studies have explicitly rejected the claim that cognitive processes mediate exceptional memory performance. Almost 100 years ago, Binet (1894) devised a memory task by which he could distinguish auditory from visual memory representations. Binet wanted to empirically validate the verbal reports of two exceptional mental calculators. One of them, Diamondi, reported using visual imagery, and the other, Inaudi, reported using auditory imagery. Binet had them memorize matrices of 25 digits similar to the one shown in Figure 7.

Insert Figure 7 about here

Once Binet's subjects had memorized a matrix, Binet had them recall the digits in various orders, as shown in Figure 7. The first order is the normal order in which the matrix was read. The next one is the inverse of normal order. With an auditory memory representation, recalling the digits in inverse order should be much slower and more effortful than recalling them in normal order. The next two patterns involve recall along the columns of the matrix. The spiral and diagonal patterns are particularly challenging, and rapid and efficient recall would suggest flexible encoding with visual images.

Table 5 displays the actual times Binet's mnemonists took to recall the digits according to the specified pattern.

Insert Table 5 about here

Consistent with predictions, Binet noted that Diamondi, who claimed to use visual imagery, had overall much faster recall times than Inaudi had with his auditory encodings. Table 5 includes corresponding recall times from the digit-span experts SF and DD; G. E. Mueller's subject, Professor Rueckle; and normal untrained students. Ericsson and Chase (1982) noticed that exceptional and normal subjects have generally similar patterns of recall times.

Recall of digits by column takes much longer than recall by row. The direction of recall had no effect on either recall by row or recall by column. From SF's retrospective verbal reports, it was clear that he encoded each of the five rows of digits as a whole, using mnemonics in chunks. During recall he retrieved all digits in a row together, effortlessly recalling digits in the same row regardless of forward or backward recall order. If recalling a new row or chunk is indeed the time-consuming element in this task, it accounts for the difference between row-wise recall, which requires 5 retrievals of new chunks, and column-wise recall, which requires 25 retrievals of new chunks. Ericsson and Chase (1982) showed that this model expressed as a regression equation fits both Diamondi's and Inaudi's performance quite well, and also fits SF and Professor Rueckle, whose study and recall processes are understood in detail. In fact, the model accounts just as well for the untrained students' average recall times. This suggests that the study times necessary for memorizing the matrix vary among memory experts and between memory experts and normal subjects but that the structure of the memory representation for the encoded matrix is the same across subjects and can be described, at least as a first approximation, as a retrieval structure.

Note that the retrieval structure imposed by the 5x5 matrix, that is, five groups of five digits, dramatically deviates from the retrieval structures subjects normally used. Hence, SF's and DD's rapid study times as well as their retrieval times for a radically different organization imply considerable transfer and flexibility in their encoding and retrieval processes using retrieval structures.

Luria (1968) studied his subject S's flexible recall of a 50-digit matrix to investigate S's claim that he stored the matrix directly as a visual image. Using the same type of data and analyses, Ericsson and Chase (1982) were able to show that the same theoretical model they had used for trained subjects like SF and even for normal subjects could also account for S's recall.

Skilled Memory and Memory Expertise: A Summary

Exceptional memory performance documented by other investigators is remarkably consistent with the three principles of skilled memory. Even alleged exceptions to the mediation of preexisting knowledge (Binet, 1894; Luria, 1968) are indistinguishable in observable performance from subjects relying on meaningful encoding and retrieval structures. The studies of memory experts also provide additional support for the conjecture that encoding and retrieval using retrieval structures can be remarkably flexible and rapid. Professor Rueckle's retrieval of digits for Binet's

25-digit matrix ranged between more than one digit to over three digits per second and implies retrieval of new digit groups in less than a second. Estimates for DD's retrieval of adjacent digit groups in his regular retrieval structure are comparable to this rate. Hence, the conjecture about the attainable speed of retrieval from skilled memory appears to be well supported by empirical evidence.

The structure of exceptional memory skill for digits is particularly interesting because most memory experts acquire their skill quite independently (Ericsson & Faivre, in press). Unlike many other skills, in particular academic skills, memory skills are not taught but are developed by the subjects themselves in a trial-and-error fashion best exemplified by SF. Given the striking individual differences in the knowledge memory experts use for encoding and given the vast amount of practice and time they spend on achieving their memory performance, consistent similarities in the structure of their skills is very interesting and probably reflects some internal processing constraints.

Skilled memory theory postulates that encoding and retrieval operations are constrained by the limitations on the capacity of STM. SF limited his encodings of digit groups to three and four digits and also limited the number of digit groups in a supergroup to three or four. An examination of all documented memory experts shows that they similarly encoded only three to five digits in a single digit group (Ericsson, 1985). We lack detailed information about subjects who encode five digits; but there is clear evidence that Professor Rueckle, who reported encoding six digits in a group, related two groups of three digits in his encodings (Mueller, 1911).

With respect to higher-level encodings like supergroups, the available evidence indicates that the same limitation applies. Even the professional mnemonist Isahara (Susukita, 1933, 1934) limited the number of phonically recoded digit groups that he encoded in a single physical location to four or less. Hence, even at an extremely high level of memory expertise, the same limits on the capacity of encoding operations occur, as has been well documented for laboratory experiments (Broadbent, 1975; Mandler, 1967).

In sum, exceptional memory performance is a reflection of acquired memory skills, which have the structure hypothesized by skilled memory theory.

Skilled Memory and Expertise

This section concerns the relation between expert-level skills, which make increased demands on and require increased capacity for retention of information, and the mechanisms of skilled memory. Any area of expertise readily fulfills the first criterion of skilled memory theory that relevant knowledge be available for meaningfully encoding the presented information. Experts have shown better retention for briefly presented material in a wide range of domains: chess (Chase & Simon, 1973a, 1973b; Charness, 1976; Chi, 1978; de Groot, 1966, 1978; Frey & Adesman, 1976; Lane & Robertson, 1979); bridge (Charness, 1979; Engle & Bukstel, 1978); go (Reitman, 1976); music notation (Sloboda, 1976); electronic circuit diagrams (Egan & Schwartz, 1979); computer programming (McKeithen, Reitman, Rueter, & Hirtle, 1981); and sports, for example, basketball and field hockey (Allard & Burnett, 1985). According to skilled memory theory, the information is stored in LTM even with brief presentation, and hence the length of the presentation time is not critical as long as it is the same for experts and novices.

Superior recall by experts has been demonstrated for texts about baseball (Chiesi, Spilich, & Voss, 1979; Spilich, Vesonder, Chiesi, & Voss, 1979; Voss, Vesonder, & Spilich, 1980). Baseball experts' superior recall was restricted to information relevant to events integral to the baseball game. If the scored recall is restricted to relevant information, then similar superiority of experts' recall has been consistently demonstrated for medical experts (Patel & Groen, 1986). Hence, there is extensive evidence that experts can recall more information presented in their area of expertise than can people who are not experts in that area.

The demands on working memory are different for different areas of expertise, and the conditions under which the information is to be retrieved differ as well. Studies of problem solving in physics (Chi, Feltovitz, & Glaser, 1980; Larkin, McDermott, Simon, & Simon, 1980) have nicely demonstrated how experts encode information about problems in close relation to the underlying solution principles. Studies of text comprehension have focused on the demands of keeping an up-to-date representation of the current situation, that is, of the situational model (van Dijk & Kintsch, 1983), which allows current information to be readily disambiguated and integrated. Other expert-level activities involving planning and design require immediate access of relevant information (Jeffries, Turner, Atwood, & Polson, 1981).

In its most general formulation, skilled memory theory (Ericsson & Staszewski, in press) proposes that information can be encoded and associated with retrieval cues at presentation and that at some later time the same information can be retrieved through these cues. The process bears some resemblance to Tulving's (Tulving & Thomson, 1973) encoding specificity principle with the important difference that the retrieval cues are internally generated according to a desired indexing principle. Furthermore, skilled memory theory proposes that with sufficient practice, the speed and reliability of encoding and retrieval processes will approach those of STM. Crudely speaking, when encountered information is always stored or put in its right place, it can easily be found or retrieved. What constitutes "the correct places" for different types of information in any particular skill or area of expertise still needs, of course, to be determined by the performer. The studies of memory skill described earlier explored only limited sets of possible retrieval cues and retrieval structures. The task of correctly recalling a presented sequence of digits requires only encoding of the digits and their serial order. Yet the memory experts described earlier showed very flexible retrieval of digits from stored matrices of digits. Hence, knowing where some information is stored has been demonstrated to result in rapid and reliable access. A still more sophisticated form of retrieval would be based on the content of the stored information in skilled memory.

The most fruitful way to use skilled memory for content-based retrieval in a domain of expertise would clearly be to generate associations to a number of different retrieval cues based on the content of the presented information. However, little evidence has been reported so far for content-based encoding and retrieval. Furthermore, there are a couple of interesting limitations on mechanisms associating the presented information with retrieval cues based on content. To do this type of encoding, the expert needs to know at the time the information is available in attention exactly how to interpret and encode that information to make <u>all</u> the correct associations with the retrieval cues. In order for the expert to delay encoding or interpretation or to reinterpret the presented information, the retrieval cues must provide flexible access to the information in a more structural fashion.

The next section presents analyses of the retrieval structures of two experts and compares them with the memory experts described previously. This research (Ericsson & Polson, 1988, in press) strongly confirms the principles of meaningful encoding and speed-up with further practice and provides clear evidence from investigations of postsession recall for storage in LTM.

Memory Skill for Dinner Orders

For excellent waiters, taking the dinner orders of a party of customers is only one of many skills. If the waiter memorizes the dinner orders instead of writing them down, he or she risks serving the wrong order to a customer who is not likely to wait serenely while others enjoy their food. Furthermore, while memorizing the orders, the waiter still has to be willing to explain and describe menu items, allow for changes, and so forth. Hence in real life memory skills have to be compatible with interruptions and many other concurrent activities that demand attention.

JC, a waiter who could memorize up to 20 complete dinner orders in an actual restaurant setting, was studied for a 2-year period by Ericsson and Polson (1988, in press). They devised a laboratory analogue in which each person at a table was represented by a card with a picture of a face. Each order was a random combination of one of eight meat entrees, one of five meat temperatures (rare to well-done), one of five salad dressings, and one of three starches (baked potato, rice, or french fries), forming a pool of 600 possible orders. The presentation procedure was self-paced, and the subject indicated when the next order should be read. Subjects were allowed to request any information to be presented again. Tables with three, five, and eight customers were used throughout these studies.

JC's performance on the laboratory analogue of the dinner order task is shown in Figure 8. His study times are dramatically faster than those observed for a group of college students and a group of waiters who regularly memorized dinner orders from tables with three to five customers. Only the group of waiters were able to approach JC's low error rate in recall. Hence even the laboratory version of the memory task shows JC's memory skill to be at an exceptional level.

Insert Figure 8 about here

Not only was JC's performance on the memory task clearly superior to that of the other two groups of subjects, but his cognitive processes during memorization and recall were also qualitatively different. At the time of recall JC would recall all items of a category together in a clockwise fashion for all customers at a table: first all salad dressings, then all temperatures, all steaks, and finally all starches. Thinking aloud protocols from his memorization showed that as a new dinner order was presented, items of each category were encoded together with previously presented items of the same category.

JC encoded the items for each category with a different mnemonic strategy. Salad dressings were encoded as a group of the initial letters of their names (e.g., Bleu cheese, Oil-and-vinegar, Oil-and-vinegar, Thousand island = BOOT or boot). With only three different starches, repetitions were frequent, and JC encoded starches in patterns (e.g., baked potato, rice, rice, baked potato = abba). Temperatures of the meat were all ordered by the degree to which they were cooked (rare to well-done), and JC would encode these relations spatially; that is, Rare, Medium-rare, Medium-well, Rare would be a linear increase from rare to medium-well (omitting medium) down to rare again, expressed by the numbers 1241. The entrees were encoded primarily by association with the position of the person ordering.

It is important to note that these encodings are configural; that is, JC needed to attend simultaneously to all or at least most of the items to access the mnemonic pattern. JC encoded up to five items in a single encoding, which is sufficient for tables of three and five people. For tables of eight people, he grouped the items for the first four and last four people together, two encodings for four items each.

Proof of the existence of retrieval structures could be established ideally by showing that these structures can be used for different types of information and stimuli. Furthermore, it would be important to show that the same retrieval structure can be used even when the order of presentation is dramatically varied. Ericsson and Polson (1988, in press) studied these issues in a series of experiments.

In one of the experiments, JC was as always presented with dinner orders from customers in the standard clockwise order according to their placement around the table. This predictable presentation order was contrasted with presentation orders varying from trial to trial, in which the sequence of customers placing orders was randomly determined for each memory list. In both conditions of this experiment, JC recalled the dinner orders by categories, and the order of items followed the standard clockwise order. JC's accuracy of recall was very high and did not differ between conditions.

An analysis of his study times showed that the only reliable difference between the two conditions occurred for study times for table sizes of eight customers. The absence of differences for table sizes of three and five customers suggests that items can be associated with the appropriate retrieval cues regardless of presentation order as long as only a single group of items for each category is involved. For table sizes of eight customers, JC used two equal groups corresponding to Customers 1-4 and Customers 5-8 for each item category. With random presentation, he had to store and maintain items in both of these groups until all four items corresponding to one of the groups had been presented. Ericsson and Polson (in press) showed that accumulating all of the items for Customers 1-4 or Customers 5-8 and thus being able to store that group away led to a reliable decrease in JC's study time for the next dinner order. Think-aloud protocols from memorization of tables with the random presentation order showed that JC immediately encoded items with their position within the retrieval structure and continued rehearsal of all items until all four items of a group had been presented (Ericsson & Polson, in press).

In two experiments, Ericsson and Polson (1988, in press) examined whether JC's memory skill would transfer to information other than dinner orders. The first experiment used lists with dinner orders and also materials with categories that matched the structural properties of categories in the dinner orders. The ordered category of meat temperatures ranging from rare to well-done was matched with a category of time intervals ranging from second to week. The five salad dressings were mapped onto five names of flowers with unique initial letters to allow for continued use of the first-letter mnemonic. The three starches were matched against three metals, and eight names of animals corresponded to the entrees.

After two to three sessions JC showed close to the same performance on the new category items as he did for dinner orders in the first experiment. All available indicators showed that he used the same processes for both the dinner orders and the new category material. In both conditions JC recalled the material by category, and even the order in which the categories were recalled was the same.

Figure 9 displays study times for individual dinner orders for the three list lengths and two types of material.

Insert Figure 9 about here

The correspondence of study times for the two types of material in Figure 9 is remarkable. Furthermore, the study time increases steadily for the first four customers and distinctly decreases for Customer 5. This pattern of study times is additional evidence for the encoding of tables of eight customers as two groups, Customers 1-4 and Customers 5-8. Think-aloud protocols showed that JC used the mnemonic encodings described earlier when he memorized matching categories in the new material.

In the second experiment on transfer, JC was presented with items from categories in formats designed to hinder him from using his mnemonic encoding processes and his category-based storage. His performance was dramatically impaired, and in at least one condition his recall was no longer based on category but instead on the order in which the information was presented.

In sum, JC was able to use his retrieval structure in a flexible manner when the presentation order was dramatically varied. Furthermore, he was able to use the same structure to encode unfamiliar material that had a structure compatible with the mnemonic methods he used for dinner orders. With a few hours of practice on the unfamiliar material, JC's memory skill showed complete transfer. However, transfer was dramatically reduced when JC memorized material lacking a compatible structure and organization.

A number of empirical results show that JC did not solely rely on associating items with the cues of the retrieval structure. In fact, the encoded mnemonic relations between items appear critical for long-term storage of the information. The pattern of increasing study times for individual orders as more items are maintained in a group suggests such relational encoding activity, which in turn is similar to the pattern of encoding times observed for the digit experts SF and NB. The importance for JC of the encoding of relations between items is best demonstrated in the restrictions on his transfer to new material. On a more speculative note, there are interesting similarities between the relational encodings reported by JC and those reported by SF and NB for relations between digit groups.

Chess

Chess has been considered a prototypical domain for studies of expertise since DeGroot's (1965/1978) and Chase and Simon's (1973a, 1973b) pioneering studies. Much of our current knowledge of expertise and high levels of acquired skill comes from or was inspired by these classic studies.

The primary focus of this section is on a special variant of chess known as blindfold chess. It appears that any chess player with a level of skill approaching that of a chess master is able to play blindfold chess essentially without practice at or close to his or her regular chess-playing strength. This ability is similar to the remarkably good memory of strong chess players for briefly presented chess positions shown by DeGroot (1965/1978, 1966) and Chase and Simon (1973a, 1973b). I will also briefly report on a training study in which a subject with a minimal knowledge of chess received extended practice on the recall of briefly presented chess positions.

Skilled Memory Theory and Memory for Chess Positions

The superior memory of chess masters for briefly presented chess positions was initially proposed by Chase and Simon (1973a, 1973b) to be mediated by larger chunks of chess pieces stored in STM. Further studies have shown that storage in STM is not necessary for recall and that the chess positions are encoded in LTM during their 5-second exposure time (Charness, 1976; Frey & Adesman, 1976). The encoding in LTM appears to be based on meaningful encoding of the relation of chess pieces. Lane and Robertson (1979) found that good chess players selecting the best move for a chess position (meaningful encoding) remembered as much about the chess configuration in a surprise recall (incidental condition) as they did when they had been told about the recall in advance (intentional condition). When the task was changed to a perceptual task that required players to find the number of chess pieces on light and dark squares, a large difference in memory was found between the intentional and incidental memory conditions.

Chase and Ericsson (1982) suggested that the superior memory of chess experts was consistent with skilled memory theory. The presented chess position is rapidly encoded in LTM by means of relevant knowledge and meaningful patterns of chess pieces. The rapid extraction of meaningful patterns of chess pieces has been nicely demonstrated by Chase and Simon (1973a, 1973b) and Chi (1978), who also found evidence for overlapping patterns or chunks, that is, for a single chess piece belonging to more than one chunk. From retrospective verbal reports of grand masters and masters after brief exposures to chess positions, de Groot (1965/1978) found clear evidence for perception of chess pieces in chunks (complexes) and for encodings relating chunks to each other to form a global encoding of the position. It appears necessary to postulate global and integrating encodings to account for the ability of chess experts to accurately recall more than one briefly presented chess position (Frey & Adesman, 1976).

Until recently, the evidence on representation of chess positions has been restricted to free recall. Through the use of cued recall we would be more able to assess the simultaneous availability of information about a presented chess position. Recent studies by Ericsson and Oliver (1984, in preparation) of blindfold chess and cued-recall of information from memorized chess positions have assessed the availability of information about the chess position and clarified the possible role of retrieval structures in such retrieval.

Blindfold Chess and Retrieval from Memorized Chess Positions

In blindfold chess extreme demands are made on a player's memory representation of the current chess configuration. To play blindfold chess near the level of his or her regular chess-playing ability, a chess player needs not only an accurate account of the current chess position but also rapid and flexible access to information about the chess position that supports selection of the best possible next move. Ericsson and Oliver's work (1984, in preparation) investigated the suggestion that the flexible retrieval of information about a chess position is mediated by a retrieval structure. They studied a young male chess player, PS, who was rated just below the level of chess master. PS had played blindfold chess a few times prior to this series of experimental studies, and a pilot study confirmed his claim that he could play blindfold chess at close to his normal playing strength.

In the first study, PS was presented with individual chess moves on a CRT and instructed to play out the game mentally. After about 40 plies into a game, Ericsson and Oliver evaluated PS's memory for the then-current chess position. Each of the 64 squares of a chessboard can be uniquely specified by the corresponding column, which is denoted by one of the letters _a_ through _h_, and by the corresponding row, which is denoted by a number from _1_ to _8_. Ericsson and Oliver's method was to present the chess notation for one square of the chessboard, for example a4 or g2, and to ask PS to name the piece in that square or report "nothing" as fast as possible. All 64 squares of the chessboard were probed with this method in random order. For purposes of comparison, Ericsson and Oliver also had PS follow the same procedure with an actual chessboard on which he could move the pieces and see the chess position under consideratioon at the time of the test.

Somewhat surprisingly, PS required only around 2 seconds to make a move in the blindfold condition. If anything, this response time was faster than the corresponding times for the perceptual condition. PS was very accurate--over 95% correct--in responding to the probes in the test of his memory for a particular chess position. His average latency of response to a probe for a square on the chessboard was around 2 seconds for the blindfold condition, about a second slower than his response when he could see the chess position. Considering the rapid updating of the chess position prior to testing, PS's rapid access of the contents of any square of the chessboard is remarkable and suggests that he used structural cues corresponding to a location on the chessboard to retrieve information about which chess piece, if any, was located in the corresponding square for a particular chess position. If PS could use structural cues, his flexible access to the chess position in memory would be similar to access of a perceptually available chess position.

A straightforward prediction from the hypothesis that structural cues are used to access information from a chess position stored in memory is that considerable interference will occur if concurrent retrieval from two different chess positions is required. In another experiment, rather than mentally playing through 30 to 40 moves to reach a middle-game chess position, PS memorized two middle-game chess positions presented in sequence. The average study time for each board was 11 seconds, which incidentally corresponds to about two 5-second exposures to a given chess position. After PS had memorized the two positions, he was probed for the contents of the 64 squares on both boards according to one of three presentation orders. In the sequential condition, all squares of one position were probed in random order and then all squares of the other position. In the alternating condition, randomly selected squares from both positions were probed in a strict, alternating fashion. In the third condition, the squares probed were randomly selected from both positions. PS's speed for saying the contents of probed locations differed distinctly for these recall conditions. Probes randomly selected from the two boards took 2.4 seconds, and in this condition there was no reliable speed-up with further probes. Probes alternating between the two boards were intermediate with an average recall latency of 1.9 seconds, and in this condition there was a reliable but small decrease in recall latency.

In Figure 10 the recall latencies for the sequential condition are plotted. The first couple of recall latencies in this condition are indistinguishable from the recall latencies of the other condition; but after just a few successive retrievals from the same board, retrieval is very fast. In Figure 10, there is clearly a peak corresponding to the start of retrieval from the other board at Trial 65. It is remarkable that within about 3 probes from this new board, retrieval is as fast as it was for the first board, which at this point was well entrenched in PS's mind. The retrieval times are just over a second, which incidentally is close to the times observed for perceptually available chess positions in the blindfold-chess experiment.

Insert Figure 10 about here

These results are consistent with the use of structural retrieval cues in that only a single chess position at a time can be thus accessed. Additional support for this interpretation comes from a detailed analysis of the data in the random order condition. This analysis examined runs of various lengths when PS consecutively retrieved probes from the same board. Figure 11 shows his recall latency as a function of the number of times a square on the same board was recalled on the immediately preceding trials. The benefit of recalling from the same board on successive trials is clear, and it increases with further retrievals from the same board.

Insert Figure 11 about here

Another implication of the use of structural cues to retrieve information from the chess position is that PS should have been able to retrieve information that was not related to the meaningful relations among chess pieces. After memorizing the board, he was probed for the number of pieces in each row and column and in all 49 possible instances of 4 adjacent locations forming a 2x2 square, for example the squares a1, a2, b1, and b2. Alternating with a randomized sequence of these complex probes were probes for the contents of individual squares. In this experiment PS was again urged to be accurate, and his accuracy was 98.5%

for the complex probes and 99% for the simple probes.

Figure 12 shows the average retrieval time for simple location probes (1.3 seconds), 2x2 squares (3.9 seconds), and rows (5.4 seconds) and columns (5.2 seconds). It also shows the time to report the corresponding information from a perceptually available chessboard. Although the retrieval times are impressively rapid, a considerable difference between retrieval from memory and perceptual report remains.

Insert Figure 12 about here

In a final condition, PS was told to relax the accuracy criterion and concentrate on speed. The response latencies for the same types of probes are given in Figure 13. The reduction in retrieval time for the complex memory probes is close to 50%. For the complex probes, the difference between perceptual and memory retrieval is reduced to a second, and for simple probes to about 200 msec. That is, retrieval of pieces from memory was faster than the naming of pieces in the earlier condition in which accuracy was stressed and the positions were perceptually available. How much did this speed-up cost in terms of accuracy? Essentially nothing! Accuracy for simple probes remained at 99% and was only slightly reduced to 95.1% for the complex probes.

Insert Figure 13 about here

This last experiment also made it possible to compare the mechanisms underlying retrieval from memory and a perceptually available chess position. The fact that these processes are qualitatively different is apparent when the patterns of retrieval time across types of probes are compared. In the perceptually available condition, the number of pieces in rows and columns is retrieved faster than for the 2x2 squares, even though the number of squares considered in a row or column is twice as large. In the memory condition, the number of pieces in rows and columns takes much longer to retrieve than the number in 2x2 squares, a finding that is consistent with some form of serial processing of the individual squares.

In another series of experiments, Ericsson and Oliver (1984, in preparation) examined the retrieval of chess-related information such as the number of black pieces attacking a square. The retrieval of the number of attacks appears to be governed by a sophisticated search constrained by knowledge about the chess position. One of Ericsson and Oliver's last experiments addressed the concern that PS might use some of the study time to make additional encodings not normally done during a 5-second exposure. In this experiment, PS was shown the chess positions for 5 seconds, and the cued recall test followed immediately. PS's accuracy of recall hardly dropped at all and was 96% correct for location of pieces. His retrieval times were almost indistinguishable from those in the earlier experiments and for information about individual squares averaged 1.4 seconds.

In sum, several experiments using cued-recall procedures demonstrated that PS was able to access information about any part of the chess position within seconds. PS was particularly fast in naming the pieces in randomly determined locations of the chessboard. When time is subtracted for perception of the probe on the CRT, PS's time for actual retrieval is consistently less than one second. Hence, PS appears to have associated the pieces of the chess position with retrieval cues specifying their locations and thereby gained flexible access to the information about the chess position.

Skilled memory in chess and memory for dinner orders

The exceptional memory of both the chess master and the expert waiter is consistent with the three principles of skilled memory. In both examples there was evidence for encodings drawing on knowledge and patterns and on use of retrieval cues at encoding and retrieval. Evidence for speed-up was obtained for both the waiter (Ericsson & Polson, in press) and the chess master (Ericsson & Oliver, in preparation) in further testing.

Equally interesting are the striking differences in the details of these experts' retrieval structures. Each of these differences can be viewed as a straightforward consequence of the demands of each expert's respective skill. The waiter was influenced by his environment and required more flexibility in storage to anticipate the order in which information (i.e., dinner orders) would be presented; but he knew exactly how the information should be encoded at the time of presentation. The situation was quite different for the chess master. In blindfold chess it is essential for the player to be able to review all possible move sequences for a given chess position. If a chess position were directly encoded in terms of its significant relations for a particular plan or strategy, it would be nearly impossible for the player to change in response to an opponent's unexpected moves. From Ericsson and Oliver's (1984) analyses, it appears that the chess master preserved a representation of the chess position that allowed him to search and explore it as he would a perceptually available chess position.

These two case studies represent only a modest beginning in the analysis of the memory mechanisms associated with expertise. They demonstrate the feasibility of detailed analysis and also provide converging support for the theory of skilled memory.

The necessity of deep knowledge about chess for superior recall of briefly presented chess positions.

The original Chase and Simon (1973a, 1973b) account as well as the account in terms of skilled memory theory of chess masters' superior memory of chess positions is based on the assumption that extensive knowledge of chess is critical to exceptional memory performance. To acquire a chess masters' knowledge of chess is estimated to take 10,000 hours of practice, or 10 years of intensive chess playing. A subject lacking knowledge about chess is predicted to be unable to recall briefly presented chess positions even after considerable practice. Ericsson and Harris (1988) investigated whether exceptional memory for chess positions could develop without corresponding development of chess expertise.

Ericsson and Harris (1988) studied the effects of practice on memory for chess positions, each of which was presented once for 5 seconds. The subject, BB, was a female undergraduate with minimal experience of chess. Before the study she knew only the names of the pieces and their legal moves. Approximately three times a week she received an hour of practice, which consisted of presentation and immediate recall of about 10 middle-game chess positions. Each position was taken from chess books and displayed between 24 and 28 chess pieces. Before the end of the spring semester when she began the study, BB completed 43 training sessions.

The average percentage of correctly recalled pieces for each training session is shown in Figure 14. BB's recall performance was 18% for the first training session, a percentage that corresponds to almost 5 correctly placed pieces for each chess position and is nearly the same as the recall performance obtained by Chase and Simon (1973a) for beginning chess players. At the end of the training phase, BB's recall performance was 67% or more than 17 correctly placed pieces for each position. This performance matches that of the master-level chess player studied by Chase and Simon (1973a), who recalled about 64%, or 16 chess pieces. Evidently BB attained in less than 50 hours a level of recall performance that usually requires several thousand hours of chess playing! BB continued her practice sessions intermittently through the summer and fall. Her recall performance during this time remained at about 60% correct.

Insert Figure 14 about here

On three occasions at an early, middle, and late stage of practice, BB's recall of randomly arranged chess positions was tested. Her recall on these occasions was 12.6%, 16.3% and 15.2% respectively. Hence, there was no indication that BB's ability to recall random chess positions was improved beyond her initial ability to recall four chess pieces. These results are remarkably consistent with those obtained by Chase and Simon (1973a, 1973b) for random chessboards with players ranging from beginners to chess masters. Furthermore, Ericsson and Harris (1988) were able to show that BB's memory for chess positions presented for 5 seconds was not stored in STM. In a separate experiment, BB's recall performance was not significantly affected when she had to count backwards by threes immediately after the presentation of a position. Similarly, Charness (1976) has shown that experienced chess players' recall of a chess position is not influenced by tasks asssumed to erase information stored in STM.

One might think that BB's encoding processes were the same as those of experienced chess players because she performed as well as they did on the same tasks; but in fact, they were different.

Initial evidence about BB's encoding processes came from spontaneous comments she made during the initial training sessions. During the continued practice period, verbal protocols were obtained more systematically, especially during five special sessions. Retrospective reports of her encoding processes were collected directly after the 5-second exposures of the chess positions. These reports showed that BB scanned the chess positions in an order reflecting the spatial layout of the pieces. A sample retrospective report from one of the trials is given in Table 6.

Insert Table 6 about here

The important function of BB's scan path was to maximize the rapid detection of familiar patterns or chunks. Several types of patterns are mentioned in BB's retrospective reports. One type occurred when chess pieces were left in their starting positions (e.g., "There were five pieces in their original positions in the black row. That's how I code it. Then I go back and try to remember which pieces they were"). Another type occurred when the chess positions reflected sequences of commonly occurring moves, as in the case of castled kings and finachetted bishops. BB was familiar with castling but did not know the terminology for finachetted bishops. She developed her own labels, some of which are shown in Figure 15, to encode pieces at locations on the board where finachetted bishops could occur. Several other configurations not shown were encoded as variations on candlesticks, such as a "backwards candlestick" and "half candlestick". Still other types of patterns were duets or perceptual configurations, like pawn chains forming diagonals ("saw three pawns in a diagonal"). Finally, BB encoded rows of pieces as sequences, such as "three pawns, a queen and a knight," "one,two,three[pawns], queen."

Insert Figure 15 about here

The verbal reports suggest that BB searched the chess position to find familiar patterns. During the continued practice period, BB was instructed to identify the pieces belonging to a single pattern or chunk. On average she would identify four patterns for each chess board position. On the average, these patterns were made up of 4 pieces. The accuracy of her recall for pieces that belonged to patterns was 97% compared to 89% for the pieces that did not belong to patterns. Hence, the patterns seemed to serve as units of recall, although recall of these units was hardly all-or-none. An analysis of BB's reports showed that the patterns she identified were quite similar across memory trials. The patterns reflected arrangements of pieces that were perceptually salient and drew minimally on knowledge of chess playing. In contrast to the chess expert, BB did not use attack or defend relationships among the pieces to encode the chess board positions. Her most frequently reported patterns matched the most frequent configurations of chess pieces in master-level chess games determined by de Groot (1966) from a statistical analysis of a large number of middle-game positions. In sum, BB was able to attain a level of recall performance for briefly presented chess positions that matched that of chess players with many years of experience. A close examination of her memory encodings showed the use of perceptual patterns and capitalization on redundancies across chess positions but no dependence on the more meaningful relationships among the pieces that a chess expert might use.

Ericsson and Harris's (1988) case study shows clearly that exceptional memory performance for middle-game chess positions can be realized in more than one way and that analysis of verbal reports can reveal the detailed structure of mediating knowledge and cognitive processes (see Ericsson & Oliver, in press-a, for further elaboration). The study also proves that when a motivated subject is given a memory task essentially lacking in inherent meaning, that subject can still use a large number of general patterns in LTM to capture regularities and redundancies in the stimuli and to rapidly encode the presented information in LTM.

Access to Large Bodies of Information in Long-Term Memory

Efficient and reliable selection of knowledge from a vast store of knowledge in LTM is one of the key characteristics of expertise. Medical students differ from expert doctors in their less extensive knowledge about diseases, but perhaps more clearly in their inability to access some relevant knowledge that they do have (Feltovich, Johnson, Moller, & Swanson, 1984). In the account given by skilled memory theory, the initial encoding of presented information is critical for subsequent access to and processing of that information. However, it seems impossible at this time to make a detailed study and description of the vast amount of knowledge experts possess and of its elaborate organization. Oliver and Ericsson (1986, in preparation) followed a different approach. They studied a domain in which subjects acquired large amounts of rigorously specified information.

Oliver and Ericsson (1986, in preparation) were initially intrigued with actors' memory for two reasons. First, the amount of information actors must learn is very large, far exceeding the amount of information typically learned in laboratory experiments. It is not entirely clear whether current models and theories of memory can be extended to memory for large amounts of information that are acquired gradually over a period of days or weeks. Of course, gradual learning occurs during the acquisition of many skills, particularly academic skills, and is thus inherently interesting. Second, much of the information actors have in memory can be specified because it is based on the scripts of plays. Only rarely can investigators of naturally occurring memory skills specify the contents of their subjects' memory because of large variability in people's learning. For instance, text books and class notes strongly influence, but do not strictly determine, how students' knowledge of course material is represented and organized in memory—otherwise, educating students would be easy to do! In contrast, the content of an actor's part is known, and Oliver and Ericsson could test the accessibility of information known to be in an actor's memory.

Oliver and Ericsson's rearch addressed three topics. First, they investigated the accessibility of the verbatim wording of parts to determine whether recall of a part is dependent on context (Godden & Baddely, 1975) or on highly reconstructive processes (Neisser, 1976), as would be expected given the highly meaningful format of a part. Second, they explored the representation or organization of parts in memory and asked whether parts are encoded hierarchically so that their objective organization as scenes, speeches, sentences, phrases has clear psychological consequences. Third, they studied the accessibility of meaningful information that actors must encode to perform a part.

The subjects who participated in Oliver and Ericsson's (1986, in preparation) experiments were mostly recruited from a local Shakespeare festival held each summer in Boulder, CO. Three plays were performed in rotation at each summer festival, and the major actors were required to play more than one role. Several other actors were recruited who were performing in plays staged by the University of Colorado Drama Department. All subjects had received academic training and had considerable acting experience. They had either very large parts (3000 words or more) or several reasonably large roles (1000 words or more). The single largest part memorized by a subject was Hamlet, which is about 10,000 words long. Preliminary tests of the actors' accuracy when reciting their parts showed that their memory was very exact, with only a very few words emended or substituted.

Many of the subjects provided estimates of the time it took them to learn their parts. Of the 100 hours they spent studying and rehearsing each part, relatively few hours were explicitly spent on memorization. Most time was spent experimenting and practicing the delivery of lines.

The actors were always tested on their memory for their own parts. The actors' official scripts were transcribed in a computer-readable format. Specially designed programs were used to randomly sample probes, or memory cues, according to constraints that varied with the particular experimental design. The subjects were tested one at a time in a quiet room. They were seated before a CRT screen attached to a computer that controlled stimulus presentation and timed vocal responses. Typically, a subject saw a memory probe on the screen and then was expected to respond out loud by giving the correct answer to the probe. The accuracy and the time between the appearance of the probe and the verbal response served as dependent variables. Brief pauses of several seconds occurred between individual trials. The subjects were given rests between blocks of trials, usually every 50 trials. In some experiments, the subjects were asked to give retrospective verbal reports after randomly selected trials. The subjects were asked not to anticipate the task of giving verbal reports and were encouraged to report only what they definitely remembered having thought prior to their responses.

Accessibility of Verbatim Wording

The size of the memory structure corresponding to a part must be very large. In addition to remembering the thousands of words spoken by his or her character, the actor must know what movements, gestures, and intonation of voice are to accompany almost every word. These details of meaning and nuances of performance are enacted in a very stereotyped way from one performance to the next, implying that they are very well learned and are part of the stable representation of a part in LTM.

An actor recalls a part sequentially. Parts are nearly always retrieved a speech at a time and in the order that speeches appear within scenes. Of course, the words within speeches form a chain of utterances that make sense when recited in a strict order. This imposed serial order on recalling a part may have marked consequences on the memory representation. Research by Rubin (1977) shows that people often rely on successive scanning to recall texts that they have memorized by rote and can only partially recall at the time of testing. Rubin had subjects recall the Lord's Prayer, the Gettysburg Address, and other texts that Americans are often coerced into memorizing. Rubin (1977) found a marked recency effect--that is, subjects could typically recite portions from the beginning of a text up to a first impasse from which they could proceed no further. Since verbatim memory is similarly involved in actors' memory for their parts, it seemed likely that actors too might rely on sequential scanning to recall their parts.

Alternatively, sequential access to a part in memory might be mediated by a context-dependent retrieval process. Such a retrieval process might depend on the actor's being aware of a sequence of cues made available to him or her as the play progresses. At a given time, the actor is aware of the words just uttered on stage, the meaning of those words, the gestures and emotions enacted on stage, etc. These multiple sources of information might combine to form highly effective retrieval cues for subsequent words to be uttered and actions to be performed. By presenting very simple memory probes to subjects, Oliver and Ericsson were able to determine how much information could reliably cue memory for words from the actor's part.

In an early experiment, Oliver and Ericsson presented unique strings of one to four words drawn from three actors' largest two roles. In this experiment only, the subjects were asked to generate several words from their part that were adjacent to or contained the probe. For example, an actor portraying Hamlet, when presented the probe "question," could respond with "that is the question", or "Whether 'tis," or "question. Whether 'tis"; any of these responses is an unambiguous sign that his verbatim memory of the part was correctly evoked by the probe. Before each block of 48 trials the subjects were told which part they would be retrieving from or merely told that the probes could come from either of two parts. In Blocks 1 and 4, each subject retrieved lines from one of his or her parts; in Block 2, each subject retrieved lines from the other part; and in Block 3, each subject retrieved lines from these two parts combined and did not know before the presentation of a given probe which of the parts it came from. The probes in Block 3 were selected so that they never occurred in both parts.

The results of the experiment showed that the length of the probe had a large effect on speed and accuracy of retrieval. Correct responses to the probes within 10 seconds occurred 69%, 90% and 97% of the time for the one-, two-, and four-word probes respectively. Speed of retrieval was similarly facilitated with correct reaction times of 2.41, 1.78, and 1.51 seconds for the one-, two- and four-word probes respectively. Surprisingly, there were no reliable differences in retrieval performance for the different blocks; the subjects appeared to respond equally well regardless of whether they knew which part the probes were to come from.

The facilitating effect of probe length on retrieval was replicated several times. In one replication, probes of one, two, and four words were sampled from 5 subjects' largest parts. The subjects were given 15 seconds to respond out loud with the words in their parts that immediately followed the probes. Thus, in contrast to the previous experiment, the correct answers were precisely constrained to particular words. The one-, two-, and four-word probes were accurately retrieved 77%, 91%, and 99% of the time respectively. There was also an effect of probe length on log-transformed reaction time, with one-, two-, and four-word probes being retrieved in 2.18, 1.93, and 1.67 seconds respectively.

In another replication, 3 subjects were presented with probes of varying lengths and were tested two times. The subjects were presented with 1-, 2-, 4-, and 6-word probes in a session well before they were to perform their parts. The six-word probes were included to provide more informative clues than the four-word probes did because the four-word probes might not have been recalled at earlier stages of practice. Some of the same probes were used in both sessions. There was little difference in performance between the two sessions, suggesting that overlearning the parts between the time the subjects went off book and finally performed the parts was not critical for direct access. Interestingly, subjects responded to the six-word probes more slowly than to the four word probes, although the accuracy of retrival was the same for both. This result shows that the additional information beyond the four-word probes was not useful; in fact, the additional time to read the longer probes slowed performance.

How directly actors access words from a part was investigated in a further series of experiments. If access were mediated by such information as the part or scene being probed, precuing the subjects with information about the scene or part could be expected to facilitate retrieval and reduce possible interference among parts.

If a part forms a structure that can be strongly focused upon when it is searched in memory, there should be little interference from other parts in memory. Thus, when subjects know which part a probe comes from, other instances of the same probe in a different memorized part should not interfere with retrieval. Lack of interference of this kind has been taken as evidence for separate memory structures consisting of thematically related concepts (e.g., Myers, O'Brien, Balota, & Toyofuku, 1984) and, in bilingual individuals, of entire lexicons (e.g., Scarborough, Gerard, & Cortese, 1984). Unique words were identified within the combined text of the two parts for three actors. In addition, words were identified that occurred exactly once in each of the two parts, and these were labeled overlapped probes. Probes were constructed by presenting the name of the part (e.g., DESDEMONA) followed either by the selected word (one-word probe) or the selected word along with the previous word in the part (two-word probe) in equal proportions. The probes were presented in a random order, and the name of the part was presented to the subjects for 3 seconds before the probes appeared. The subjects were instructed to say out loud the words in their parts that immediately followed the probes. Two-word probes were included in the design to determine whether they would form holistic cues that could be easily retrieved despite other occurrences of the constituent words elsewhere in the actors' parts.

The subjects were far less successful at retrieving the overlapped probes (41%) than they were at retrieving unique probes (74%). There were no main effects or interactions involving the number of words in the probes. Analyses of the response times yielded no reliable effects, perhaps because so few of the probes were retrieved that statistical power was reduced. The poor accessibility with the overlapped probes strongly suggests that information about the part is not useful for retrieval in this task and that the principal cues for retrieval are the words.

Although it appears that actors may not always be able to restrict their search to a single part if instructed to, the role that global information plays in retrieval is still unclear. It was possible that telling the subject which part was to be retrieved from reduced, although it did not eliminate, interference and that responding was generally facilitated. Global information was manipulated in another experiment by precuing subjects with the name of the part they were to retrieve from on some trials, and telling them to retrieve from either of two parts on other trials.

The 3 subjects who participated in the previous experiment and an additional subject participated in the experiment on global information. From each actor's scripts equal numbers of unique words were selected from each part. Two-word probes were constructed by adding the subsequent words from the actors' parts for half of these selected words. Subjects were shown the name of the part (e.g., VIOLA) or the word EITHER, followed by a one-word or two-word probe. On half of the trials the name of the part preceded the probes, and on the other half the word EITHER preceded the probes. The subjects' task was to respond out loud with the words from their parts that followed the probes.

Probability of recall within 15 seconds differed only as a function of number of words in the probe. The percentage of correctly recalled words was 62% and 86% for the one- and two-word probes respectively. The analysis of the log-transformed reaction times for correct retrievals showed a reliable difference for the length of the probe and for the availability of information about the part, but no interaction between these variables. The average response time for the experiment was 2.37 seconds. Providing the name of the part facilitated response speed by .40 seconds; providing an additional word to the one-word probes facilitated response speed by .35 seconds. In sum, adding an extra word to the one-word probes both reduced retrieval time and increased the probability of retrieval, whereas identifying the part to be probed faclitated only response speed.

Because the precuing effect found in the previous experiment was relatively small, it is difficult to argue that information about the part is important for retrieval. Names of parts may not be effective cues because the representation of a part in memory is too informationally dense (Hayes-Roth, 1977) or complex. Entire parts may simply encompass too many other units, such as speeches and scenes, to be activated as wholes. Scenes, however, may provide units that are better integrated. Reference to a scene might cue memory for constellations of events and emotions that could be held in mind and used as retrieval cues in a way that reference to an entire part could not.

In the next experiment, three types of probes were used to determine whether scene precuing could both facilitate retrieval and prevent interference. Three subjects were told on 1/4 of the trials which of two scenes of a part the probe came from (precue-unique probes), and on 1/4 of the trials they were told only that the probe could come from either of two scenes (either-unique probes). Each probe appeared only once in the entire part. On the remaining 1/2 of the trials, probes were presented that appeared once in a specified scene and once elsewhere in the part (overlapped probes). Unlike previous experiments, only single words were used as probes. The subjects were always told which scene they were to focus on for these probes. Verbal protocols, as in the first two experiments, were collected on half of the trials.

The probability of successful recall within 15 seconds did not greatly differ between the precue-unique probes (80%) and the either-unique probes (78%); however, the precue-overlapped probes (56%) were retrieved significantly less often. An analysis of the log-transformed reaction times showed a similar pattern of results. The average response times for correct retrievals were 3.10, 2.97 and 3.85 seconds for precue-unique, either-unique and precue-overlap conditions respectively. These results indicate that providing information about the scene did not significantly facilitate retrieval or prevent interference during retrieval.

The results from all of these experiments show that actors have remarkable access to the wording of their parts and that they cannot focus their search at will upon a part or scene. The subjects were unable to search their memory for words from a part or scene without associative interference from another part or scene they had memorized. in addition, information specifying which part or scene was to be probed did not greatly facilitate retrieval. The small facilitation of speed of retrieval by part precuing was the single piece of evidence that parts can be activated separately. Further research is called for to better understand the conditions under which the effects of precuing are obtained.

Perhaps the most striking finding from Oliver and Ericsson's research is that in relatively brief periods of time, actors learn their parts in such a way that they are directly accessible with minimal cues. A large body of information is simultaneously accessible, and attention can be diffusely focused on several parts at once without seriously affecting retrieval. This finding is all the more surprising considering that the actors did not learn their parts with the aim of having direct access to individual phrase units.

Representation of Parts in Memory

An actor's part is organized in a way that would be expected to influence how it is represented in memory. The part is divided into acts and scenes, the scenes into speeches, the speeches into sentences, the sentences into phrases, the phrases into words.

Using a probe latency task, Oliver and Ericsson (in preparation) found evidence for the hierarchical organization of a part in memory. In one experiment representative of their findings, all probes were four words in length and were drawn from the largest roles performed by the subjects. For half of the probes the subjects were to retrieve the words from their parts that immediately preceded the probes and for the other half they were to retrieve words that immediately followed the probes. Underlined blank spaces preceding or following the probes indicated to the subjects which words from their parts were to be retrieved. The first grouping of probes were all adjacent to sentence boundaries (demarcated by periods, question marks, and exclamation points) in the actors' parts. Sentence boundaries were selected randomly without replacement so that no more than one probe was ever associated with the same sentence boundary. Equal numbers of probes were selected such that they either immediately preceded or followed sentence bondaries, or they were shifted one word to the left or right of the sentence boundary. For the second grouping of probes, equal numbers of four-word strings were sampled from the beginning and end of speeches. When the probes began speeches, the subjects were to retrieve the last word of their immediately preceding speech; and, likewise, when the probes ended speeches, the subjects were to retrieve the first word of the speech that immediately followed. Retrieving across sentence boundaries was slower than any retrieval within boundaries. The reaction times for conditions involving retrieval within boundaries did not greatly differ from one another. Crossing speech boundaries, particularly backwards, required a fair amount of time. It is interesting, however, that jumping to the first word of the following speech took approximately the same amount of time as going backwards across sentence boundaries to immediately adjacent words.

The relatively long times required by the subjects to cross speech and sentence boundaries indicates that processes beyond direct retrieval processes are sometimes required to retrieve words adjacent to the probes. That words within the same sentence can be retrieved quickly suggests that these words are encoded as part of the same unit, which can be directly retrieved. These findings can be accounted for by assuming that representation of a part that has been memorized verbatim is segmented into sentences and speeches. Sentences may in turn be segmented into phrase units or chunks, although boundaries within sentences are not easy to identify. When the subject must retrieve a word from a chunk that is adjacent to the one in which the probe falls, the subject must first retrieve the adjacent chunk and then unpack it. During normal recitation of a part, associations between chunks, presumably mediated in part by meaning, permit orderly retrieval of the lines. Retrieval of the beginnings of speeches, however, sometimes requires accessing organizing information in memory, such as cue lines spoken by other actors, action and positioning on stage, and so on. Thus, the hierarchical organization of the part has clear consequences for retrieval, provided that the task requires the subject to use this organization, as it does when the subject is required to jump to the next sentence or speech. However, it appears that several words can cue recall of individual phrase units without mediation by other information in the hierarchy. It also appears that sequential scanning for information in parts must be slow and effortful because time-consuming retrieval processes are required to cross sentence and speech boundaries.

In other experiments Oliver and Ericsson (in preparation) have looked at the effect of sentence boundaries on retrieval. In all cases, additional time was required to cross boundaries, even after subjects practiced on the same probes. The results strongly suggest that parts, like other verbatim memories, are stored as chunks.

Effects of Meaning on Retrieval

The meaning of a part as well as the words is represented in an actor's memory. Obviously, an actor must understand a part thoroughly to give a creditable performance. The meaning of the words may therefore also provide useful retrieval cues and be used in the encoding of a part in memory.

One experiment investigated whether combinations of words formed configurations that were better cues to memory than the constituent words were. In research on cued recall of memorized sentences, many investigators have explored whether the recall of multiword cues can be accounted for as independent contributions of individual words or whether additional configural effects are present. Oliver and Ericsson obtained recall estimates for single-word cues and were able to determine whether the recall of two-word probes showed so-called configural effects. Four out of 5 subjects retrieved two-word probes more accurately than would be predicted from the retrievability of constituent words. Thus, subjects were probably using the meaning derived from the combination of the words to cue retrieval, an explanation that accounts for at least some of the advantage of the longer probes.

Another experiment investigated how fast subjects could assign pronominal reference. Strings of four words were identified in the actors' parts that contained single instances of pronouns. The subjects, when shown these probes one at a time on a CRT, were asked to respond out loud with the names of characters that these pronouns referred to. The subjects could disambiguate the pronouns very rapidly, in about 2 seconds. However, they took slightly more time to name characters than they did to respond with the next word in their parts, a finding suggesting that the wording of a part is more directly accessible than references are. The rapid access to pronominal reference shows rapid access to meaning.

Generalizable Findings

Actors certainly differ from other experts in their goals and in their manner of acquiring knowledge. Inferences from these experiments to the cognitive processes of other experts are therefore questionable. Nevertheless, actors in the cued-recall experiments were performing an organization task. Their immediate access to memory using fragments of phrases evolved as a side effect of memorizing the parts. In this regard the actors' immediate access of phrases in a part is comparable to the superior memory of experts for briefly presented information in their domain of expertise and to chess masters' ability to play blindfold chess. Furthermore, the studies of actors' access to their parts demonstrate that rapid access to a large body of highly similar and interrelated chunks of information is possible. These studies also show that access is determined almost exclusively by unique surface cues and unique combinations of surface cues with minimal effects of context. The bottom-up character of the retrieval of stored information in LTM is consistent with the rapid and unmediated access of knowledge in experts in chess (de Groot, 1978) and medicine (Feltovich et al., 1984). Further empirical and theoretical work is necessary before more than tentative generalizations can be made from the actors' access of their parts to experts' access of their vast knowledge.

Concluding Remarks

Chase and Ericsson (1981; Ericsson, Chase & Faloon, 1980) sought to determine how digit-span performance that improved through practice could be reconciled with an STM of limited capacity. Chase and Ericsson made a detailed analysis of a single subject, SF, and attempted to induce generalizable mechanisms, which they have called the principles of skilled memory. Verbal reports were critical to Chase and Ericsson's analyses of SF's acquired memory skill. Newell and Simon (1972) had collected verbal reports in their study of problem solving, and Simon used them in a wide range of case studies (Simon, 1979). Chase and Ericsson's use of verbal reports was different from that of previous research in two respects. First, Chase and Ericsson obtained an extremely large number of verbal reports from the same subject while he performed similar tasks. Second and more important, they analyzed these reports to identify hypothetical mechanisms, which were evaluated in specially designed experiments. These experiments have consistently confirmed the cognitive processes reflected in the verbal reports.

Although verbal reports were central to the assessment of the structure of memory skill, analysis of other types of data were essential for discovering other characteristics of improved memory performance. The general goal of these experiments has been to provide a detailed account of memory skill that is consistent with all available types of data. Subsequent research on skilled memory, which has been supported by ONR, has extended the methods for establishing converging support for hypothesized processing mechanisms in single subjects. (For a comprehensive discussion of the way different types of data reflect a common cognitive process, see Ericsson & Oliver, in press-b.) However, obtaining a detailed description of a single subject's cognitive processes is only a prerequisite for identifying generalizable principles of memory.

In the introduction I argued that it was necessary to obtain a detailed description of the encoding processes used by different subjects. The case studies discussed in this report support that argument; they show marked individual differences in the knowledge and retrieval structures subjects used to encode presented information (Ericsson, 1987). Even for the subjects selected for their extensive knowledge of running times, reliable differences were observed in their preferred encodings of digit groups and their preferred grouping of digits in their retrieval structures. In spite of these individual differences in the details of memory skill, the three principles of skilled memory—meaningful encoding, use of retrieval structures, and speed-up of encoding and retrieval—describe the characteristics not only of memory skills but also of other skills that make demands on extended working memory.

The research on the effects of practice on memory performance is also relevant to the identification of cognitive functions that cannot be improved through practice. The development of skilled memory is not a passive consequence of practice. The studies of the acquisition of skills in particular demonstrated that subjects deliberately searched for relevant knowledge for encodings and also evaluated potential retrieval cues by trial and error. The acquisition of skilled memory is hence an active process by which useful encodings and ways of reducing interference are discovered.

Given the constant pressure on both the students and experts to discover the best methods of encoding information in the studies described, it is remarkable that this research has uncovered such consistent evidence for an optimal number of units that can be contained in a single encoding. For life-long memory experts and trained students, the optimal number appears to be three or four units. Even after extensive practice, the limits on the capacity of their attention appear to correspond closely to those of untrained subjects studied under laboratory conditions (Broadbent, 1975; Mandler, 1967). However, although the available evidence indicates that storage of new information in LTM is limited by the fixed capacity of attention, the capacity to store information in highly available form, that is, a form functionally equivalent to storage in STM, can be dramatically improved with practice, within the constraints acknowledged in skilled memory theory.

This report has described the detailed structure of cognitive processes involved in the encoding and retrieval of information in memory. However, the general intent of this research has been to describe the structure and content of any cognitive processes involving preexisting knowledge and acquired cognitive structures. The research initiated by Chase and Ericsson (1981, 1982) demonstrates that dramatic changes in performance can be produced through practice and that an individual's improvement in performance follows a very orderly pattern, which facilitates detailed assessment of the corresponding cognitive processes. The stable structure of one individual's acquired skill provides much better conditions for detailed analysis and theory-driven experimentation than does the traditional group experiment. Only through detailed analyses of individual subjects will future research uncover the limits and possibilities of the mind.

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Figure Captions

Figure 1. Digit span as a function of practice for SF (filled circles), DD (filled triangles), RE (filled squares), and NB (open circles).

Figure 2. Proposed hierarchical organization of SF's memory encoding of thirty presented digits. The first level contains mnemonic encodings of digit-groups and the second level consists of supergroups, where the relative location of several digit groups are encoded. [From Ericsson (1985)]

Figure 3. The average study time per digit group for SF at three different times during practice. [From Chase and Ericsson (1981)]

Figure 4. Percent correct cued recall of presented four-digit groups as a function of the position of the digit within the four-digit group for expert runners (circles) and recreational runners (triangles) at a short delay (unfilled symbols), and 1-week delay (filled symbols).

Figure 5. Average study time for four-digit groups as a function of their serial position within a 21-digit list memorized under self-paced conditions shown separately for the last three blocks of training sessions, i.e., Block 2 (triangles), Block 3 (circles), and Block 4 (squares).

Figure 6. The amount of study time required for memorization of a given number of digits for normal subjects (average study time for a group of subjects (Lyon, 1917)), for the mental calculator Diamondi and the mnemonist Arnauld (the reported times by Binet (1894) include time to recall the digits), for R in 1906 (I) and in 1911 (II), (Mueller, 1913), and for Isihara (Susukita, 1933). [From Ericsson (1985)]

Figure 7. At the top 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 five-digit number.

Figure 8. Study times for individual "dinner orders" as a function of order of presentation for dinner-order (circles) and animal-list (filled circles) conditions in Experiment 3; for lists of 3 "orders" (upper panel), of 5 "orders" (middle panel), and of 8 "orders" (lower panel). [From Ericsson and Polson (in press)]

Figure 9. Mean total study times as a function of "table size" for the three types of experimental lists and dinner orders (control) in Experiment 4.

Figure 10. Mean reaction time to name the piece, if any, occupying a specified square of one of the two chess positions as a function of serial order of probe and three presentation conditions.

Figure 11. Average reaction time in the piece-retrieval task in the random condition as a function of the number of consecutive times that the same chess position had been retrieved from an immediately preceding retrieval trial.

Figure 12. Average reaction time in the piece-retrieval task and the piece-counting task for 2x2 squares and rows (R) and columns (C) for perceptually available chess positions and for memorized chess positions.

Figure 13. Average reaction time in the piece-retrieval task and the piece-counting task for 2x2 squares and rows (R) and columns (C) for memorized and perceptually available chess positions with an instruction to respond rapidly.

Figure 14. Improvement in the recall of chess positions as function of practice for BB.

Figure 15. Examples of the patterns used by BB to encode chess positions with her verbal labels.

Distribution List

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1030 Green Street
Pasadena, CA 91101

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Learning and Development
National Institute of Education
1200 19th Street, NW
Washington, DC 20208

Table 1. Examples of mnemonic encodings.

3526 ------> 3 minutes 52.6 seconds near world record mile time
90.26 ------> 90.26 seconds for 660 yards
1874 ------> "year"
9675 ------> two people's ages: 96 and 75 years old

Table 2. Description of encoded information for predictor variables entered into the hierarchical regression analysis of log-transformed study times for individual digit groups. The order of entry into the analysis is shown below.

<u>Source of Differences</u>

1. Test-session.
2. Serial position of digit group within 21-digit list.
3. List number with session (trial number).
4. Characteristics of digits within digit-group.
   a. Repeating digits.
   b. Availability of zeros.
   c. Occurrence of adjacent digits that were ascending or descending, i.e., 56 or 98 respectively.
5. Verbal report variables for each digit group.
   a. Reported pattern.
   b. Reported mnemonic encoding.

Table 3 A frequency table relating the first digit of a digit group and the distance used to encode the digit group as a running time.

Type of distance for running time	1	2	3	4	5	6	7	8	9
(meters)									
100	90	1						1	2
200		141	115					2	1
300				121					1
400			2		112	105	121	3	5
600								80	81
Other	2	1	1					4	2

Table 4. Correlations of residuals for specific positions of digit groups for the 4th and last block.

		Position of 4-digit group within 21-digit list				
		1st	2nd	3rd	4th	5th
	1st		0.003	-0.061	-0.146	-0.078
Position of 4-digit group within 21-digit list	2nd			-0.330**	-0.032	-0.109
	3rd				-0.483***	-0.143
	4th					-0.342**

** $p<0.01$
*** $p<0.001$
$n=65$

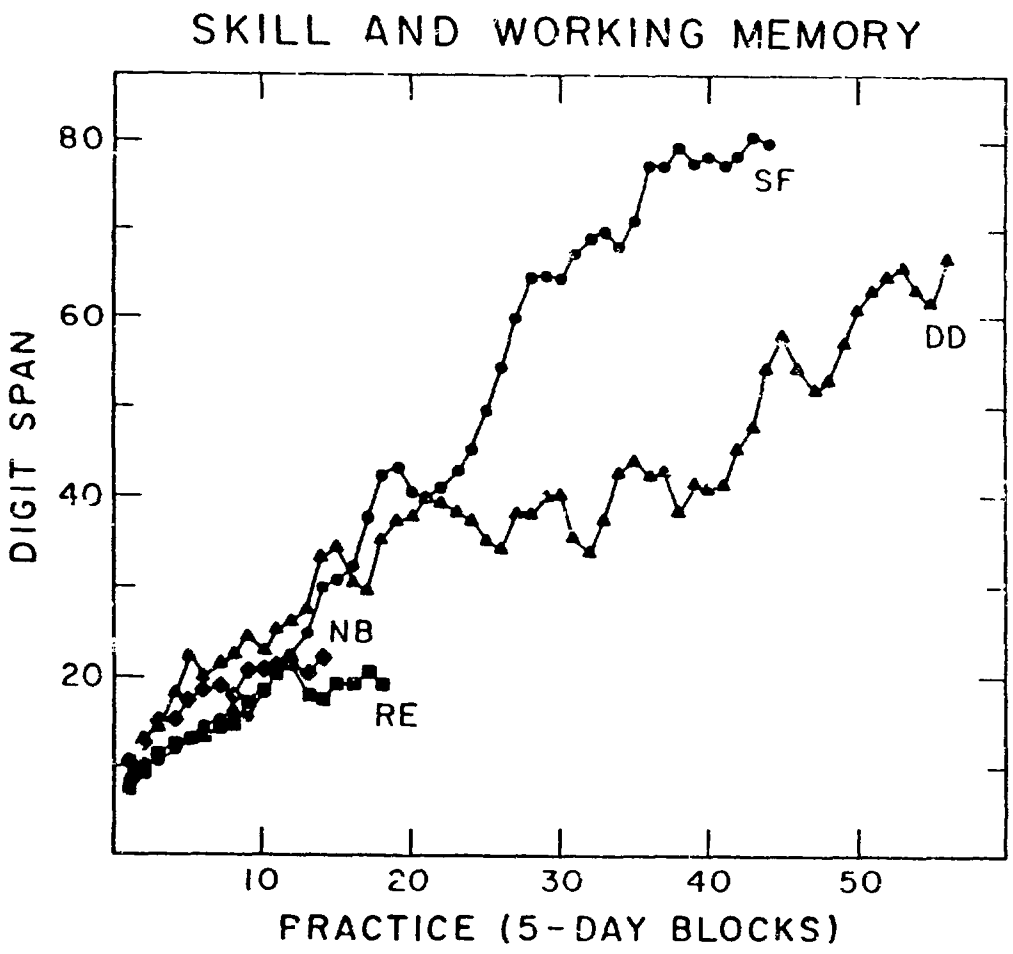
Table 5. Time in seconds needed to study and retrieve Binet's matrix.

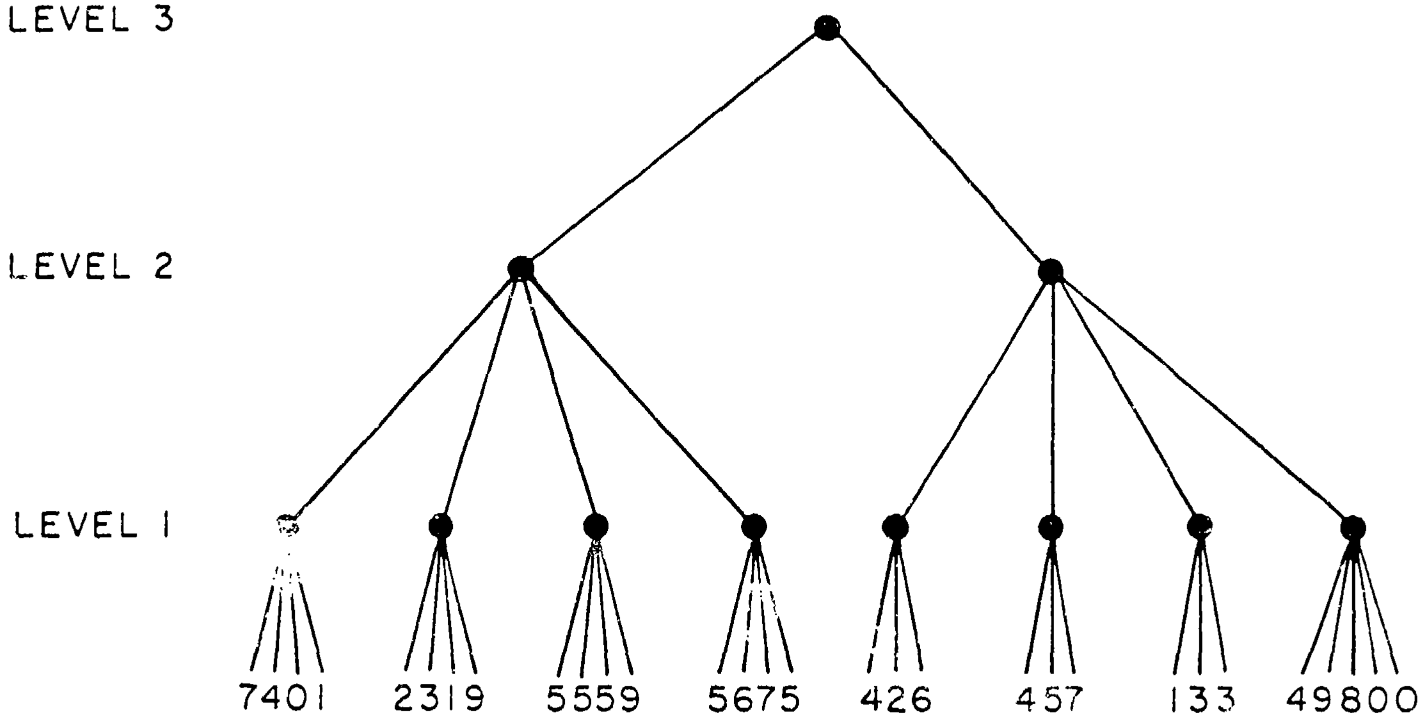
	DD	SF	BINET	INAUDI	DIAMONDI	RUCKLE	RUCKLE (MORE THAN 1 YR LATER)	NORMAL Ss
Study Time	56.9	26.8	----	45	180	20.2	12.7	229.6
Retrieval Time								
Rows	19.8	41.8	14	19	9	7.2	8.7	24.0
Individual Row As 5-digit Number	16.9	28.7	15	7	9	7.8	8.3	31.2
Backward Row	19.6	22.9	----	----	----	9.0	7.0	33.9
Columns	68.5	64.0	55	60	35	23.9	19.1	71.6
Upward Columns	71.7	58.5	60	96	36	24.6	18.5	----
Spiral	45.4	43.3	----	80	36	29.7	8.5	73.8
Diagonals	96.6	92.6	112	168	53	58.7	18.4	124.0

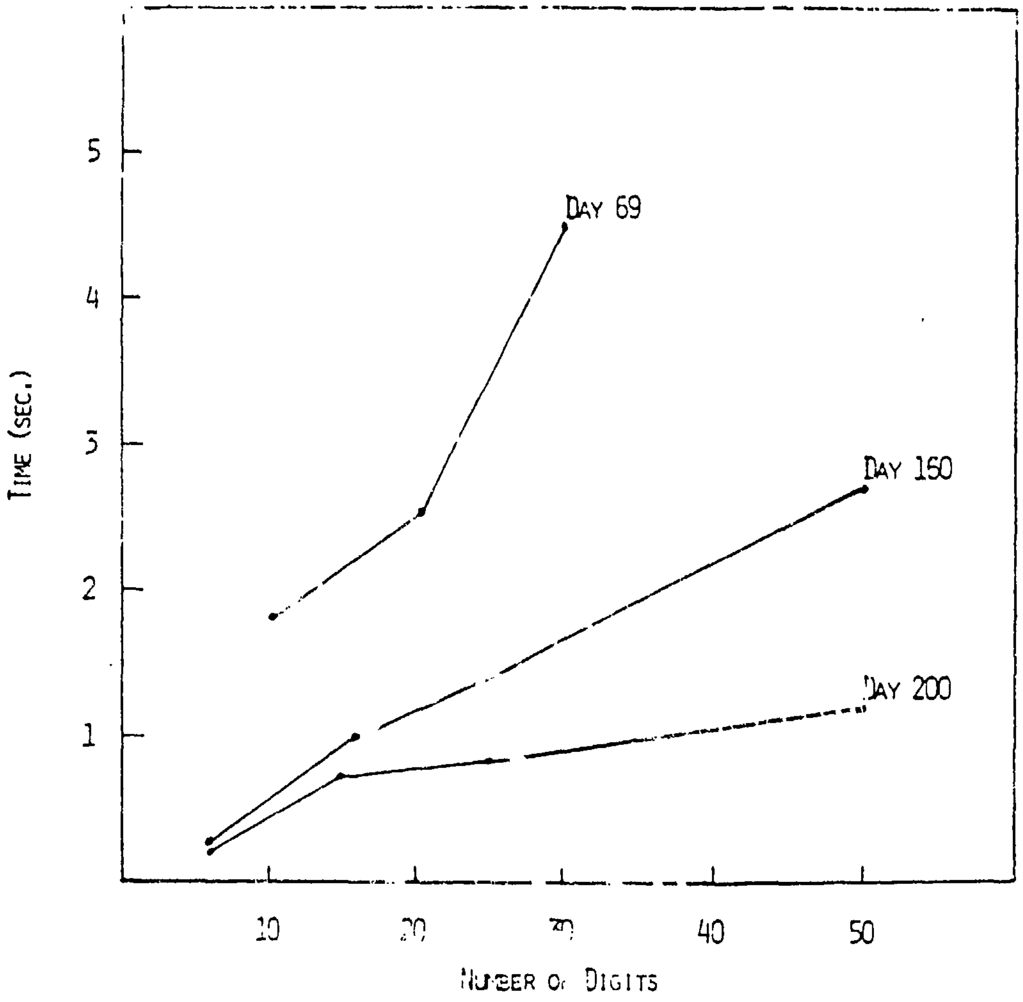
Table 5

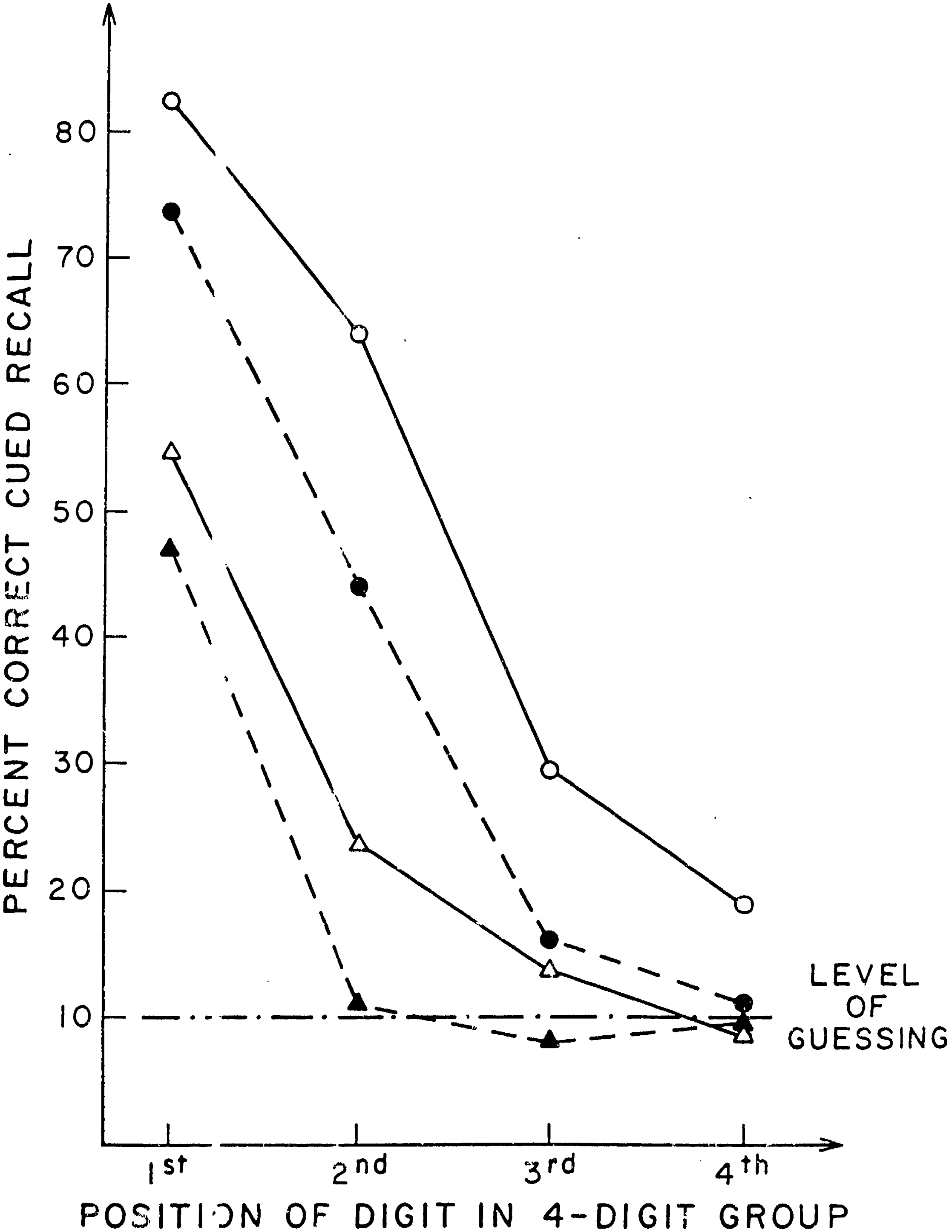
A transcription of the retrospective verbal report for the subject TB after she had recalled a chess board position. See the text for details.

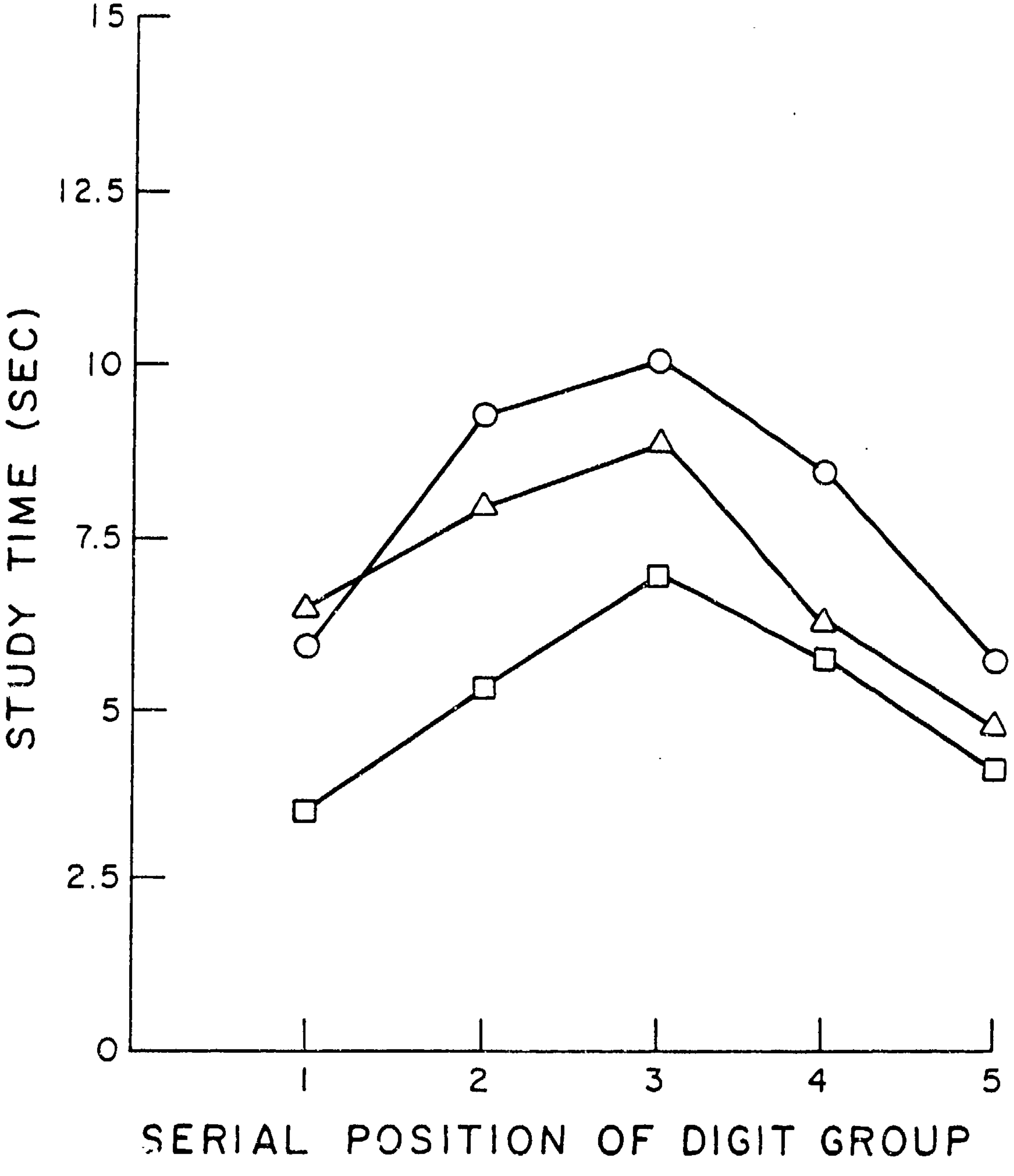
Looked back and saw the black castle, counted three pawns. Came to the white and saw the king castled, empty candlestick. Went back to the lefthand corner of the black and saw the queen on her original color, the rook in its original place. And then a black pawn, white bishop, black pawn. Came back to the white back line on the left side, saw the queen, bishop rook, in a row and a pawn on the very far left.


SKILL AND WORKING MEMORY
DIGIT SPAN
80
60
40
20
10
20
30
40
50
PRACTICE (5-DAY BLOCKS)
SF
DD
NB
RE

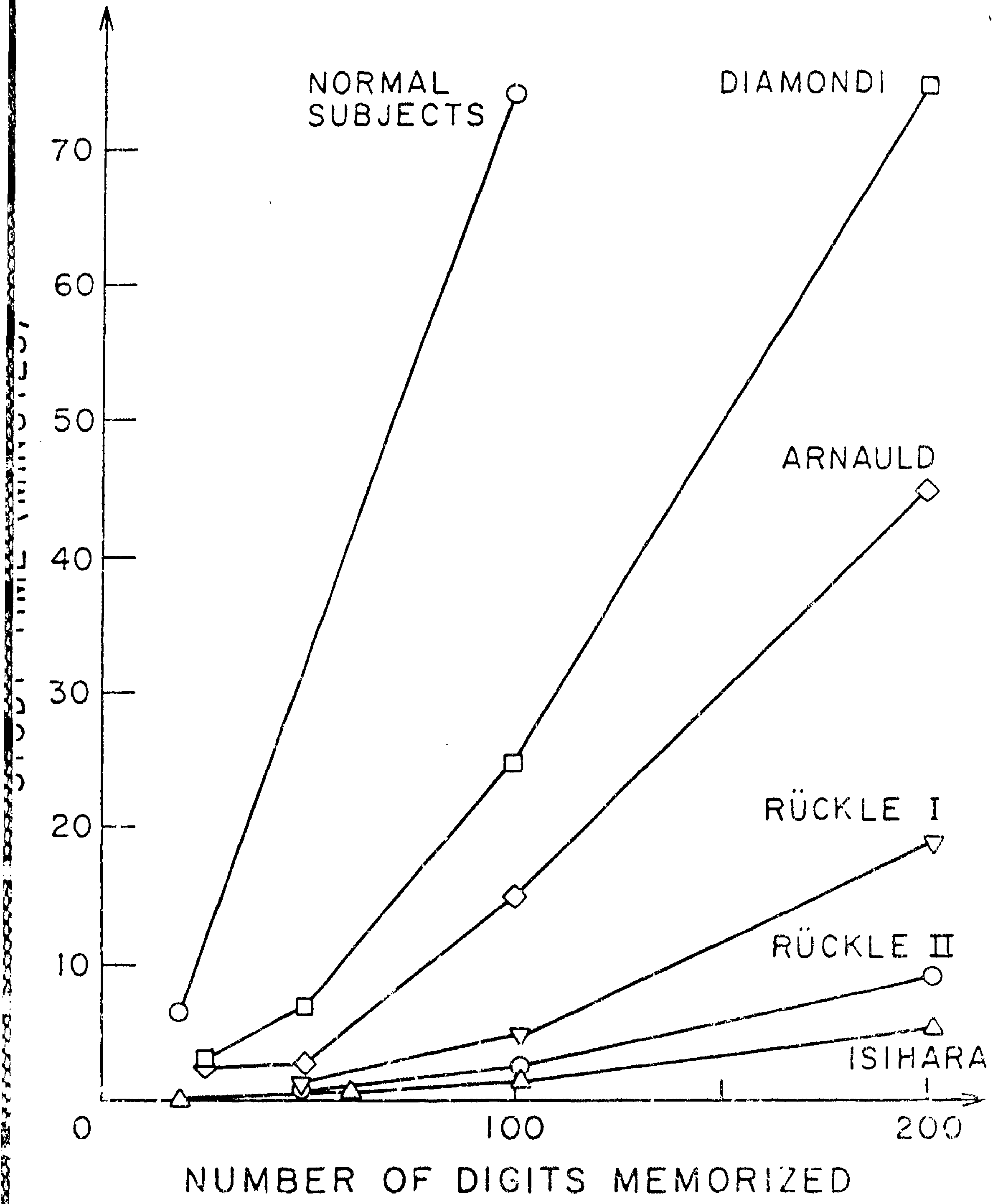

LEVEL 3
LEVEL 2
LEVEL 1
7401
2319
5559
5675
426
457
133
49800


DAY 69
DAY 160
DAY 200
TIME (SEC.)
1
2
3
4
5
10
20
30
40
50
NUMBER OF DIGITS


PERCENT CORRECT CUED RECALL
80
70
60
50
40
30
20
10
LEVEL OF GUESSING
1st
2nd
3rd
4th
POSITION OF DIGIT IN 4-DIGIT GROUP

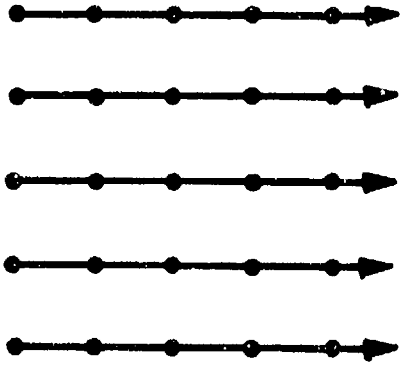


15
12.5
10
7.5
5
2.5
0
STUDY TIME (SEC)
1
2
3
4
5
SERIAL POSITION OF DIGIT GROUP

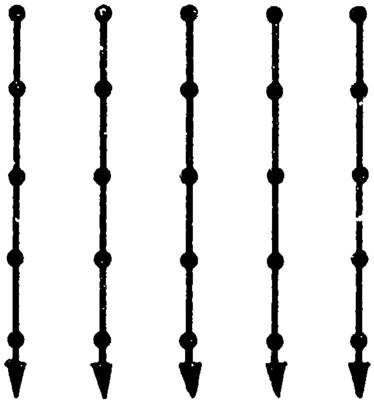

NORMAL SUBJECTS
DIAMONDI
ARNAULD
RÜCKLE I
RÜCKLE II
ISIHARA
70
60
50
40
30
20
10
0
100
200
NUMBER OF DIGITS MEMORIZED

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

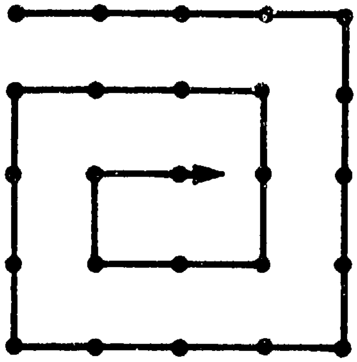
ROWS



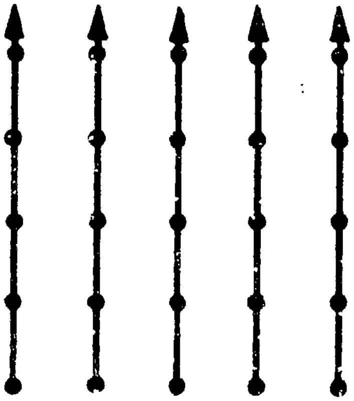
COLUMNS



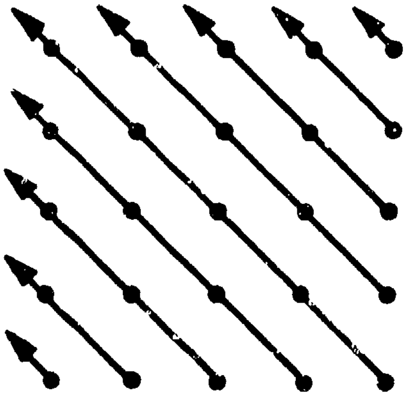
SPIRAL



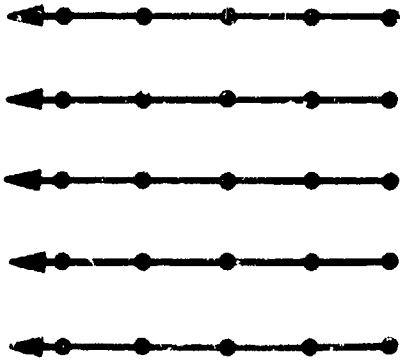
UPWARD COLUMNS

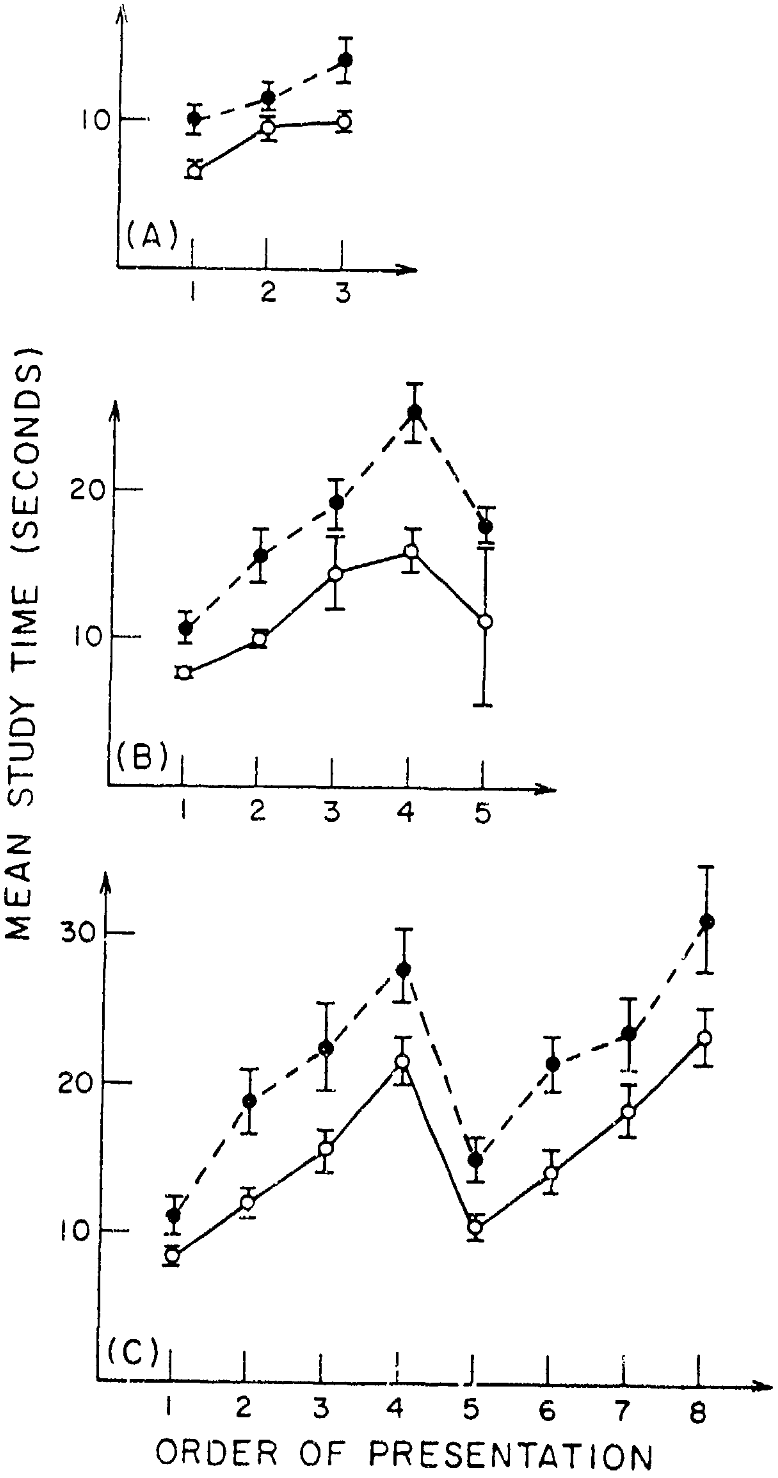


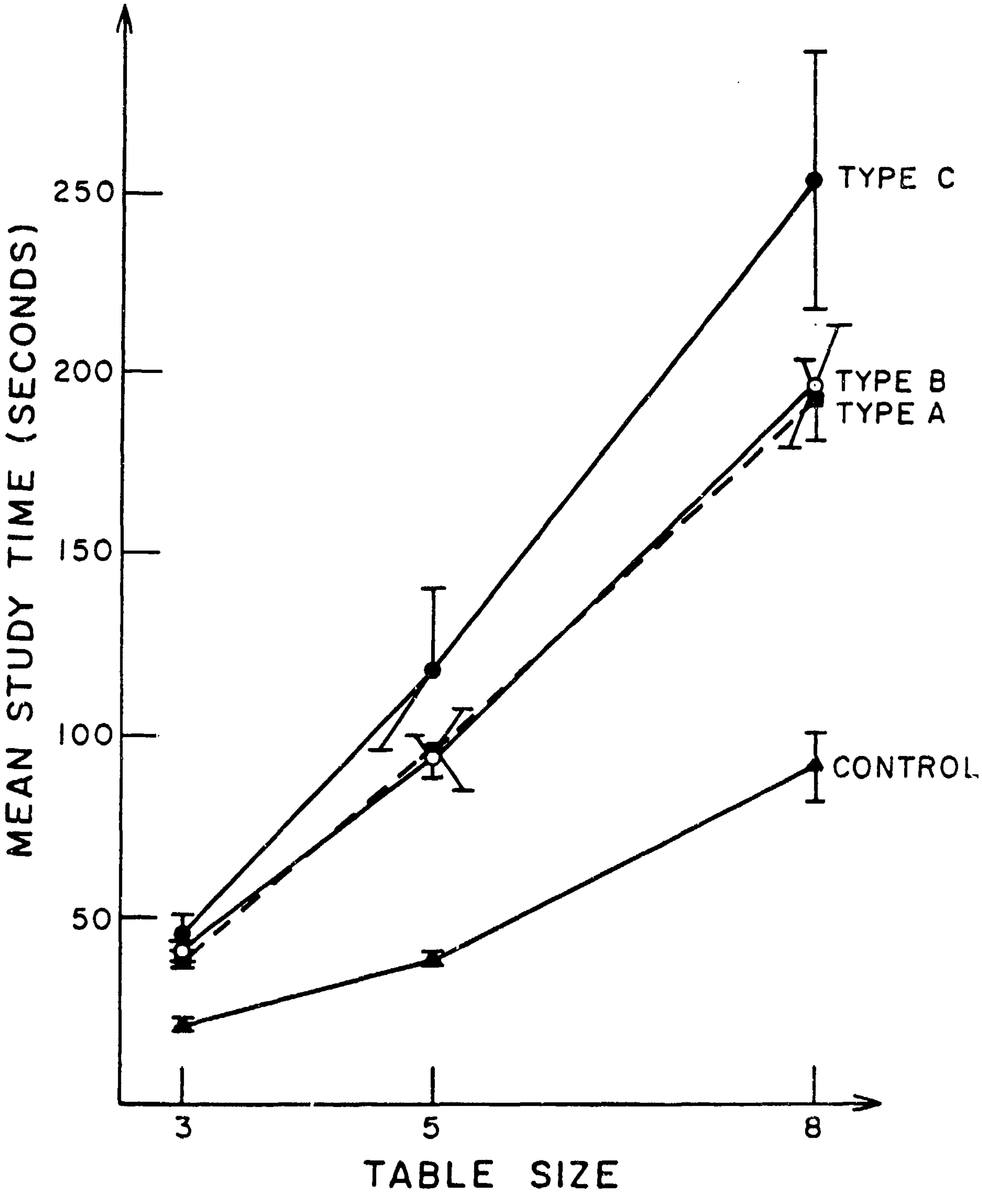
DIAGONALS

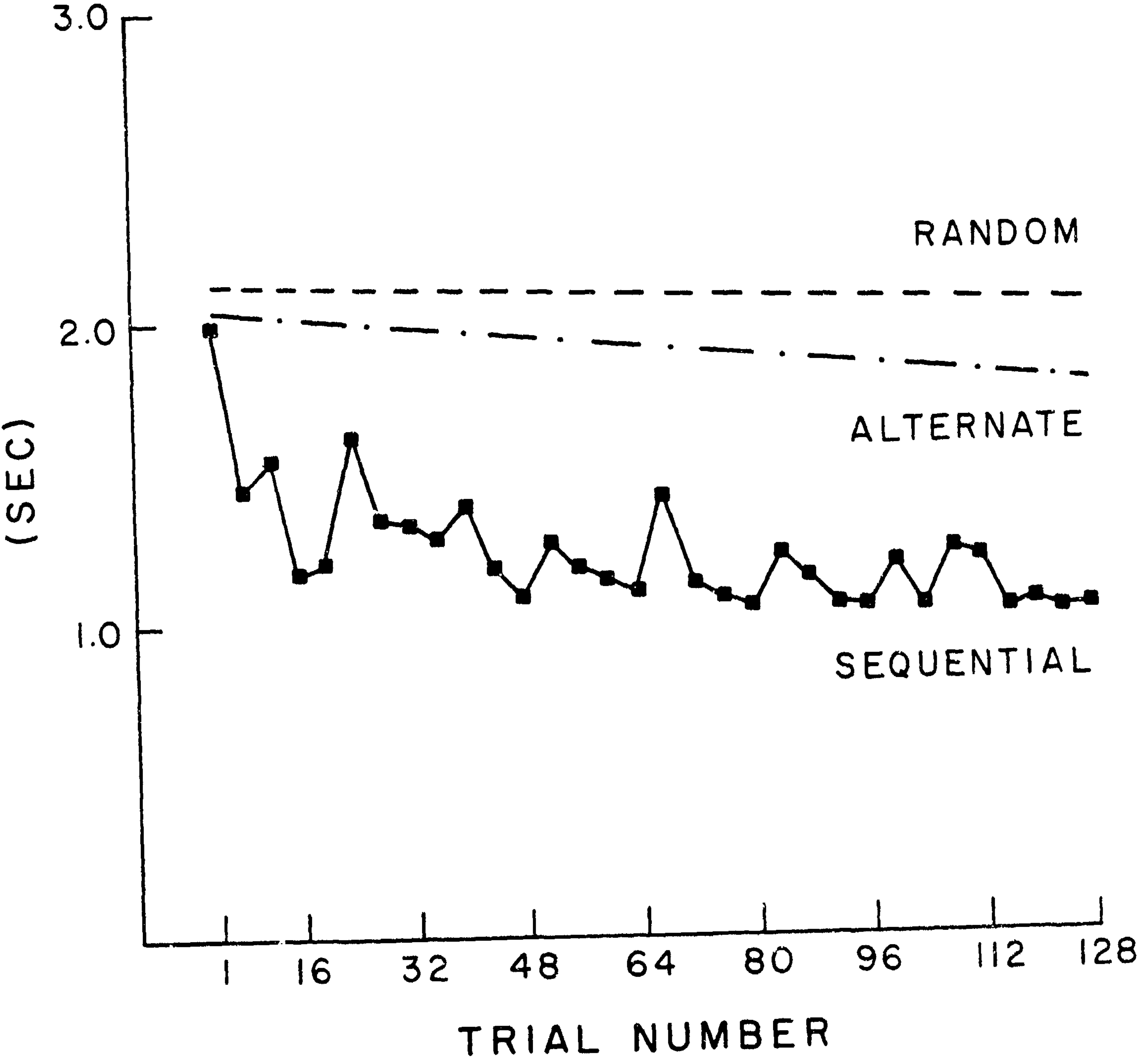


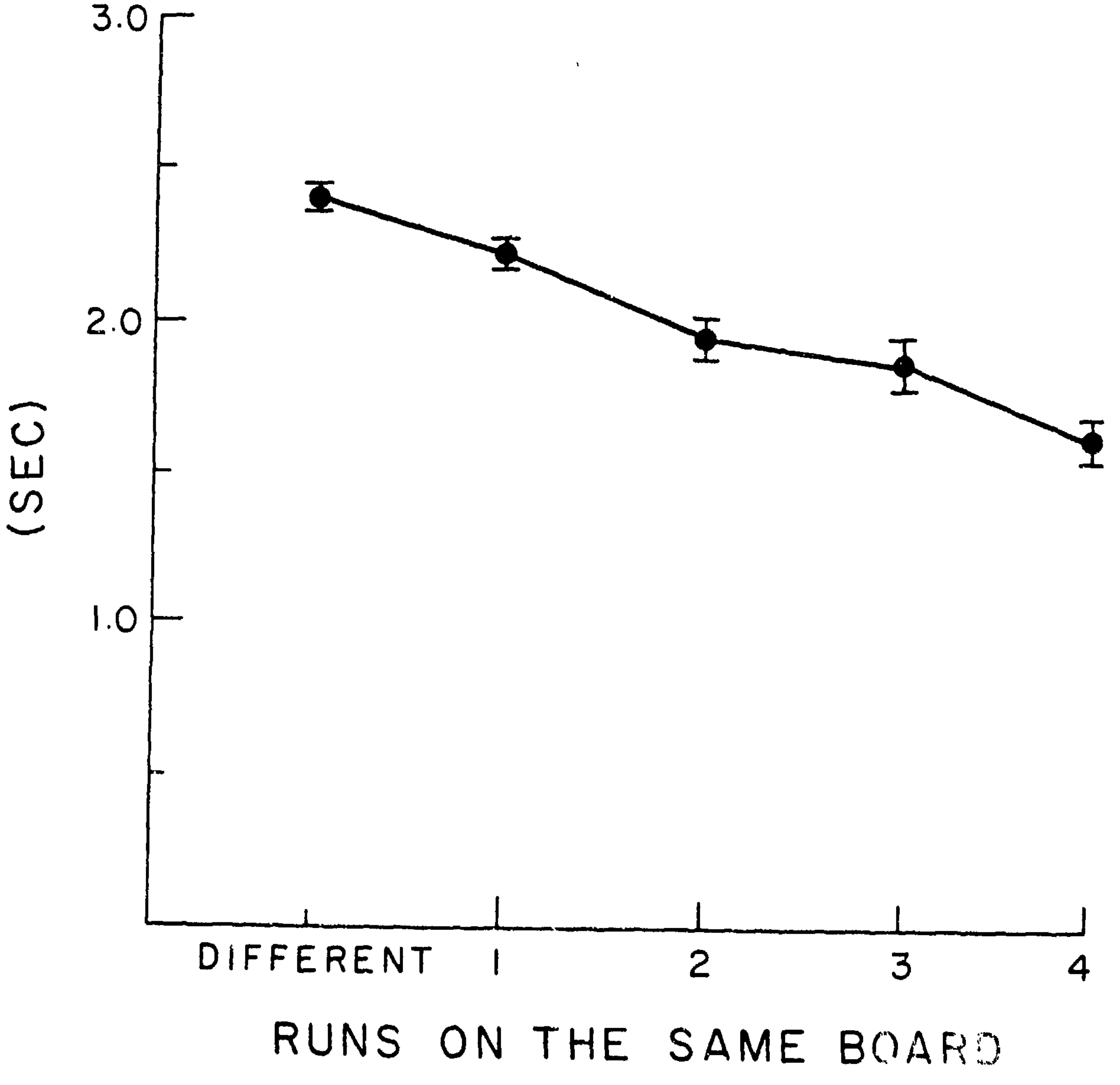
BACKWARD ROWS

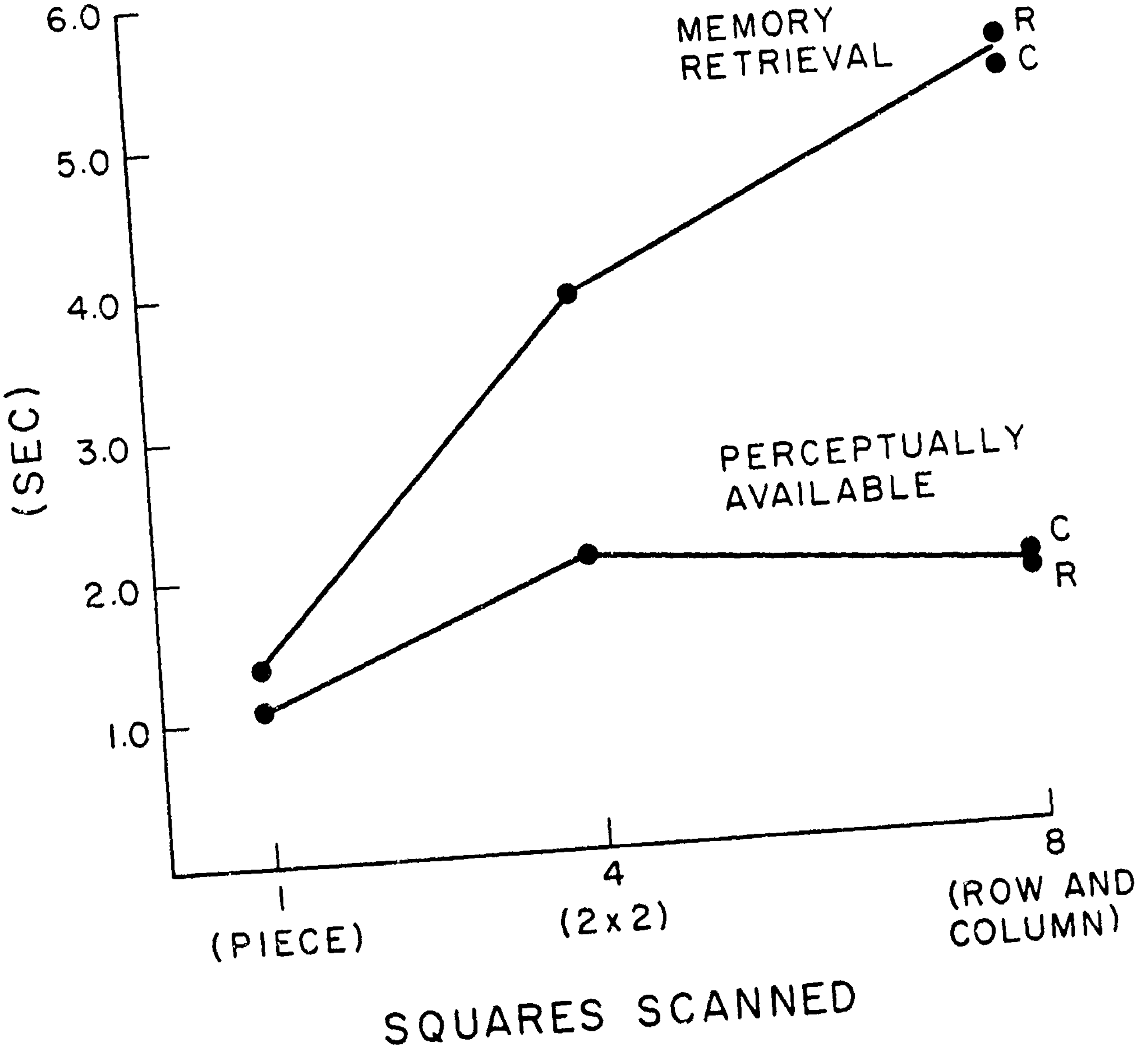


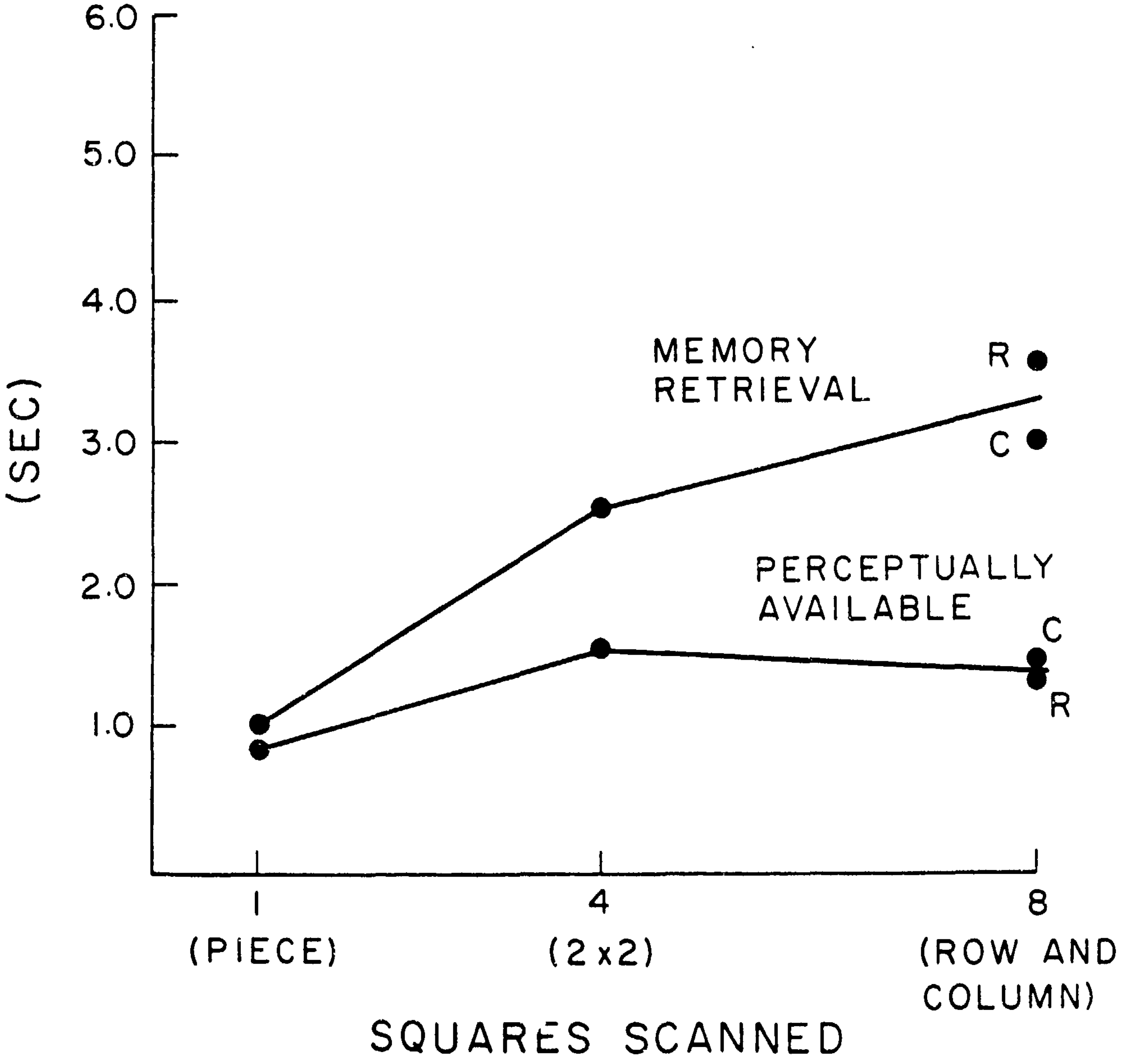

MEAN STUDY TIME (SECONDS)
(A)
10
1
2
3
(B)
20
10
1
2
3
4
5
(C)
30
20
10
1
2
3
4
5
6
7
8
ORDER OF PRESENTATION

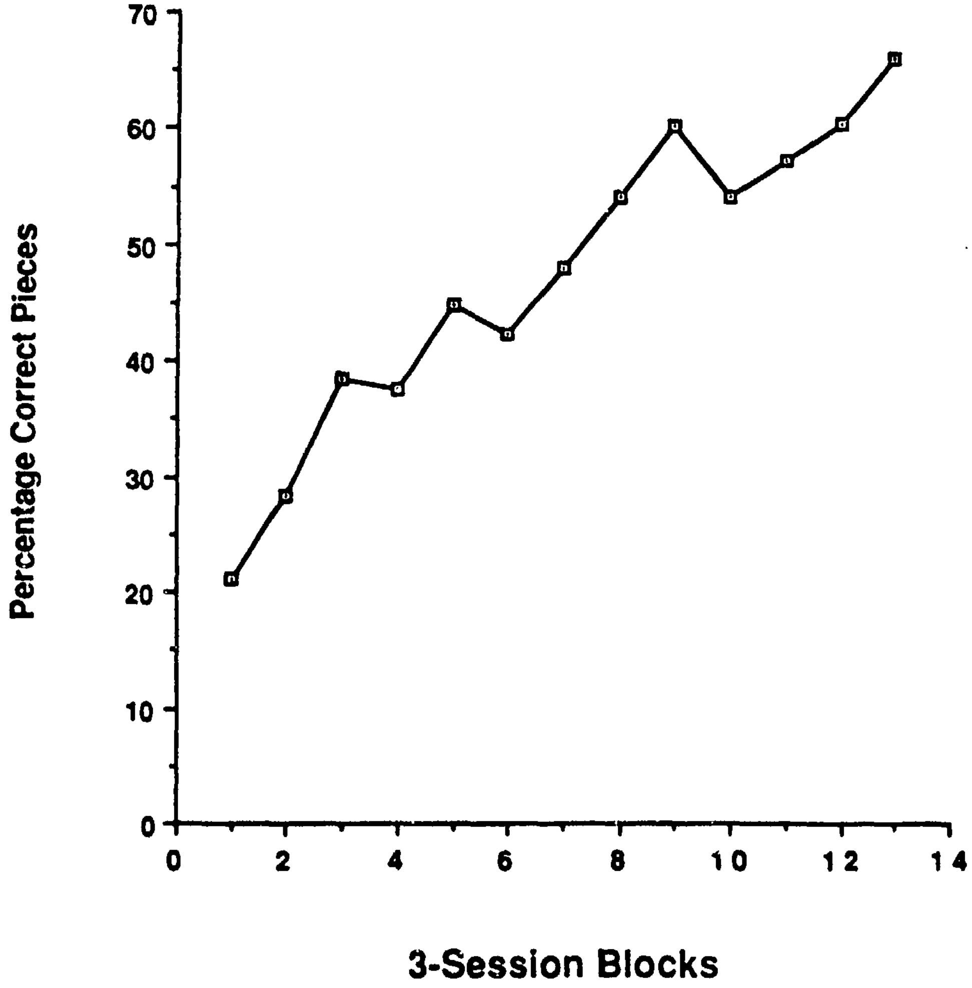

MEAN STUDY TIME (SECONDS)
250
200
150
100
50
TYPE C
TYPE B
TYPE A
CONTROL
3
5
8
TABLE SIZE


3.0
2.0
1.0
(SEC)
RANDOM
ALTERNATE
SEQUENTIAL
1
16
32
48
64
80
96
112
128
TRIAL NUMBER


3.0
2.0
1.0
(SEC)
DIFFERENT
1
2
3
4
RUNS ON THE SAME BOARD


6.0
5.0
4.0
3.0
2.0
1.0
(SEC)
MEMORY RETRIEVAL
R
C
PERCEPTUALLY AVAILABLE
C
R
1
(PIECE)
4
(2x2)
8
(ROW AND COLUMN)
SQUARES SCANNED

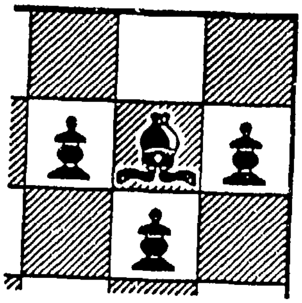

6.0
5.0
4.0
3.0
2.0
1.0
(SEC)
MEMORY
RETRIEVAL
R
C
PERCEPTUALLY
AVAILABLE
C
R
1
(PIECE)
4
(2x2)
8
(ROW AND
COLUMN)
SQUARES SCANNED



Percentage Correct Pieces
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
3-Session Blocks

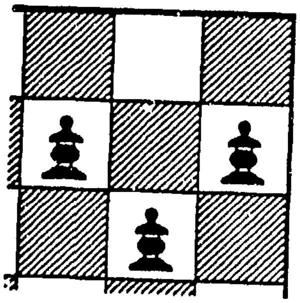
"candlestick"

A



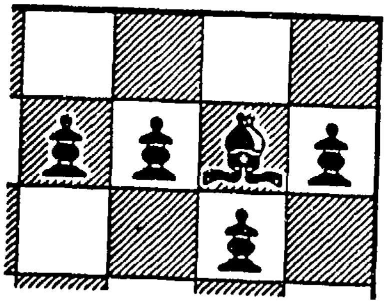
"empty candlestick"

B



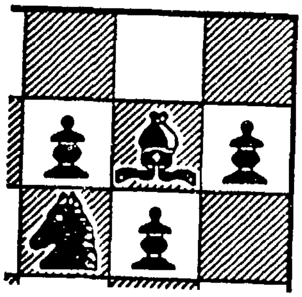
'candlestick with
extra pawn"

C



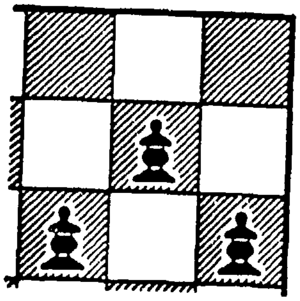
"candlestick with
knight filling in"

D



"backwards candlestick"

E



"half candlestick"

F