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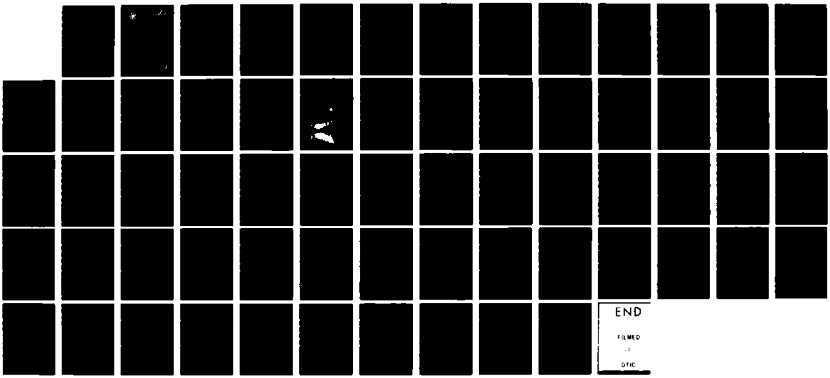

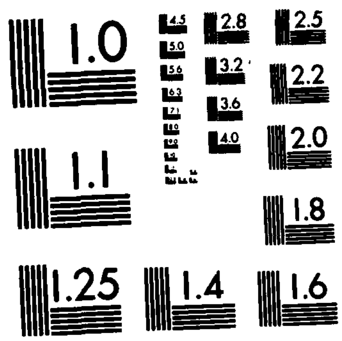

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ACQUIRING EXPERTISE

Alan M. Lesgold
Learning Research and Development Center
University of Pittsburgh

January 1983

Technical Report No. PDS-5

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This report reviews the roles played by knowledge and automatized skill in expert performance. Special attention is given to the importance of initial problem representations in expertise and to capacity limitations that make using such initial representations difficult at intermediate levels of skill. The role of strategy in skilled performance is discussed in light of the especial importance of domain specific knowledge to expertise. Suggestions are made for development of a theory of coaching.

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20. based upon emerging cognitive psychological principles of expertise.

Acquiring Expertise

Alan M. Lesgold

Learning Research and Development Center
University of Pittsburgh

Technical Report No. PDS-5
Office of Naval Research
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Outline

This chapter benefited from comments by John Anderson, Dale Klopfer, Harriet Rubinson, James Voss, and Carol White. Its preparation was supported by a contract from the Office of Naval Research (Personnel and Training Programs, Psychological Sciences Division, NR 667-430) and by the Learning Research and Development Center through funds from the National Institute of Education. Neither agency has approved or endorsed the views presented in this chapter.

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1.0 OVERVIEW

Many social roles require substantial training if they are to be performed with facility and accuracy. The concern of this chapter is with roles that are complex enough to require thousands of hours of practice, such as the ability to do arithmetic well enough to prepare a home budget, the ability to diagnose disease from chest x-ray pictures, the ability to guess what the Soviet government will do in the face of crisis, the ability to find efficient routes in a large city as taxicab drivers do, and the ability to read best-selling novels well enough to make good cocktail party conversation. As can be seen from these examples, some forms of expertise are part of common roles and others are to be found only in specialists. This chapter considers psychological issues that span both forms.

The folk view of expertise may be a good starting point. I suppose that the average person thinks that expertise requires a combination of practice, special knowledge, lore, and innate ability. This chapter is concerned with practice and with the effects of existing knowledge on both performance and further learning. It does not consider genetic factors in expertise; they are probably important in super-human extreme performances, but research on instruction seems more useful than research aimed at using selection to avoid the need for instruction. Issues of strategy are not covered either, although strategy is an important aspect of expert performance. In addition to practice and knowledge effects, the ability to construct representations of problem situations seems to be a major aspect of expertise, and it is discussed near the end of the chapter.

Consider two metaphors for expertise. The first is the long distance runner. This athlete prepares for his/her performances largely by practicing. S/he runs every day, building his/her endurance, cutting his/her times. The effort is relatively non-specific. Perhaps world-class runners give great attention to the specific types of practice they need, but one can hardly compose a list of the 1000 things the runner must learn in order to be successful. In contrast is the chess master, who seems to know just how to respond to each of thousands of moves made by his/her opponents. Such expertise is extremely knowledge-specific. If s/he played the same game every day, never exposing him/herself to new opposition, learning would proceed rather slowly. A chess master needs to know about the problems s/he faces in each of hundreds of situations. In the sections that follow, I will be concerned with both aspects of learning, knowledge which comes from variation and knowledge which comes from repetition. Then, I will examine the ability to build useful mental representations, a central capability that involves both these aspects. I conclude with a few recommendations for the training of cognitive skills.

2.0 THE ROLE OF KNOWLEDGE IN EXPERTISE

2.1 Chess

Comparing experts to novices allows us to discover what changes take place as expertise is acquired. Many forms of expertise were studied by early psychologists. For example, Bryan and Harter (1897) observed railroad telegraphers at various points in their development of Morse code skills. However, it is convenient to begin our development with recent studies of chess experts by de Groot (1966) and Chase and Simon (1973a, 1973b). This work extended the quantitative expert-novice comparison paradigm by shifting emphasis to qualitative comparisons as well. Some of the results were rather surprising.

Prior to de Groot's (1966) work, it was generally thought that the expert chess player is the one who can think many moves ahead in the game, following up on the implications of every possible move, while the novice is tripped up because s/he fails to think far enough ahead, something that presumably comes with practice and perhaps innate ability. However, de Groot found that neither experts nor novices think ahead more than a few moves; if anything, it was the intermediate level player who did more thinking ahead, following up on the consequences of bad moves as well as good ones. Nor were there any differences in the number of moves considered or in the heuristics used to consider the consequences of those moves. What experts could do better was to temporarily remember board positions. Masters could remember any real game board after seeing it for five seconds, although they did no better than weaker players in remembering random arrangements of chess pieces on the board.

William Chase and Herbert Simon were inspired by this work to conduct an extensive amount of experimentation on chess experts (Chase & Simon, 1973a, 1973b; Simon & Barenfeld, 1969; Simon & Gilmartin, 1973). The outgrowth of their work was a picture of the chess master as a person who can recognize 10,000 to 100,000 different meaningful board positions and make the optimal response to each. As Newell (1973) has pointed out, this description suggests a theory of expertise--that the expert can recognize each situation which s/he might encounter and has associated each with a specific response. Such a theory of knowledge-specific expertise might seem to offer a rather dismal future for cognitive psychologists studying expertise, in which we become mere cataloguers of the thousands of microskills which constitute expertise. What has kept us going is the belief that there are elements of common structure in the memory for these patterns and in the mappings of pattern memory onto memory for appropriate actions. Nonetheless, work on chess suggests that a wide variety of specific knowledge must be learned in order to become an expert.

2.2 Reading

The general skill of reading also depends on specific knowledge. Voss and his research group have studied the role of domain-relevant knowledge in reading and related literate performances (Chiesi, Spilich, & Voss, 1979; Spilich, Vesonder, Chiesi, & Voss, 1979; Voss, Vesonder, & Spilich, 1980). In some respects, the picture they have built is similar to that of the chess master. People who know a lot are better than the less expert at recalling stories relevant to their expert knowledge. Voss has also found that high-knowledge people use their knowledge to anticipate what a text will say, as an anchor for information that must temporarily be held in mind, and as a framework that permits recall of more elaborating detail. These effects are knowledge-specific, just as was found in the case of chess. That is, the exceptional capability is to be found only when the text deals with a person's areas of expertise.

The evidence for the assertions just made comes from experiments in which Voss and his colleagues tested a pool of people for knowledge of the intricacies of baseball. They identified a group of subjects (the high-knowledge pool), who knew quite a bit about the strategies of the game[1] and a second group (the low-knowledge pool), who knew the basic rules of the game and a bit about which professional teams were currently doing well but little about the game's finer points. These subjects were asked to produce a narrative account of a half inning of a fictitious baseball game. Both groups produced about the same amount of text and had about the same types of basic plots. However, the high-knowledge group devoted more text to elaboration of game activities such as changes in the basic state of the game, while the low-knowledge group produced more statements on irrelevant, nongame activities. The subjects were asked, two weeks later, to recall what they had written. In their recalls, the low-knowledge subjects were less likely to correctly recall what happened to each batter (e.g., pop fly, single, strikeout), were less able to reproduce the basic action sequence, and reproduced less game-relevant detail.

Related work has been done which deals more specifically with reading. For example, Spilich et al. (1979) attempted to apply a quantitative model of the short-term memory dynamics of reading to the task of specifying how the abilities of high-knowledge people differ from those of people with less knowledge. Using a variant of the Kintsch and van Dijk (1978) model of text comprehension, they showed (a) that the short-term memory dynamics for the main points of a passage differed from those for details, and (b) that high-knowledge individuals could hold more main-point (macrostructure) information in mind while reading a text relevant to their expertise. Chiesi et al. (1979) asked subjects to write down all of the possible outcomes they could think of for a specific baseball situation. They found that high-knowledge individuals knew more possible outcomes and could better specify which ones were likely to occur.

This leads to the following basic account of the effects of knowledge on expertise. Experts can use their knowledge to keep track of the information they are being given when they read. Their effective short-term memory is greater, especially for the "main plot" of the material they are reading. Their knowledge of the kinds of events that can occur in their domains of expertise allows them to more easily remember complicated events. Their ability to anticipate what is likely to happen greatly decreases the effort they must invest to understand a text. Thus far, we do not have a good sense of the specifics of knowledge acquisition effects on reading acquisition. That is, we do not know what kind of knowledge acquiring activity is optimal for improving reading skill, although considerations in later sections of this chapter may be relevant.

2.3 Problem Solving In Less-Structured Domains

Knowledge is also an important key to expertise in problem solving. Voss, Tyler, and Yengo (in press) conducted an important study in which they asked political scientists specializing in the Soviet political system to solve the following problem and others like it while thinking out loud:

> Assume you are the Head of the Soviet Ministry of Agriculture, and assume crop productivity has been low over the past several years. You now have the responsibility to increase crop production. How would you go about doing this?

As a control over the contributions of general political science reasoning strategies and even more general scientific reasoning methods, Voss et al. also used subjects who were political scientists with other specialties, scientists in a totally different field (chemistry), and undergraduate political science majors.

Voss et al. examined the extent to which effort was invested in building an initial representation of the problem situation. For the problem stated above, this would include the current agriculture scene in the Soviet Union, relevant political constraints, peculiar aspects of Soviet agricultural activity, and similar data. In fact, the non-specialist political scientists devoted more of their thinking aloud (16% of the nodes in their protocol graphs) to this initial representation information than did the chemists (1%) or the students (0%). However, the specialists devoted the most effort of all (24%) to initial representation of the problem. This suggests that specific knowledge is an important factor in the creation of such representations and that very little expertise rests on fully general strategies (else the chemists would have looked more expert).

Soviet area experts tended to offer a small number of solutions that were stated in rather abstract form, developed in some depth, and backed by detailed support. By depth, Voss et al. meant the size of the chain of causes that backed up an assertion. Expert arguments had three times as deep a structure of detailed support than did those of novices. Also, much more of the expert analysis was an analysis of an abstracted representation of the problem rather than of the specifics of the problem statement.

This two-stage approach (representation, then solution) usually pays off by decreasing the amount of thinking needed to produce a good solution. A good abstracted problem representation will adequately capture the constraints that are relevant to a solution, while working directly from the specific problem statements leaves the resolution of these constraints as a separate task to be done after a potential unwieldy set of possible solutions is generated. One example that arose in Voss's laboratory illustrates this problem. An expert, at the beginning of his analysis on the agriculture problem, pointed out that the problem involved several ministries and the entire agriculture system, from its raw materials of fertilizer, seed, labor, etc., to its ability to distribute the final product. By thinking this way, he was able to keep in mind from the outset that any changes requiring more fertilizer might fail because substantial amounts of Soviet fertilizer are lost due to inadequate packaging. Information about the ministry that controlled bag making needed to be considered from the outset.

Voss, Greene, Post, and Penner (in press) have suggested some of the changes that take place in the course of acquiring expertise in a domain, such as political science, in which problems are wide ranging and solutions not easily verified. They noticed that graduate students in this area showed three differences from undergraduates in their protocols: they had some knowledge of subproblem interactions (ways in which solving one subproblem might interfere with a solution that otherwise makes sense for another), their descriptions of the problem situation were more abstract, and their reasoning in support and evaluation of their plans more extensive. From these differences, Voss et al. concluded that the graduate students have more complete knowledge networks, containing more explicit causal knowledge and organized more hierarchically.

Experts, they concluded, presented further knowledge development as well as refined discipline-specific and domain-specific strategies for using that knowledge. Some of their strategies were general across all of political science, while others, such as extensive use of historical analysis, were more specific to the Soviet situation. Finally, Voss et al.

noted the importance of expert flexibility in using knowledge and suggested that this flexibility comes from experience with a wide variety of problems. In certain other domains, such as engineering or physics, where problem solutions are more clearly defined, the number of experiences with problems of a single type might be more important; in political science, experience with problem variety seemed of especial centrality.

2.4 Vocabulary

The work in Voss's laboratory has concentrated on the effects of knowing a lot about a specific subject on understanding discourses or solving problems involving that subject. It is also possible to consider the contribution of knowledge at a less specific level, namely general vocabulary. Virtually every intelligence or verbal aptitude test includes a vocabulary component because vocabulary is so predictive of verbal competence. My colleagues Beck, Perfetti, and McKeown (in press) and Glaser and Curtis (personal communication) have been trying to discover why extensive and speedy word knowledge is important in the overall acquisition of reading skill and other verbal competences. Since vocabulary is often tested in aptitude tests, Glaser and Curtis undertook the task of determining the specific vocabulary capabilities that distinguish the high verbal person from the less skilled. Their basic findings have been that the high verbal person not only knows the definitions of more words, but also has more knowledge that relates to each known word. Thinking of human knowledge as a network of conceptual relationships, we can describe their results as showing that the high verbal person has more words tied into his/her network and also has more links, on average, from any given word's encoding to other concepts that s/he knows about. Much of our power to understand complex or ambiguous text rests in word-specific knowledge (e.g., Small, 1980).

Classroom research by Beck et al. (in press) strongly suggests that reading ability can be improved by a vocabulary training program that emphasizes the speed of access for word knowledge as well as the richness of that knowledge. Fourth grade children were taught approximately 100 words over a five-month period. Following instruction, the children performed tasks designed to require semantic processes ranging from single word semantic decisions to simple sentence verification and memory for connected text. On all these tasks, instructed subjects performed at a significantly higher level than control subjects matched on measures of vocabulary and comprehension prior to instruction. Further, words for which more instruction was provided were processed more quickly by the subjects than words for which they had received less special intervention. Instructed subjects learned the word meanings taught by the program and used instructed words more efficiently in tasks involving comprehension. Indeed, they even improved on standardized reading comprehension tests faster than their matched control classmates.

This work leaves unresolved the relative importance of breadth of vocabulary knowledge and level of efficiency or facility that is needed. One possibility consistent with these results is that knowing all sorts of things about the words one is likely to encounter is the key to successful reading. On the other hand, the critical factor may be the extent to which the words one does know have been practiced sufficiently to produce capabilities that can execute without substantial conscious planning. Quite probably, both of these effects are involved in reading; there were some indications of this in the Voss work on political reasoning described above. Issues of practice and process automation will be considered later in this chapter.

2.5 Physics

Quite a bit of the work on differences between novices and experts has been done in the domain of physics (e.g., Chi, Glaser, & Rees, in press; Larkin, McDermott, Simon, & Simon, 1981; McCloskey, Caramazza, & Green, 1980). A central finding, stated more or less explicitly in different studies, is that representing the problem is a central part of problem solving for experts. Novices tend to invoke equations quickly, selecting those that include both what is given and what is to be found. In contrast, experts concentrate first on understanding the problem. Experts are more likely to draw diagrams, for example, and a bigger proportion of their total problem solving time elapses before they write any equations. Once the representation is built, the solution methods also differ. Simon and Simon (1978) found that novices are more likely to use a working backwards strategy when solving physics problems, while experts are more likely to use a working forward strategy.

One might initially be tempted to say that the novice merely needs to be taught the working forward strategy. This is not likely to be sufficient. The problem is that a working forward strategy requires (a) a sufficient representation of the problem from which straightforward inferences can lead to solution and (b) enough knowledge of the course such inference will take to permit focusing attention on those partial solutions that are most promising. A working backwards strategy, in contrast, requires little goal-related knowledge. At each step along the way, there is a list of things which, if known, would result in solution. Less specific knowledge is required to use such a strategy but more partial results must be kept in short-term memory.

The importance of knowledge is also illustrated by repeated findings that people, even those who have taken a term of physics, maintain very naive views about the effects of forces on objects (McCloskey et al., 1980). Even after they have spent a term solving mechanics problems, students' beliefs about the world are inconsistent with Newton's laws. For example, they believe that a body in motion will change speed even when no force is applied. Their qualitative predictions about physical events are often incorrect even though they are able to solve equations and quantitative problems about force, mass, acceleration, velocity, and displacement correctly. When we look at how physics is taught, we get some sense of why this might be so.

Much of an introductory physics course consists of solving numerical problems about masses, movements, and energy. Thus, there is emphasis on the fundamental relationships, as captured by equations. Sufficient richness and facility in mentally representing physical events takes longer to develop and involves not only knowing the principles in declarative form but also developing procedures for mapping those principles onto concrete situations. There are no final exams in mental representing, while there are tests requiring the knowledge of formulas and the use of such formulas to solve problems.

2.6 Radiological Diagnosis

To further illustrate the importance of organized knowledge, I next discuss some work that Robert Glaser, Paul Feltovich, Yen Wang, Harriet Rubinson and I have been doing on radiological expertise (Lesgold, Feltovich, Glaser, and Wang, 1981, describes the earlier parts of this work). Part of that work deals with the way in which physicians acquire the organized bodies of knowledge (schemas) that constitute radiological anatomy, the science of relationships between anatomical structure variations and x-ray plate patterns. To provide a richer sense of the development of expert knowledge and to give a sense of the data with which one deals in this area, this work is presented in some detail. This is necessary in order to provide a sense of the dependence of the meaning of individual perceptual features on a complex decision-making context.

When a radiology resident in a teaching hospital learns a complex diagnostic schema for a disease, s/he is initially in a very precarious position. This precariousness is illustrated by data from subjects who were asked to diagnose a film showing a collapsed lung lobe (atelectasis). The most obvious cue for collapsed lung is the presence of a local increase in tissue density (a white region on the film; cf. Figures 1 and 2). Certain properties of the density (e.g., "triangular," "sharp borders," etc.) make it more likely to reflect atelectasis, but even a density with those special features is insufficient for a certain diagnosis of atelectasis, since other diseases could produce the same sign. Listed below are six other general indicators for atelectasis; these include indirect signs of the changes that occur throughout the chest when the space taken up by a previously-inflated lung lobe becomes unoccupied.

Figure 1

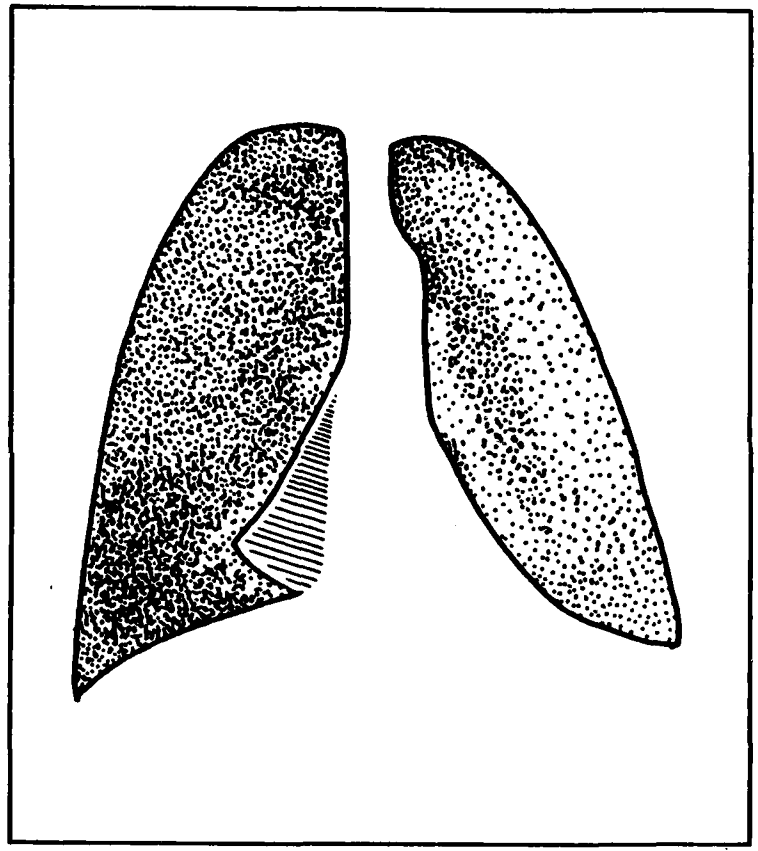

Figure 2

- *Mediastinal shift*: the anatomy contained between the lungs is pushed to one side or the other;

- *Displaced fissure*: the boundaries between lung lobes are not in their normal locations;

- *Elevation of the diaphragm*: the diaphragm is pressed higher into the chest than is usual;

- *Narrowing of the rib cage*;

- *Compensatory hyperinflation*: the noncollapsed lung balloons because of decreased external pressure;

- *Hilar displacement*: the major vascular structures feeding the lungs are not in their normal places.

We assume that the atelectasis schema is triggered by the presence of a subset of the seven features and that all seven are conditional criteria for supporting the diagnosis over alternatives. However, the indirect features vary with the location, severity, and recency of the collapse. A radiologist must have a well-tuned understanding of dynamic changes which occur when the lung loses volume and a mapping of that understanding onto procedures for constructing the representation of a chest from a film. The presence of one feature may increase the criterial importance of another, while decreasing the expectation for a third. Verifying atelectasis requires a mental representation of the patient that takes account of these complexities.

The predicament of the novice can be illustrated with the following simplified account of a series of simulations that we conducted. In these simulations, there were rules which represent the triggering conditions for schemata. For example, a general rule for atelectasis states that

Rule 1:

```
IF you have seen mediastinal-shift, THEN
        ASSUME a diagnosis of atelectasis
        IF ANY OF THE FOLLOWING have been seen:
                displace-fissure
                elevated-diaphragm
                narrowing-rib-cage
                compensatory-hyperinflation
                hilar-displacement
                local-increase-in-density.
```

Going further, it seems likely that once such a rule has triggered the atelectasis schema, one would expect to see the other features. The next rule provides for this conditional expectation.

Rule 2:

```
IF the diagnosis is atelectasis, THEN expect to see
        ALL of the following:
        hilar-displacement
        compensatory-hyperinflation
        displace-fissure
        elevated-diaphragm
        narrowing-rib-cage
        mediastinal-shift
        local-increase-in-density.
```

Finally, it seems reasonable to raise a flag whenever one cannot see something one expected to see, as shown in the next example:

<u>Rule 3</u>:

IF you expect to see X BUT you don't, THEN
DECLARE A CONTRADICTION.

This, though, sets the stage for a situation in which ordinary truth maintenance operations[2] will cause the physician to talk himself out of atelectasis after first talking himself into it, at least in some cases. Consider the case in which there is mediastinal shift and hilar displacement but no visible displacement of the appropriate fissure. For some of our subjects, this is what they saw on our film.

They, and our simulation, reacted to the contradiction between the inference of atelectasis and the failure to see the displaced fissure by <u>dismissing the atelectasis hypothesis</u>. One of our subjects, a second-year resident, said this very directly:

> "I am also indicating, drawing a line, over what I think is the minor fissure because the other differential to be considered is right middle lobe collapse, and there's no depression of the minor fissure or loss of volume in the right lung lobe to support right middle lobe collapse. I'm also showing that the right hemidiaphragm is in proper position and not elevated as you would see in right middle lobe collapse."

This subject needed each of several signs to be present to be sure of his diagnosis. He missed some that were present but more subtle and attenuated than usual. Others sometimes do not appear in this specific kind of case.

There is some complexity to what a successful subject should have done on the film in question. An expert would have known that when the specific kind of atelectasis shown in Figure 1 occurs, the fissure is hard to see in a front view; his/her recognition capability would be tuned to expect the fissure to be hidden in certain cases. We can represent this by changing the rule that sets our expectations for atelectasis to include the fact that we really only expect a fissure displacement to show in a lateral view.

Some of our more expert subjects have elaborated their knowledge in a somewhat different way. Specifically, they have learned special indications for different atelectasis forms. There is a specific feature in our film which strongly signals the possibility of atelectasis, even in the absence of some of the usual signs. A sharply pointed, sail-shaped density is located near the right heart border. This is the shadow of the deflated right middle lobe itself, which is sandwiched between the upper and lower lobes.[4] The location and unique characteristics of the density are an important additional cue, which should be incorporated into a specialized schema for right middle lobe collapse.

In both our simulations and our data, the diagnosis of atelectasis raised by the <u>general</u> atelectasis schema is <u>rejected</u> because of a contradiction of expectation with observation, as in our first simulation, but the diagnosis of <u>right-middle-lobe</u> <u>chronic</u> atelectasis made by a more specific schema-triggering rule is <u>retained</u>.

What can we learn from this type of data analysis and modeling? Basically, two points are made more apparent. First, an important way in which knowledge is organized is with schemata. Schemata, for our purposes, are sets of assumptions and rules for interpreting new information that are triggered when certain conditions are satisfied. A likely trigger mechanism is the presence of information that confirms a threshold number of the schema's assumptions, but more refined trigger mechanisms probably are learned with sufficient practice.

The second conclusion drawn from our results is that there have to be ways in which a schema can spawn an offspring that is a more specific and detailed version of the original. In this "clone-and-refine" process, the initial atelectasis schema is retained, but a specialized schema also develops, which is a particularized expansion of the initial one. This specialized schema is not merely a reweighting of the diagnosticity of different perceptual features but reflects weightings of some features that are contingent on which other features have been noticed. These specialized schemata may operate at the perceptual level in domains like radiology. In a domain like chess, they may operate at a slightly higher level. A rook in a particular space will not be misinterpreted as a pawn; the contingent meaning lies in how the locations of other pieces and the movement restrictions they have bias the meaning of the rook's location.

Much work remains to be done in order for a detailed model of the schema specialization process to be specified and tested. Two principles might guide further theorizing. First, while many aspects of expertise are best understood when studied at the level of schemata, some aspects of learning may be easier to understand at a more microscopic level. Second, learning must, in some way, operate on a trace of the recent course of thinking. That is, the episodic memory trace of recent schema activity, recent actions (mental or physical), and the immediate consequences of those actions must be the foundation for new learning. I next consider a number of learning mechanisms that are consistent with these principles.

2.7 Learning And Refining Cognitive Skills

John Anderson (1982) has recently developed a theory of skill acquisition that is a good starting point for understanding the initial acquisition of specific knowledge and the effects of practice. Taking the work of Fitts (1964) as a starting point, the theory divides the course of learning into three parts: the declarative stage, the knowledge compilation stage, and the procedural stage. Anderson's theory allows a clearer understanding of both the types of knowledge that are involved in skill and how each of those types is acquired. I shall sketch its main points (see Anderson, 1982, for details).

Anderson proposes that initial performance in a novel situation involves the operation of general strategies that use <u>declarative knowledge</u> to guide performance. In our case, for example, we can imagine some very general strategies for diagnosis that a physician might acquire in medical school. The basic process might go something like this:

a. Make a list of all abnormalities or patient complaints you can notice.

b. Is there a disease that you know to be associated with all of these complaints? If there is exactly one, then it is the appropriate diagnosis, so stop. If there are more than one, then go to <u>c</u>. If no disease matches perfectly, go to <u>d</u>.

c. Search memory for information on data that might separate the candidate diseases. Collect some of that data and recur through the procedure.

d. Make a list of the diseases that are consistent with the symptoms. Look for data which is needed to confirm one or more of the candidates on the list and recur through this process. If you hit a dead end, then use other procedures to decide which of the potential candidates to pick (use of other procedures might depend upon the cost of treatment and the consequences of nontreatment).

By reading textbooks, receiving advice from attending physicians, and monitoring one's success in patient management, a variety of bits of declarative knowledge (facts about how to perform rather than procedures for performance) can be acquired. However, these bits of knowledge must be accessed as needed by the general diagnosis procedure, a slow process subject to capacity limits. Much of the training time that is invested by radiologists involves the conversion of slow declarative knowledge interpretation into faster compiled procedures.

Anderson suggests that we think of the second stage, knowledge compilation as being somewhat analogous to compilation of a computer program. Languages such as BASIC and LISP permit programs to be specified in two forms, interpreted and compiled. Compiled knowledge, like compiled computer programs, runs faster, but at the cost of greater difficulty of modification. Actually, the situation is a bit more complex, according to Anderson. Newly acquired knowledge should not be trusted as much as well-practiced procedures. Hence, it is useful for it to have effect only as a result of conscious processing. Compiled procedures, according to Anderson, are relatively automatic. They are in the form of productions, or condition-action pairs. When a production's conditions are satisfied, it will act (within the constraints of an execution discipline that may limit how many productions can act at once). The only conscious control over a production tends to lie in the fact that some of the conditions for productions are likely to be goal states that can be consciously set. Nonetheless, a production may well fire accidentally even if the goal states do not match perfectly (Norman, 1981). Consequently, there is probably adaptive significance to the Anderson formulation, in which new knowledge is slowly, but consciously, processed.

Anderson proposes two processes for knowledge compilation. First, there is proceduralization, in which snapshots are made of a successful, just-completed activity. The scenario proceeds as follows:

- A compiled general strategy procedure finds a potentially useful piece of declarative knowledge and sets up a task of checking conditions of the knowledge and then performing the relevant actions.
- The task is successful in achieving a conscious goal.
- A snapshot of the conditions at the time of the successful action is combined with a snapshot of the action itself and is stored in memory as a production.

Anderson's second compilation process is composition. Composition is the process whereby two productions which execute successfully in immediate sequence can be combined into a single production. The conditions for the composed production are the conditions for the original first production plus those conditions of the second that are not created by the first. The action is the sequence of the two original actions. This, then, is essentially an abbreviation process, while proceduralization is an automation process.

In Anderson's third stage, the newly acquired productions are tuned. The snapshot process, based upon recording specific successful applications of declarative knowledge, is likely to result in productions that are too specific. Also, there are bound to be occasions when a piece of declarative knowledge is successful for accidental reasons. For example, if you had a production that diagnoses atelectasis every time you see a sail-shaped density, you would have a skill that is correct part of the time but not enough to be useful, since some other diseases you had not been told about can mimic the conditions to which you were sensitive.

Tuning is accomplished by three mechanisms that look a lot like those of behavioral learning theory except that they operate on bonds between mental events and mental actions rather than between physical events and behaviors. The first mechanism, strengthening, derives from the mechanism that decides which productions with satisfied conditions will be allowed to act. The probability of selection is a function of strength values which are assigned to each production. New productions start out weak and thus tend to be executed mainly when their conditions match the current mental state more closely than other productions. Each time they are followed by success, they become stronger.

The other two methods of tuning are generalization and discrimination. Generalization applies to two productions whose conditions have identical structure but slightly different content. The result of generalization is to build a production that has the same structure but with a variable at the point of difference. For example, Productions 1 and 2 can lead to the generalization shown as Production 3.

[1] IF I need my teddy bear to fall asleep and I am sleepy, THEN look for my teddy bear.

[2] IF I need my blanket to fall asleep and I am sleepy, THEN look for my blanket.

[3] IF I need my X to fall asleep and I am sleepy, THEN look for my X.

3.0 PRACTICE

Anderson's work helps to integrate knowledge acquisition and practice, two central components of learning. I considered knowledge acquisition in the previous section. This section considers issues of practice, attending to classical studies of the effects of overlearning trials in simple learning paradigms and to the effects of cognitive practice which might be accounted for by such theories as Anderson's. We start by considering relevant work on the effects of practice in simple perceptual search tasks.

3.1 Automatic And Controlled Processes

Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977) proposed a theory of information processing that dealt with practice in which the mappings of inputs onto necessary responses is consistent over the course of the practice. Such consistent practice, they asserted, leads to the development of automated processing capability, in which the input triggers a response sequence that operates independently of the subject's control, requiring no attention or conscious processing while still attracting an investment of such resources. In contrast, responses that are not yet adequately practiced or that are not consistently mapped onto possible inputs (which they called controlled processes) require attention, use limited short-term capacity, and tend to be more serial in nature. One can think of the distinction as being similar to Anderson's distinction between declarative and proceduralized knowledge.

Schneider and Shiffrin supported their theory with data from experiments in which subjects had to search a tachistoscopically presented display for target letters. In some conditions, the targets were from a set that were always targets. In other cases, the same symbol could be a target on one trial and a distractor on a later trial. Consistency of mapping led to better search performance. Both the number of items in the memory set (the symbols being searched for) and the number of items in the display were varied. Ordinarily, as the size of the memory set (e.g., Sternberg, 1975) or the display set (Atkinson, Holmgren, & Juola, 1969) is increased, a linear increase in response time is observed. However, after consistent practice, the functions became almost flat, suggesting that processing was not only rapid but also parallel rather than serial. That is, subjects' response times were consistent with a model in which each target letter had a production "watching for it." For inconsistent mappings, where items were targets on some trials and distractors on others, this did not happen, even after substantial practice. These results support Anderson's theory and suggest the importance of defining the meaningful units of a task in ways that preserve consistent mappings over the course of practice.

3.2 Training Effects On Negative Transfer

While a consistent relationship between mental events and the mental acts these events should trigger can help induce efficient learning, it is not always possible. It is of great adaptive importance that a person be able to learn new responses to the same apparent conditions. Fortunately, there is some indication that the interference produced by inconsistencies can be overcome with sufficient practice. Muensterberg (1889, as cited in Siipola & Israel, 1933) claimed to have conducted relevant experiments on himself. Every so often, he would switch his watch from his right pocket to his left or back again. Each switch meant that habits of reaching for his watch on one side would have to be changed. He claimed that after maintaining this inconsistent practice regimen for long enough, the temporary interference effect of each switch attenuated and eventually disappeared.

This assertion was directly tested by Siipola and Israel (1933) in an experiment on telegraphy. After varying amounts of practice (up to an average of 308 trials for the most-practiced condition), the code was changed so that each code used before was now the code for a different letter, clearly an interference condition. The new telegraphy scheme was then practiced to a very high level. The results were expressed in terms of percentage of positive or negative transfer, defined by (F1-F2)/F1 where F1 is the amount of training time needed to reach a given performance criterion on the first task and F2 is the time needed to reach the same criterion on the second. The general pattern, in line with earlier results, was that as the level of learning of the first task increased, negative transfer increased up to a point, after which the transfer effects became more positive as the level of first-task training rose further. Substantial positive transfer was found if the first-task training lasted long enough. The relationship between transfer and amount of original training, then, was U-shaped. However, as the criterion for learning was increased, the negative transfer effect extended to greater amounts of initial training, suggesting that negative transfer is an increasing problem as the target level of ultimate skill is increased.

How can these findings be explained? Mandler (1954) examined the U-shaped functions that Siipola and Israel (1933) and others had reported and theorized that they arose because of a combination of response learning and association learning at both the response level and at a cognitive level. Several aspects of Morse code task performance should transfer positively when the codes are reassigned. First, the motor program to send each code will still be used. Second, each letter of the alphabet will have to be quickly recognized in the experimental context. Third, a cognitive representation of each code may have to be formed. The negative factors will involve the ties between letter and code, both direct and symbolic. Presumably, the positive effects of practice on the code sequences eventually outweigh the negative effects of incorrect pairings.

A high final-task criterion may require learning to the procedural level. Here, the interfering effects of proceduralized interference will play a role. In contrast, a low criterion for final task performance primarily will involve use of declarative knowledge about the letter-to-code mapping. Automation of the code-sending response will facilitate final performance even if competing declarative knowledge from the initial learning poses some problems. In the high criterion case, interference will be present at both the declarative and procedural levels, making it unlikely that automation of the code-sending response alone will overcome the negative factors.

3.3 Extra Practice Improves Speed Of Response

There are several other types of findings that help in clarifying the role of practice. One implication of multi-stage skill acquisition theories such as Anderson's is that one can expect to find nonlinearities in curves that map measures of performance onto amount of training. This is because different processes are involved at each stage. One such finding is due to Judd and Glaser (1969). They examined accuracy and latency in a paired-associate learning task and found that for any individual item, response latency was constant until the trial of last error. After that, additional trials produced drops in response time. Presumably, the trial of last error is a reasonable indicator of a point at or before the point at which proceduralized performance becomes dominant over performance driven by declarative knowledge.

Different performance measures, then, are sensitive to different stages of learning. Also, it seems likely that complex tasks involve multidirectional flows of control between procedural and declaratively-driven components. Because of the cognitive processing limits faced by processes that use declarative knowledge interpretively, it should often be the case that some of the declarative learning cannot take place until other subprocesses have been proceduralized. Thus, not only will there be procedural capabilities that depend upon earlier declarative learning but there will also be declarative learning goals that cannot be realized until some subprocesses have been compiled.

3.4 Complex Performances Require Component Proceduralization

Perfetti and Lesgold (1978) applied a variation of this notion to the problem of explaining why some children cannot read very well. Building on theoretical accounts of the use of schemas in comprehension of discourse (Rumelhart & Ortony, 1977; Schank & Abelson, 1977; inter alia), they suggested the following theoretical view (see also LaBerge and Samuels, 1974): The reading process is too complex to operate completely at the declarative processing level. It can only work well when every component that can be automated is practiced enough to be compiled into an automatic form.

There are two kinds of data that support this assertion. First, there are numerous studies (e.g., Perfetti & Hogaboam, 1975; Frederiksen, 1978) that show specific speed-of-processing differences between children who do and those who do not read at normal levels for their age. In a longitudinal study of reading acquisition (Lesgold & Curtis, 1981; Lesgold & Resnick, 1982), there are strong suggestions that overall reading achievement as measured by standardized comprehension tests has accurate and speedy word recognition as a prerequisite. The second kind of evidence is that both text structure manipulations and global reading ability differences seem to affect learning of the main points of a discourse less than the learning of details. All of this is consistent with a model of reading skill in which most students have a reasonable general plan for reading but can only carry it out completely if many aspects of it are automated.

Consider, for example, the following small passage:

> Howard went to the bank. He wanted to buy the house he had seen yesterday. The owner had said that the bank gave the best interest rates in town.

After reading the first sentence, the only main point is that Howard went to the bank. However, given adequately automated understanding of bank, i.e., an adequately automated bank schema, certain facts ought to be activated in long-term memory, e.g., that banks give mortgage loans. If the bank schema is less automated, the activation will not occur till the second or third sentence is read. If the recognition capability for the words of the first sentence are not automated, short-term memory will be swamped with the episodic trace of the word decoding process, which will decrease the effectiveness of automated domain-relevant knowledge and decrease the likelihood that a house-buying schema could be activated enough to make the expectation of going to the bank to get a mortgage salient. Reading between the lines (in this case, not very far between the lines) depends heavily on the ability to carry out very active, elaborated understanding of what is being read. Issues that have not yet come up directly need to be expected. The success of this expectation process will depend on the extent to which components of the reading process are proceduralized (automated).

Because of capacity limitations, reverting to the declarative level of processing may hurt more than it helps. Characteristically, effective strategies call for putting off decisions as long as possible while making a mental note that information has appeared which imposes a constraint or that may eventually require a decision. In almost every human endeavor, trying to make decisions as soon as new constraints arise is a bad policy. It diverts attention from systematic planning. This leads to the hypothesis that while elaborated, active understanding activity is essential to adequate comprehension of a complex text, it may be counterproductive to try to produce much uncontrolled elaboration if such activity can only be sustained at the declarative processing level.

3.5 Radiology

I turn now to a different phenomenon that demonstrates the role of practice and proceduralization in acquisition of skill. Across two different empirical investigations, my colleagues and I have found a nonlinear, U-shaped relationship among beginning, intermediate, and expert radiologists; beginning residents and experts were better than intermediates. This does not happen in every case, but it is a recurrent result in our studies.[3] We have been studying this phenomenon, and we think we understand it, at least in part.

What follows is a caricature of some of our detailed protocol analyses. For new residents, film analysis is tightly bound to physical features of the film, e.g., densities of various textures, sizes, and shapes. These features are construed literally. Thus, for example, a rather well-defined, dense abnormality of the sort present in one of our films might be interpreted as a collapsed lung, without any rich consideration of the context in which it appears nor of the medical physiological condition of the patient, just as the poor reader processes only the most central and immediate meaning of what s/he reads. In fact, though, the actual shadow cast on the x-ray film plate by certain lung collapses is no different from shadows certain tumors could cast. Only context can distinguish the two.

Diagnosis that is insensitive to context, that only maps shapes on the film to prototype templates, will often lead the diagnostician to error, because many alternative structural forms map to the same manifestations. Correct diagnosis, when it occurs, will be highly dependent on a fortuitous relationship between true pathology and the novices' primary interpretations of chest features. But this can readily happen, and it does for some of our cases that are almost perfect examples.

Intermediate trainees are in the process of compiling and tuning their ability to perceive complex anatomical details and to take account of interactions or constraints imposed by film context and by variations in film quality. They are also developing their ability to construct a global model of the patient's medical condition and the conditions of film production. However, they suffer in some cases because their new, more complete, schemas assert control but are insufficiently automated to finish the job; i.e., they no longer have the simplistic recognition abilities of the new trainee and they have not yet automated the refinements they have acquired.

This period of short-term loss, however, is a necessary developmental phase which ends in the automated, refined, flexible schemata of the expert. Expert interpretations are, once again, relatively direct, but in the process of their construction, they come to incorporate appropriate contextual factors. For example, the expert might develop a set of "chest forms" (e.g., the emphysematous chest, the underinflated chest, the under- or over-exposed chest) along with distinct and specially tailored recognition, interpretation and evaluation rules applicable within each of these forms.

4.0 REPRESENTATION CONSTRUCTION

While much of what seems important about expertise can be lumped under the categories knowledge and practice, there is one more aspect that deserves special mention. This is representational skill. Again, the case of radiology helps us make the point. Radiologists need to see a patient when they look at a film, not just a complex visual stimulus. All of their medical knowledge is organized around the human body; it would be counterproductive to reorganize it around blips on a film. Also, the meaning of any given film feature is determined in part by surrounding context. The same blob will appear to be a tumor in one set of surrounding features and just an engorged blood vessel in a different context. Again, the best way to organize this contextual knowledge is around principles of human physiology and learned variations (both benign and pathological) in human anatomy.

Our analyses of expert and resident radiologists showed that subjects differed in the precision with which they "zeroed in" on the target feature within the film. In those analyses, we found that not all subjects thought primarily about a mental representation of the patient. Some thought aloud more in terms of film properties.

To examine this more systematically, we looked at all of the statements about locations of abnormalities from our subjects' discussions of one of our films. These statements were classified into four categories in order of increasing anatomic specificity: (1) Spatial statements referred to two-dimensional surface areas of the film itself and were, in a sense, non-anatomical. (2) Gross anatomical location statements referred to components of anatomy in conglomerate without indication of which specific components were involved, e.g., "hilar vasculature." (3) Nominal anatomical location statements mentioned anatomical components by name, e.g., the "pulmonary artery." (4) Finally, target anatomical localization statements explicitly restricted the abnormality to an appropriate subpart of an anatomical structure. Examples of these four kinds of location statements are given in Table 1.

Table 2 shows the number of subjects within each group who achieved the increasingly specific levels of anatomical localization within their analyses of the target abnormality. Spatial location statements were all that some of our subjects generated. For example, one subject spoke of a prominent right hilum or mediastinum. Neither term refers to specific, systemic anatomy. In contrast, seventeen of nineteen subjects who correctly detected abnormality used anatomic location statements. However, these localizations ranged from gross anatomy to components of specific anatomy within the target area of the film. Table 2 shows that this anatomic specificity was tied closely to expertise--all experts mentioned specific components of anatomy within the target region, while hardly any first and second year residents did (1 of 7, 14%).

When these findings are taken in conjunction with other findings in our studies, they suggest that experts rely upon a mental representation of specific anatomic structures in a specific patient to separate abnormalities from other structures in the area. Third and fourth year residents, perhaps more knowledgeable of the structure of anatomy within the target region than new residents, were nonetheless largely unsuccessful in referring x-ray shadows to this anatomy appropriately. This could be due to imprecision in their knowledge of the anatomical structures themselves, to limitation in

Table 1
Examples of Different Types of Localization (Film 9)

Localization Type	Examples
Spatial	
	. . . Prominent right hilum or mediastinum
Anatomical: Gross	
	. . . hilar prominence . . . may be due to right hilar vasculature. . .
Anatomical: Nominal	
	. . . could be pulmonary arterial hypertension. . .
	. . . enlarged pulmonary arteries from chronic obstructive pulmonary disease. . .
Anatomical: Target	
	. . . slight density above right hilum; I think it's the azygos vein. .
	. . . Pulmonary hila themselves not enlarged. . . fullness in the right mediastinum. . . a little above the hilum. . . not part of the aorta. . . definitely separate from the aorta. . .

Table 2
Most Detailed Level of Anatomical Localization for Each Subject on Film 9

Level of Localization	Residents 1st / 2nd Year	Residents 3rd / 4th Year	Experts
Spatial	1	1	0
Anatomical			
Gross	2	1	0
Nominal	3	1	0
Target	1	4	5

knowledge of how these structures vary normally and under perturbation, or, more directly, to deficiency in mapping this anatomy onto radiographic manifestations. First and second year residents were, perhaps, more limited to recognizing gross visual properties of the film and were equally likely to respond to these with interpretations of tumor or vascularity.

One of the most striking findings from these data was that many diagnostic errors resulted from a combination of misperception of anatomy and the inability to see simultaneously two structures that projected onto the same region of a film. The phenomenon is seen clearly in the atelectasis film discussed above (Figures 1 and 2). Recall that the triangular (sail-shaped) density in the right lung is a critical feature. It is also pretty obvious, even to nonphysicians. However, some of our subjects did not see this feature. The reason is that they attributed part of the whitened area to the pulmonary artery, leaving a much smaller abnormality, which they then thought was a tumor. This can be seen in Figure 3a, which shows the entire sail-shaped region and the portion that some residents marked off as really being artery.

In outlining critical regions on the film, half of our residents showed the pulmonary artery taking up part of the sail-shaped region. All then reported a smaller abnormality instead of the sail-shaped hallmark of middle lobe collapse. The only others to draw any pulmonary artery in the sail-shaped region were two experts who correctly drew a collateral branch of the artery that occupied 5 to 10 percent of the region, overlapping the sail abnormality, as shown in Figure 3b. (The contours in Figure 3 are actual lines drawn by subjects in an anatomy sketching task.)

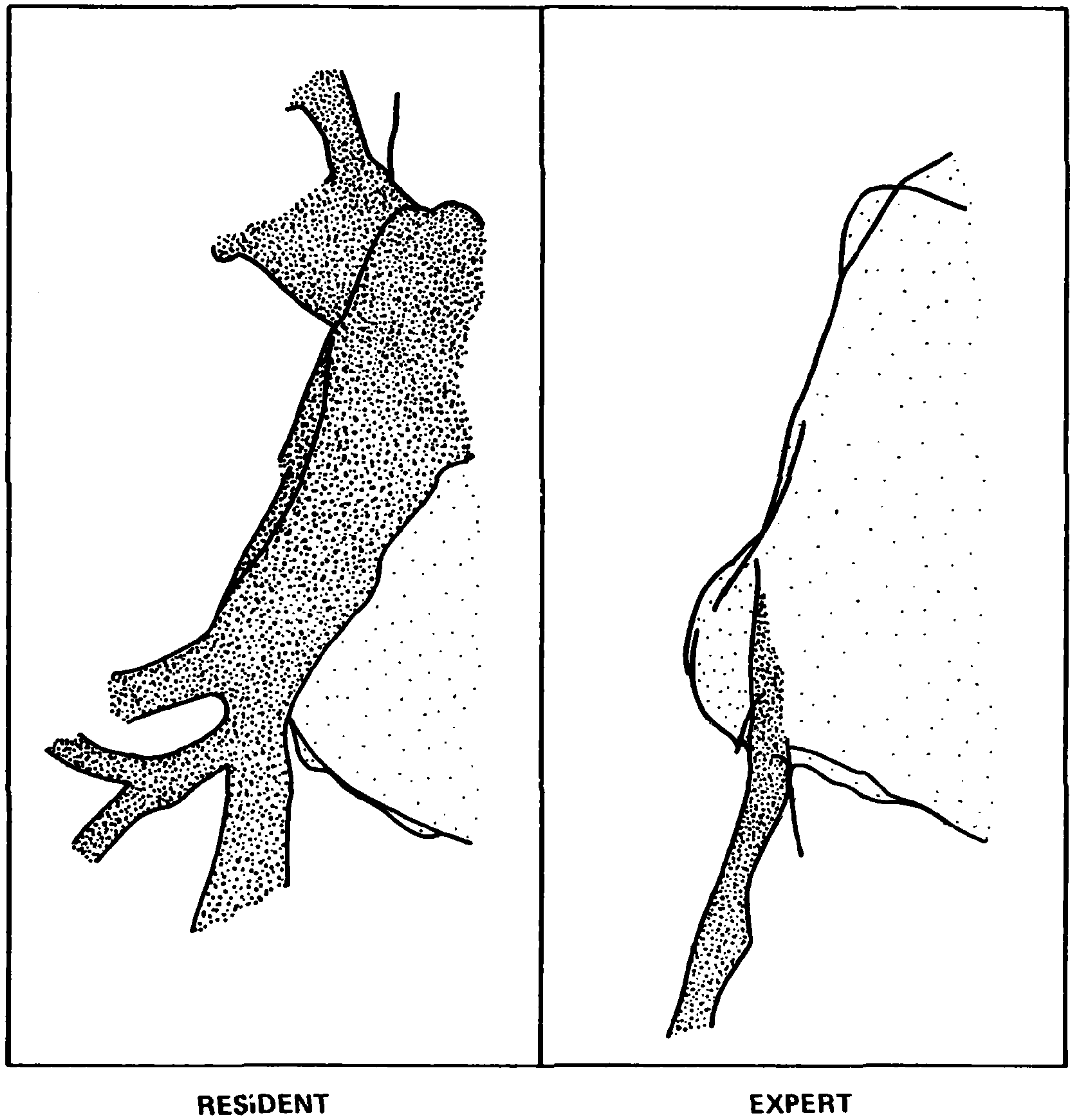

Figure 3

We can summarize this result, which was obtained in at least one other film as well, by recasting it a bit. To our residents, reading an x-ray picture is like doing an embedded figures test. At any instant, each local feature in the film can only be assigned to a single anatomical structure. For our experts, though, there is a greater ability to recognize overlapping anatomical structures. Their mental representation of the patient can be decoupled from film features. This allows overlapping structures to be detected. We speculate that this automated capability is a part of the apparently greater ability of the expert to envision the patient's internal anatomy even while questioning some of the evidence that led to that envisionment.

5.0 IMPLICATIONS FOR INSTRUCTION

Consider the stereotypic Socratic dialogue that goes on when a resident is questioned during grand rounds. He or she proposes a diagnosis, which turns out to be wrong. Then the senior attending physician asks a series of rhetorical questions that walk the student through the correct diagnosis. The student realizes that s/he knew the rules for making the right diagnosis but did not use them at the right time. S/he thinks that s/he was negligent or inattentive, but the kind of model proposed by Anderson suggests otherwise. Perhaps the knowledge of the resident student is not sufficiently proceduralized, something that happens only with practice. Or, it may not be able to take account of complex context dependencies in the meanings of manifestations in the patient, something that can be improved through appropriate variation in the cases the resident experiences.

A more serious research issue also arises when we think about the status of complex procedures that can only execute when many of their components have been automated (proceduralized). We have assumed in this chapter that expert performance involves the neatly sequential execution of complex procedures. However, the mechanisms of automation that we have discussed apply to individual productions. That is, snapshots of small pieces of a complex procedure each become automated. Should those automated pieces execute in a fixed sequence a number of times, they can then be composed into longer sequences. However, there is a likely state of affairs in the midst of learning when the components of a procedure are each automated but their sequence is not yet fully constrained.

In this state of affairs, thinking is not well described by sequential procedure descriptions. It is more like a Pandemonium (Selfridge, 1959) in which many fragments of the target activity occur in parallel. Indeed, some researchers (e.g., McClelland & Rumelhart, 1982; Rumelhart & McClelland, 1981, 1982) have proposed models for mature performance which remain strongly parallel and fragmented. Nonetheless, it seems likely that linear plans do drive problem solving in experts, at least to some extent. An open research question is: Where do these plans come from? One obvious source is the composition mechanism, which will tend to form recurrent, successful sequences of processing into unified procedures. A second source is declarative knowledge. Specifically, I suggest that a verbal plan, a list of steps toward solution, can help in the composition process. Such a plan, taught only to the declarative level, can act by introducing a useful oscillation between self-conscious attempts to achieve successive subgoals of the plan and the Pandemonium-like activity of automated fragments. The verbal plan components can act to entrain the parallel processing activity of automated fragments that are not quite reliable enough to assure an efficient processing sequence without such intervention.

If this is the case, then we need to consider whether the plans that we teach the student should be the same as a caricature of the master's activities or whether there are other alternatives that are more effective in shaping efficient and reliable performance. Glaser (1982) has spoken of pedagogical theories, theories for a phenomenon that are used as temporary teaching tools and then discarded as more sophistication develops. My suggestion is a specific instance of this idea. Just as we teach physics students Newton's Laws first and then show why they aren't quite adequate given the special theory of relativity, we might teach simple verbal rules to guide problem solving and then replace them as bigger components of the overall target performance are automated.

If one examines the training exercises used by ballet instructors, by gymnastics coaches, and by many other teachers, we see hints that teachers' practical wisdom includes this concept. Certain drills are repeated regularly even though they are not, themselves, target performances. However, they may have the effect of building the right procedural subsequences. Sometimes this involves a separate activity, like a ballet exercise; sometimes it involves a mnemonic, as when a mother helps a child put on mittens by saying "thumb in the thumb place, fingers all together;" sometimes it involves verbal coaching, as when a teacher coaches a student through the proof of a geometry theorem. In any case, devising a theory of the principles for guiding the development of systematic procedures from incompletely organized pandemonia of fragmentary productions is a major task for cognitive psychologists who wish to improve instruction aimed at high levels of skill.

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Footnotes

1. Historians have not yet verified that baseball has always involved complex cognitive activity. Particularly, it is not known whether our festschriftee engaged in cognitive activity while pursuing baseball expertise.

2. Truth maintenance refers to the process of maintaining consistency of beliefs as new assumptions are being "tried out" (cf. deKleer, Doyle, Steele, and Sussman, 1977).

3. All of our films involve situations in which several alternative possibilities must be considered. As John Anderson pointed out in comments on an earlier draft, it is unlikely that the learning curve averaged over the mix of films on which radiologists are trained is nonmonotone.

4. The right lung is divided into three connected lobes; the left lung has two.

Figure Captions

1. Frontal x-ray film of the chest of a patient with a collapsed right middle lung lobe. Patient faces forward (his right is on your left).

2. Illustration of the location of the collapsed lung tissue in Figure 1.

3. Anatomical sketches of structures seen by subjects in the "triangular density" region of the film shown in Figure 1. (a) Residents often "used up" the region by filling it with pulmonary artery. (b) Experts saw only a small collateral of the pulmonary artery in the critical region.

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