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ABSTRACT

This report addresses how the influence of cognitive science is developing and what future directions it may take as a theory of instruction. The discussion of the recurrent findings and the prevalent themes emerging in cognitive science includes: limited-capacity learners; the role of prior knowledge in learning--schema theories of reading and problem solving; learning as coherence-building; learning as theory change; learning as invention-sensible constructions on limited data; and self-monitoring and learning. The following applications to a cognitive theory of instruction are considered; adapting instruction to limited-capacity learners; schemata for learning--the question of instructional representations; the problem of coherence--taking learner's theories of the world into account; and improving learning skills--teaching strategies for learning. (PN)

LEARNING RESEARCH AND DEVELOPMENT CENTER

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COGNITIVE SCIENCE AND INSTRUCTION

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In the last twenty years we have witnessed a profound change in experimental psychology. Whereas most past psychological theories sought to account for all human behavior in terms of simple associations and observable overt reactions to stimuli, psychology has become cognitive, fundamentally interested in mental processes and in thinking. Along with linguists and computer scientists, especially those concerned with artificial intelligence, psychologists are now developing a vigorous new *cognitive science* whose research questions and methods are shaping a new concept of human mental functioning. Cognitive science is interested in the content as well as the mechanisms of thought, and it accords a central place to the intentional strategies an individual uses to make sense of information and events. It seems evident that these new views of human mental functioning ought to affect our educational theories and, eventually, our practices. In this chapter, I address the question of how this influence is now developing and what directions it might take in the future. A response to this very broad question is sketched by outlining some of the recurrent findings and the strong themes that are emerging in cognitive science, and then by considering their possible applications to a cognitive theory of instruction.

Before proceeding with this task it is important to begin with a definition of instruction. The definition I propose is considerably broader than the traditional one, which implicitly equates instruction with acts of direct teaching such as lecturing, organizing recitations, or preparing textbooks. Those traditional activities certainly fall within the domain of instruction, but instruction can be much more than those alone. I propose that *instruction is anything that one does with the intention of helping someone else acquire a new capability.*

This broader definition is not just a pleasant expansion of the traditional field of consideration of psychologists interested in education. Rather, I believe that it follows necessarily from the new view of human intellectual functioning that places at the heart of learning the active construction of knowledge by the learner. It thereby makes instruction an accessory to the act of learning, rather than an act that can be described or assessed independently. Any act, then, that intentionally arranges the world so that another's processes of knowledge construction will proceed more successfully qualifies as instruction.

Foundations for a Theory of Instruction

This definition of instruction points us toward the necessary elements of a theory of instruction. There are three. First and most obviously, an instructional theory requires a theory of *intervention*, a set of principles that can be used to prescribe actions to take in the course of instructing. These actions, however, are interventions in the ongoing knowledge acquisition processes of another individual. These processes are the focus of the second necessary element in a theory of instruction: a theory of *acquisition* that describes the cognitive processes involved in modifying one's knowledge or skill. I purposefully use the term "acquisition" rather than either "learning" or "development" in order to avoid the pitfalls of the arguments between learning psychologists and developmental psychologists over how cognitive growth occurs.

Third, since instruction is always intended to help someone acquire particular capabilities, an instructional theory requires a theory of *expertise*—that is, of the specific knowledge and processes that are involved in skilled performance in a domain. Descriptions of expert performance and of performances known to be associated with progress toward full expertise serve, in effect, as goals for instructional interventions. They specify the desired outcomes of the processes of acquisition that are set in motion or influenced by instruction.

These, then, are the necessary elements of a cognitive theory of instruction: a theory of expertise, a theory of acquisition, and a theory of intervention. Where do we stand with respect to each of them? How strong a theory of instruction can we derive now from research in cognitive science?

An Emerging Theory of Expertise

Cognitive scientists have already made great progress toward building a theory of expertise. In the past several years, the field has seen increasing interest in studying complex forms of cognitive behavior. Researchers are now examining performance on tasks that are more like the messy, ill-structured ones of real life than the self-contained problem-solving tasks and tightly controlled exercises of the psychology laboratory. As a result, much attention is now being given to the cognitive analysis of tasks that are similar to those involved in learning school subjects. Among the kinds of tasks now under study are comprehending and composing extended written or spoken messages, solving problems in physics and other sciences, solving mathematics problems ranging from simple arithmetic to geometry and algebra, programming computers, repairing electrical equipment, reading x-ray films, and performing medical diagnoses. The analysis of these complex tasks has in turn led to a growing interest in the role of knowledge in thinking, particularly in how knowledge brought to a new problem may influence the processes of thought applied to solving the problem. Much effort is, therefore, now directed at finding ways to represent the structure of knowledge and the ways in which it is accessed. As a natural outgrowth of this effort, there is new interest in the knowledge structures and processes of thought characteristic of specific domains of learning. All of this means that large parts of basic research in cognitive science can be construed as providing the theories of expertise that are a crucial element of a theory of instruction.

When we turn to the question of how knowledge and skill are acquired, however, we are on less well-developed ground. The emergence of cognition as a major concern in American experimental psychology has been accompanied by a loss of interest in learning and acquisition processes. Meanwhile, developmental psychology (largely in the theories of Piaget) has offered only a sketch of the kind of processes that might be involved in the acquisition of new cognitive competence. The fields of artificial intelligence and linguistics have not produced very detailed theories of acquisition either, although both recognize the eventual importance of the question. Until very recently, then, cognitive research has focused almost exclusively on the analysis of complex cognitive performances while ignoring the issue of how these performances are acquired. However, although work toward a cognitive theory of acquisition is relatively recent, it is now recognized as a major agenda for the field. A small amount of research now has been accomplished on skill acquisition, and some small-scale computer simulations that modify their own procedures--that "learn"--now have been created. In addition, close inspection of some of the theories of expert performance on complex tasks points to the shape that future theories of acquisition are likely to take. In this chapter I will use the themes that emerge from the detailed analyses of complex cognitive tasks and from recent work on skill acquisition to sketch outlines of a future theory of acquisition relevant to instruction.

For a theory of intervention we still need to be patient. With a cognitive theory of acquisition only beginning to emerge, it is not yet possible to point to a vigorous cognitive theory of intervention. In fact, the question of intervention has barely been addressed within cognitive science. Existing principles for instruction that claim a scientific basis are largely drawn from associationist and behavioral psychology, which have a strong history of involvement in questions of instruction. As a result, the best I can do in this chapter is to suggest what are likely to become some of the major questions for an eventual cognitive theory of intervention.

I begin, then, with an emerging cognitive theory of acquisition, and then go on to suggest what this might mean for a theory of intervention. Readers familiar with the literature in cognitive science will recognize that I am taking some leaps of inference in using current research on cognitive task analysis as a basis for deriving the outlines of a cognitive theory of acquisition. My leaps of inference must necessarily be even larger in going from acquisition to intervention. Although there are risks in such a venture, there are now enough strong indicators of future directions within cognitive research that this is nevertheless a useful way to make progress toward an eventual well-grounded cognitive theory of instruction. The difficulties encountered are more likely to be ones of over-generality than of absolute error. I will draw my examples throughout the discussion from cognitive research on core school subject matters such as reading, mathematics, and science. I hope this will make it clear that, although much remains to be learned, a significant branch of cognitive science is working directly on questions relevant to instruction.

Major Themes in a Theory of Acquisition

Limited-Capacity Learners

One of the first factors that a cognitive theory of acquisition will have to take into account is the fact that humans are limited capacity learners. This is probably the single earliest fact that emerged from the beginnings of cognitive psychology. In a seminal work, Miller (1956) suggested that adults have only seven "slots" (plus or minus two) for receiving information in working memory. This notion of a limited capacity for information processing is central to all cognitive science. Psychologists are no longer certain that slots in memory is the best way of describing capacity limitations, nor that there is any reality to the number 7 ± 2 as the capacity of working memory. Nevertheless, all cognitive scientists agree that there is some "computing" work that has to go on for thought to proceed, that the capacity for doing this is limited, and that this creates a "bottleneck." That is, if too much capacity is devoted to any one component of a complex learning task, then other components will suffer.

Despite this limited processing capacity, people are able to perform these complicated tasks. How? There are two major mechanisms that allow people to overcome memory capacity limitations: (1) Certain components of a task become automated so that they require very little direct attention and therefore use up little working capacity. (2) Information is "chunked" so that each slot in working memory is filled with a cluster of related knowledge. The evidence for each of these mechanisms and their implications for theories of acquisition and intervention are worth considering in more detail.

Automaticity. The role of automatic processing in facilitating complex performances has been investigated most in the context of acquiring basic reading skills. A growing research literature contrasting good and poor readers at various stages of development is identifying particular components of reading skill that distinguish the contrasting skill groups. A consistent finding in this research is that people who read "poorly" (i.e., who score poorly on standardized reading comprehension tests) also are generally slower at recognizing words. It is *speed*, rather than accuracy of word recognition, that seems to be important. Some individuals apparently have large recognition vocabularies and quite adequate word recognition skills as long as they are permitted indefinite amounts of time to process each word; but they seem to proceed so slowly that they cannot effectively understand what they are trying to read.

The observation of an association between slow word processing and reading comprehension skill is a relatively recent one. About ten years ago reading researchers began to apply the methods and theory of the then relatively new cognitive psychology to reading. In an initial study, LaBerge and Samuels (1974) showed that poor readers were less automatic in processing individual words in the sense that they needed to devote more attentional capacity to word recognition than did the more skillful readers. Subsequent research on automation of word recognition (e.g., Curtis, 1980; Frederiksen, 1981; Perfetti & Lesgold, 1979; Perfetti & Roth, 1981) has focused more on speed of access than on directly assessing ability to overcome competing demands for attention. In multiple studies using populations of both children and adults, including some handicapped readers, it has now been shown that those who score low on various reading achievement measures that stress comprehension almost always are slow in accessing individual words (e.g., Curtis, 1980; Frederiksen, 1979; Jackson & McClelland, 1979; Perfetti & Hogaboam, 1975).

This repeated finding has led to an important reformulation of theories of reading acquisition. Instead of pitting word recognition skill *against* skill in interpreting meaning, new theories are concerned with ways in which lower and higher level (i.e., word level and context level) processes *interact* in reading (see Lesgold & Perfetti, 1981). The new theories are concerned with how information from text interacts with information from previously read material and from an individual's general prior knowledge to produce both word recognition and comprehension (cf. Rumelhart & McClelland, 1981). To do this, the theories must account for the manner in which information is entered and processed in the various memory stores. In these interactive theories timing is often crucial, for several sources of information must be integrated and thus must be present in working memory at the same time. Memory capacity is also crucial. Processes that take up too much working memory capacity or too much direct attention may drive out the other processes that are needed to provide all of the necessary information simultaneously to the system. Automation of the word recognition component of reading may be necessary both for quick and timely processing of meaning, and for the reductions in working memory demands that allow reading to proceed smoothly.

Establishing a correlation between automatic word recognition and comprehension skill does not of itself tell us how automaticity is acquired, nor does it necessarily mean that automatic recognition *causes* the development of comprehension skill. To the contrary, practice in reading and comprehending texts might be the cause of improved automaticity; or automaticity and comprehension skill might both depend on some other, as yet unidentified, process. A recent longitudinal study helps to limit the possibilities. Lesgold and Resnick (1983) found that children who have large automaticity problems early in first grade are very likely to show difficulties in comprehension a year or two later. By contrast, early comprehension difficulty does not predict later automaticity difficulties. The relationship is time-lagged and runs in only one direction. This asymmetric relationship allows us to reject the possibility that comprehension skill causes automaticity and suggests that automaticity difficulties may indeed be helping to cause difficulties in learning to comprehend written texts.

If automaticity is a prerequisite for acquiring comprehension skill, then it should be the case that training in automaticity of word recognition should produce improved comprehension. Does it? In one study (Fleisher & Jenkins, 1978) it was found that while speeded practice can significantly increase speed of recognizing isolated words, there is no immediate transfer to comprehension. This means that comprehension skill is not ready and waiting to be "released" by improved word recognition automaticity, but the processes of *acquiring* comprehension skill may nevertheless be enhanced by increased recognition speed. If that is the case, the effects on comprehension performance would be visible only after some delay—during which time reading comprehension was practiced. We do not yet know the long-term effects of training in fast word recognition. Furthermore, training that focuses *only* on speed, rather than on aspects of word analysis believed to function in highly skilled reading performance, may deflect learners' attention from the very features of words that allow for automated access to meaning. A current research program (Frederiksen, in press) is pursuing the hypothesis that training in quickly recognizing frequently recurring *spelling patterns* will improve general reading performance in adolescents with very poor reading skills. These patterns are the building blocks of words and according to some theorists (e.g., Venezky & Massaro, 1979) are the units in reading that correspond directly to meaning.

Chunking: The role of structured knowledge. The second major way in which people overcome limitations in memory capacity is by organizing knowledge so that each available "slot" in memory is not filled with a single piece of information but instead points to a "chunk" of related and organized material. For example, a single word can refer to a body of interconnected knowledge, thus allowing all of this knowledge to function at the same time. Chunking is possible because humans' long-term memory is much more structured and organized than the lists of bonds proposed by Thorndike (1922) and other associationists would have suggested. Knowledge is organized into highly interconnected networks of concepts, and individual "facts" take their meaning from the networks in which they are placed. Structured knowledge plays a central role not only in performance, but also in acquiring new knowledge. In fact, so central to cognitive theory is the idea of structured knowledge and its role in learning that this must be treated as a second major theme in a cognitive theory of acquisition.

The Role of Prior Knowledge in Learning: Schema Theories of Reading and Problem Solving

Current cognitive science recognizes a critical role for prior knowledge in new learning. The earliest demonstrations of the role of prior knowledge came in research on reading and oral text comprehension. A dramatic demonstration that made it impossible to ignore the phenomenon was given by Bransford and Johnson (1972). Their study showed that certain texts in which all words and individual sentences were understandable made no sense until readers were told what the passage was about. The text in Figure 1 is an example. It seems garbled and senseless until the picture in Figure 2 is shown, then it becomes totally comprehensible and even humorous.

If the balloons popped the sound wouldn't be able to carry since everything would be too far away from the correct floor. A closed window would also prevent the sound from carrying, since most buildings tend to be well insulated. Since the whole operation depends upon a steady flow of electricity, a break in the middle of the wire would also cause problems. Of course, the fellow could shout, but the human voice is not loud enough to carry that far. An additional problem is that a string could break the instrument. Then there could be no accompaniment to the message. It is clear that the best situation would involve less distance. Then there would be fewer potential problems. With face to face contact, the least number of things could go wrong.

Figure 1

Ambiguous textual passage, from Bransford and Johnson (1972).

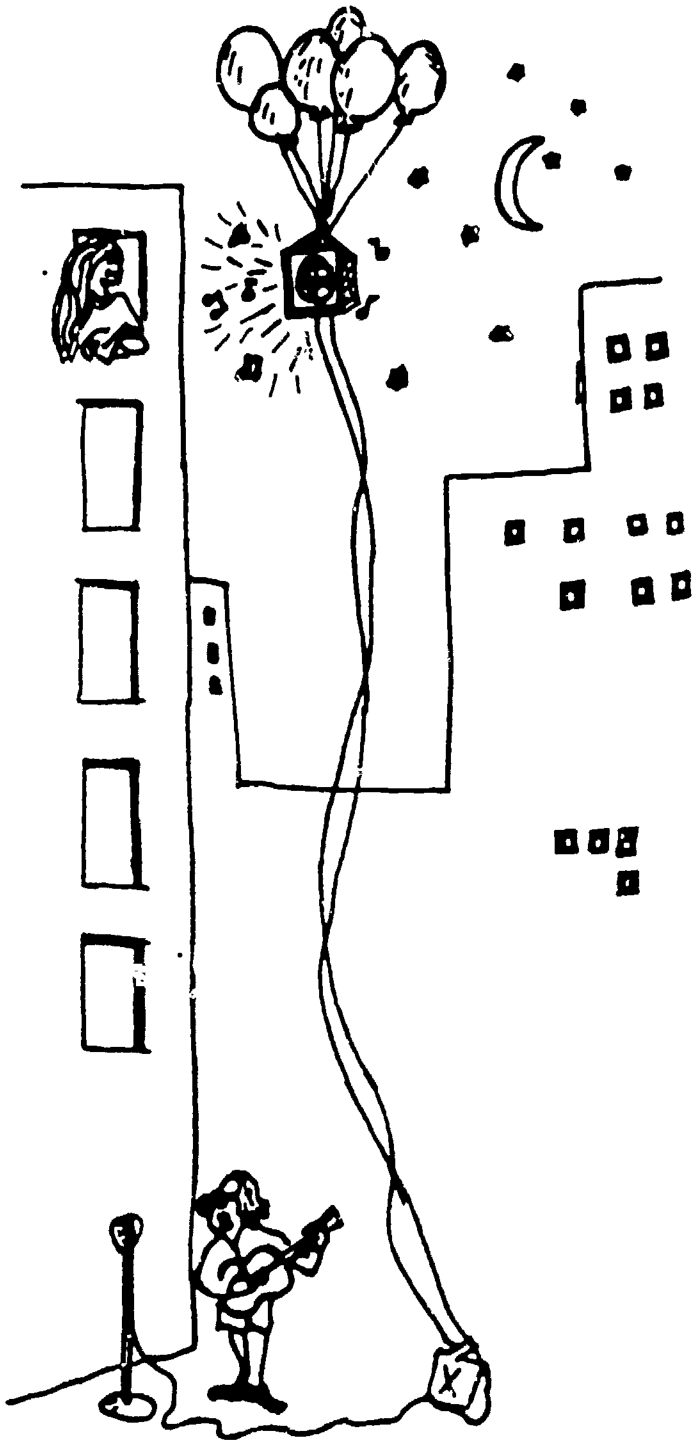


Figure 2
Appropriate context for ambiguous passage, from Bransford and Johnson (1972).

The Bransford and Johnson text, of course, is a particularly ambiguous one, chosen to make a point. Yet the same phenomenon has been observed in much less extreme situations as well. Hints provided in advance by the experimenter or the reader's own background have been shown to make a difference in what one understands from a text. For example, one study (Anderson, Reynolds, Schallert, & Goetz, 1977) shows that music students interpret the passage in Figure 3 as an evening of playing chamber music, while physical education students interpret it as an evening of playing cards. This kind of study shows clearly that the background knowledge and interpretive schemata that readers bring with them to a text make a difference in what they understand the text to be saying. Clearly, this knowledge also will affect what they can learn from the text.

Every Saturday night, four good friends get together. When Jerry, Mike, and Pat arrived, Karen was sitting in her living room writing some notes. She quickly gathered the cards and stood up to greet her friends at the door. They followed her into the livingroom, but as usual they couldn't agree on exactly what to play. Jerry eventually took a stand and set things up. Finally, they began to play. Karen's recorder filled the room with soft and pleasant music. Early in the evening, Mike noticed Pat's hand and the many diamonds. As the night progressed, the tempo of play increased. Finally, a lull in the activities occurred. Taking advantage of this, Jerry pondered the arrangement in front of him. Mike interrupted Jerry's reverie and said, "Let's hear the score." They listened carefully and commented on their performance. When the comments were all heard, exhausted but happy, Karen's friends went home.

Figure 3

Interpretation of this passage depends on reader's background knowledge.

Demonstrations of these kinds, together with many more formal experiments, underlie what has become known as the "schema theoretic" view of reading comprehension. The theory holds that *schemata*, which are prototypical versions of a situation, are carried around in one's head and are used to interpret new instances and events. The schemata describe classes of situations specifying the relationships among objects and events. The specific events will vary according to the particular case, but the relationships specified in the more general schema still hold and are used to interpret the case at hand. Schemata result from a cumulation of prior learning and experience. They are necessary if one is to comprehend new verbal material, and thus they are important to all learning that depends on verbal presentations. Schemata of this kind are at the core of most artificial intelligence models of language understanding (e.g., Schank & Abelson, 1977).

They also are central to linguistic work on text grammars (e.g., vanDijk, 1977).

Story grammars provide a particularly well-developed example of how schemata can work in controlling and supporting comprehension. Several investigations (see Stein & Trabasso, 1982) have shown that there is a prototypical structure of narratives that is used by people in interpreting stories. The idealized story--in effect, a schema of a story--organizes and directs peoples' interaction with the particular story they are reading or hearing. The story schema specifies the types of information that should be presented and the types of logical relationships that should link the story elements. Several categories of information must occur in order: a setting, an initiating event, an internal response, an attempt to obtain a goal, an outcome or consequence, and a reaction.[1]

Some of the categories in this structure are more central than others. This is shown by substantial regularities in which portions of stories people omit and in which ones they add when asked to retell stories they have heard. Initiating events, attempts to achieve a goal, and consequences are nearly always included, but other categories, especially internal cognitive responses of the characters, are likely to be omitted (Mandler, 1978; Mandler & Johnson, 1977; Stein & Glenn, 1979; Thorndyke, 1977). Story comprehension and recall also are sensitive to the

[1]Some recent research (e.g., Black & Wilensky, 1979) suggests that the semantic content, rather than just form or placement of the information within the story, may be determining recall. Attempts to enlarge story research beyond the simple demonstration of grammars have been leading psychologists increasingly to a concern for the specific kinds of social knowledge held by children of different ages and stages of development.

order in which categories of information are presented. People have difficulty recalling stories when information is given in orders other than those specified in the grammar, and they tend to recall story information in the order predicted by the grammar even when the text from which they learn the story uses a nonstandard order (e.g., Bower, Black, & Turner, 1979; Kintsch, Mandel, & Kozminsky, 1977).

Inference. One reason that prior knowledge is so important in comprehension is that normal texts are never complete. Something is always left for the reader or listener to infer. There are gaps in the story or the argument as it is related, and it is the task of the reader to fill in those gaps. While there are many points of disagreement among people doing cognitive research on reading and natural language understanding, they would all agree with the following general characterization of the process of comprehension: When you read a text you build up in your mind a knowledge structure that represents the same situation that the text represents. This knowledge structure is not meant to be a direct match to the text. It leaves out some things that the text says and puts in some things that are not mentioned. The items of information it leaves out are the items of information that the reader construes as not crucial. What it puts in are the items of information needed if the total message is to make sense. The only way that a decision can be made about what is sensible and that necessary new inferred material can be added is on the basis of prior information.

The centrality of inference in comprehension is the major reason why the processes of comprehension can shed light on the processes of learning. Since comprehension is not a matter of registering a copy of what is read or heard but rather of *constructing* links and interpretations, it involves the acquisition of new knowledge--thus, learning.

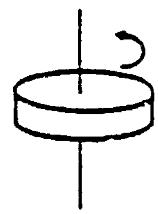
Further evidence of the importance of prior knowledge and constructive interpretation comes from recent work on the learning of physics. This work shows that the kind of prior knowledge that people have not only affects what answers they are able to develop for a problem but the very processes by which they develop them. There are two important lines of work to be cited. One set of studies, by Chi, Feltovich, and Glaser (1981), shows that the initial representation of mechanics problems is different for expert physicists (advanced graduate students) than for novices (undergraduate students who had just successfully completed a semester of physics). When these two groups of people are asked to sort and classify physics problems, the novices do so on the basis of the kind of apparatus involved, the actual words used in the problem statement, or other surface characteristics such as diagrams. By contrast, experts sort on the basis of underlying physics principles. Some typical novice classifications are shown in Figure 4. Note the surface similarities of apparatus, language, etc. Expert classifications of the same kinds of problems are shown in Figure 5. Here problems are grouped together because they involve the Law of Conservation of Energy, or Newton's Second Law, despite differences in surface features.

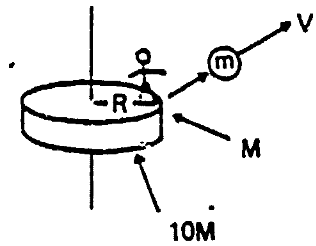
These differences in initial representation seem to be linked to differences in subsequent processes of problem solution. This has been shown in a line of research conducted by Larkin and her colleagues (Larkin, McDermott, Simon, & Simon, 1980). In these studies, novices appear to go about solving textbook problems in physics by directly translating the information given into formulas and then working more or less algebraically on the formulas. The experts, however, begin by doing a lot of reinterpretation of the problem. Their think-aloud protocols are filled with mumbled partial sentences that eventually emerge as a re-representation of the problem. Unlike novices, in other words, experts do not often take the problems as given. Their re-representations result in interpretations of the problems as instances of general laws of physics and to restructured relationships between elements of the problem. As a result, experts usually have very few equations to write and the problem is virtually solved by the time they start doing any mathematics. A general characterization that can be made of these performances is that beginners in a field behave as if they are doing puzzles in which the terms to be manipulated have almost no external reference. Their protocols look very much like the ones that Newell and Simon (1972) reported for logic exercises and other puzzle-like tasks. Experts, on the other hand, analyze the problems by drawing on a storehouse of personal knowledge that is directly represented in their reinterpreted problem statements. In the hands of experts the problems are situated in a network of knowledge that lends them meaning.

It is not inappropriate to think of experts in these experiments as those who called on a limited number of schemata that express basic physical relationships. The schemata served to organize the experts' thinking effectively, at least on the kinds of problems (difficult for beginners but simple for experts) that have been studied up to now. Once a schema is identified as being relevant to a particular problem, the schema specifies what kinds of data are needed and how different quantities will be related to each other. The original problem statement is then searched for the information that the schema calls for. The schema in effect directs interaction with the

Diagrams Depicted from Problems Categorized by Novices within the Same Groups

Novices' Explanations for Their Similarity Groupings

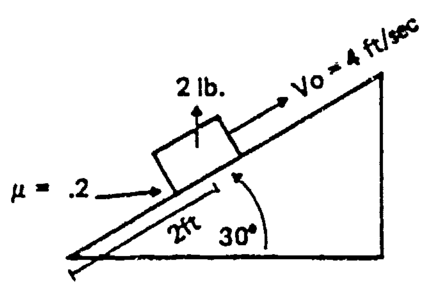


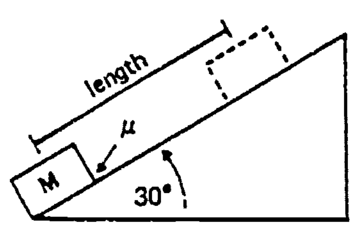


Novice 2: "*Angular* velocity, *momentum*, circular things"

Novice 3: "*Rotational* kinematics, *angular* speeds, *angular* velocities"

Novice 6: "Problems that have something *rotating; angular* speed"





Novice 1: "These deal with blocks on an *incline plane*"

Novice 5: "*Inclined plane* problems, coefficient of *friction*"

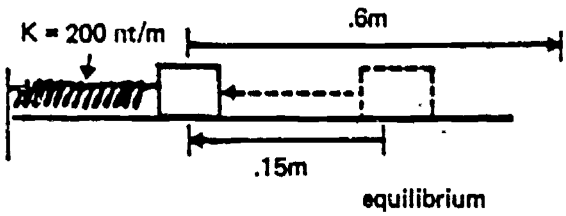
Novice 6: "Blocks on *inclined planes* with angles"

Figure 4

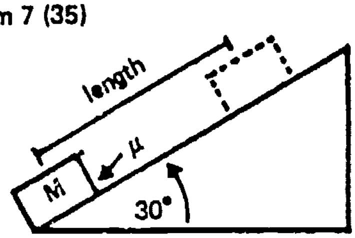
Diagrams depicted from two pairs of problems categorized by novices as similar, and samples of three novices' explanations for their similarity. Problem numbers given represent chapter, followed by problem number, from Halliday and Resnick (1974). (From Chi et al., 1981.)

Diagrams Depicted from Problems Categorized by Experts within the Same Groups

Experts' Explanations for Their Similarity Groupings



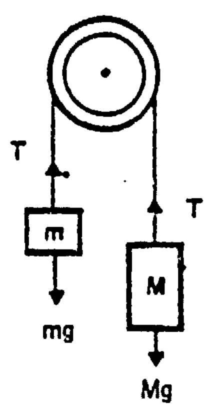
Problem 7 (35)

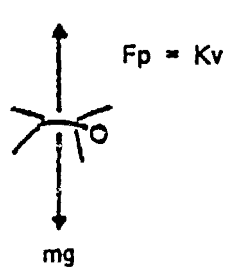


Expert 2: *"Conservation of Energy"*

Expert 3: *"Work-Energy Theorem.* They are all straight-forward problems."

Expert 4: "These can be done from energy considerations. Either you should know the *Principle of Conservation of Energy*, or work is lost somewhere."





Expert 2: "These can be solved by *Newton's Second Law"*

Expert 3: "F = ma; *Newton's Second Law"*

Expert 4: "Largely use F = ma; *Newton's Second Law"*

Figure 5

Diagrams depicted from pairs of problems categorized by experts as similar, and samples of three experts' explanations for their similarity. Problem numbers given represent chapter, followed by problem number, from Halliday and Resnick (1974). (From Chi et al., 1981.)

problem statement. This leads to a process quite different from the novice's direct translation process, in which the problem statement itself largely controls the process.

The parallel roles of pre-existing schemata in text comprehension and problem solving suggest a more general role for schemata in acquiring new knowledge. We can think of learning as the process of putting new information into relationship with knowledge that is already held. Rarely, outside the psychology laboratory, does one seek to learn something totally new and unconnected to past knowledge and experience. Moreover, both common experience and scientific experimentation tell us that these occasions of acquiring totally new and unconnected facts tend to be the most difficult and least durable of all learning attempts. On such occasions, learners are like novice physics problem solvers or readers unfamiliar with the structure of stories: They are at the mercy of the material as presented, without the resources necessary to do the reinterpretation that will give it sense and meaning. This dependency of learning on past knowledge has two effects: (1) What people already know can make learning easier in cases where they can find points of coherence and connection between the old and the new. (2) Prior knowledge can interfere with new learning when existing knowledge structures are incompatible with the new ideas to be acquired. In the following sections, I consider these two aspects of the knowledge acquisition process.

Learning as Coherence-Building

When knowledge to be acquired is compatible with pre-existing knowledge structures, learning can be viewed as a process of connecting the new information with what one already knows, thus making the new information sensible. Indeed, a third major theme that emerges from an inspection of recent cognitive research is a characterization of learning as coherence building. Once again, the strongest theoretical statements come from research on reading comprehension, especially the work of Kintsch and vanDijk (1978). These investigators and their colleagues (Kintsch & Vipond, 1979; Miller & Kintsch, 1980) have shown that the comprehensibility of text is a function of how explicit the text is in making clear the connections between successive sentences. A text is coherent in the Kintsch and vanDijk analysis to the extent that each new proposition (i.e., actor-action-object sequence) makes explicit reference to prior propositions. In Figure 6, for example, proposition sequences 1-4 and 5-11 are internally coherent because the actor (subject) in each proposition already has been named in a close prior proposition. However, line 5 is not explicitly coherent with its predecessors. To understand the text--that is, to construct a fully coherent representation of it--the reader must infer a linking

Text:

The Swazi tribe was at war with a neighboring tribe because of a dispute over some cattle. Among the warriors were two unmarried men named Kakra and his younger brother Gum. Kakra was killed in battle.

Propositional analysis of text:

1. The Swazi tribe was at war.
2. The war was with a neighboring tribe.
3. The war had a cause.
4. The cause was a dispute over some cattle.
5. There were warriors.
6. The warriors were two men.
7. The men were unmarried.
8. The men were named Kakra and Gum.
9. Gum was the younger brother of Kakra.
10. Kakra was killed.
11. The killing was in a battle.

Figure 6

A text and its propositions, adapted from Kintsch (1979).

proposition, for example, "The Swazi tribe had warriors." The number of missing propositions and the distance in the text that must be traveled to find explicit links affect not only the processing time for a text, but also the demand on short-term memory. Too much local incoherence can render a text incomprehensible, but a completely explicit text would be uninteresting. Optimal texts thus require just the right amount of inferencing work by the reader, as if there were an implicit contract between the writer and the reader.

This notion of coherence can be extended to learning in general if we think of the learner as one who works to relate new information from the environment to existing knowledge, one who in effect inserts new propositions into an established network of already interrelated propositions. The idea of learning as adding new knowledge to old is not unfamiliar in instructional theory. It is, for instance, an established principle in behavioral theories of learning. Most significant for instructional theory is Gagne's (1962, 1968) theory of cumulative learning, which describes acquisition of new *performance* capabilities as the addition of new component skills to existing ones. However, behavioral theory was silent about the processes by which an individual learner seeks and creates coherence in a *knowledge* base. Furthermore, recent evidence on the ways in which learners utilize previously established knowledge suggests a relationship between old and new knowledge that is much more complicated than simple cumulation. This is considered in the next section.

Learning as Theory Change

A growing body of evidence, mostly collected in studies of science learning, now is showing how prior knowledge actually can interfere with new learning. A recurrent finding in studies of physics instruction, for example, is that people bring with them to their formal science study a quite powerful set of beliefs about how the physical world works (Resnick, 1983; McDermott, in review). These beliefs are robust and resistant to the new data and theoretical principles taught in physics courses. Their "naive" beliefs allow people to construct explanations of various phenomena that accord quite well with their perceived experience in the real world. The difficulty is that these beliefs do not always match well with the Newtonian principles taught in physics courses, yet they are not always abandoned as the result of instruction in Newtonian physics. Some students can perform adequately on the textbook problems in a high school or college physics course; but when given practical problems that are not easily recognized as applications of textbook formulae, problems that require them to construct their own representation of the situation, the students will revert to their pre-instruction conceptions and theories. These students show evidence of having a very well-integrated knowledge structure that must be given up or radically altered before they can acquire Newtonian conceptions at anything beyond an equation-solving level. However, the internal coherence of naive theories of physics together with the adequacy with which these explain events as experienced in the world, makes them resistant to modification as a simple result of new information taught in the physics course. It thus appears that people maintain two separate knowledge structures, each called upon in different situations, rather than a single integrated one.

These findings force us to broaden our thinking about the relations between established and new knowledge in the course of learning. We must think not only about the cumulation and linking of knowledge structures, but also about fundamental shifts in knowledge structures. The cognitive research on physics suggests that it may be useful to view learning as a process of theory change, and to seek to describe the mechanisms and circumstances of such change in some detail. Such a view of acquisition is not entirely new. It is inherent in the Piagetian conception of complementary processes of assimilation and accommodation (Piaget, 1971) as major mechanisms of cognitive development. A similar view has been offered by Rumelhart and Norman (1977), who sketch processes of "accretion" and "tuning" of cognitive structures. Nevertheless, there has not yet been much research of a kind that can actually reveal the *processes* of theory change and the mechanisms of resistance to such change. Precisely how do already-held schemata drive attention away from new interpretations? What kinds of confrontations between old conceptions and new ones, or between established theories and new data, are necessary for the process of theory change to begin? Once it begins, how are new theories or schemata built? What happens to old schemata as new ones take over? These are among the important questions to be addressed by the emerging cognitive theory of acquisition.

Learning as Invention: Sensible Constructions on Limited Data

Using existing schemata to interpret new information, seeking coherence between old and new knowledge, building and sometimes modifying theories--all of these characterizations of learning share a common feature: They recognize that learning is a process of knowledge construction by the learner rather than the simple recording of information. This theme of learning as knowledge construction is so central that it warrants separate consideration here. It is especially important to examine emerging evidence that the same processes of knowledge construction, or cognitive "invention," can produce either successful learning or persistent difficulties depending on the kind of information that is available and used.

Let us begin with evidence of successful cognitive inventions. An important body of evidence comes from research in a domain of learning long thought to be a prime example of rote acquisition of associations: simple single-digit addition and subtraction problems. School textbooks typically define addition as a process of "counting out" objects to represent each addend, combining the subsets thus created into a single large set, and then recounting the combined set. Teachers generally expect children to memorize the answers to simple addition problems rather quickly, and thus to cease to depend upon any form of counting. Research in several countries, however, now has made it clear that there is a period of time in which children continue to use a counting method to do addition, but they use a different procedure than the one they were taught. The procedure most children use is much more elegant than the one they were taught, because it minimizes the computational steps and because it appears to involve an intuitive appreciation of the mathematical principle of commutativity. What children typically do is behave as if they had a counter in their heads. They initially set this counter to the larger of the two addends, and then increment it by a number of steps equivalent to the smaller addend. For example, to add 3 + 5, the child starts at 5 (even though it is named second) and counts on: "5...6, 7, 8." The final count ("8") is then given as the answer. This procedure has been documented in reaction-time and interview studies of a number of children in different countries and of different measured mental abilities (e.g., Groen & Parkman, 1972; Svenson, 1975; Svenson & Broquist, 1975). A study by Groen and Resnick (1977) shows that the procedure can be invented by children as young as four or five just as a result of practice in addition—with no direct instruction, demonstration, or explanation.

A similar story can be told for subtraction. Typical textbooks demonstrate either (a) a counting-out procedure in which a starting set (the minuend) is established, a specified number of objects (the subtrahend) is removed, and the remainder is counted, or (b) a matching procedure in which sets to represent two quantities are established, objects from these sets are paired one-for-one, and the remaining unmatched objects are counted. However, after practice, children do something rather different from either of these procedures: They count *down* from the minuend, or count *up* from the subtrahend, ***whichever will take the fewest counts***. Thus, for 9 - 2, children say, "9...8, 7" and answer, "7"; but for 9 - 7, they say, "7...8, 9" and answer, "2" (Svenson & Hedenborg, 1979; Woods, Resnick, & Groen, 1975). This procedure behaves as if the children who invented it understood the complementarity of addition and subtraction. Furthermore, it is not just a shortcut—a dropping of redundant steps in the algorithm that had been taught—for it involves, for each case, a decision whether to count down or up. It is a true *invention* of a new procedure.

Studies of this kind demonstrate the centrality of invention even in apparently simple and "rote" domains of learning. However, they should not be taken to imply that inventions are always successful. In fact, one of the recurrent findings in cognitive science during the past few years has been the frequent occurrence of systematic but wrong rules--for example, procedures for doing arithmetic (e.g., Brown & Burton, 1978) or rules for predicting the behavior of physical systems (Siegler, 1978). Errors of responding that once had been attributed to carelessness or lack of any systematic understanding of a system have now been shown to be based on very strong conceptions of how the system works. In the case of arithmetic, it has been shown that these systematically used wrong procedures are variants of the correct ones. They are analogous to computer algorithms with "bugs" in them, and thus have been christened "buggy algorithms." A finite number of bugs, which in various combinations make up several dozen buggy algorithms, have been identified for subtraction--the most heavily studied arithmetic domain so far. The children who display these buggy algorithms are systematically applying rules that no one could have taught them, for no one would deliberately teach a wrong rule. Buggy algorithms are thus clear examples of inventions that are unsuccessful.

Despite their failure as rules of calculation, buggy algorithms demonstrate an important characteristic of human learning and performance. Close analysis of the various incorrect algorithms that have been observed among children makes it clear that most of them are small and often quite sensible departures from the correct algorithm. As the examples in Figure 7 reveal, buggy subtraction algorithms tend to "look right" and to obey a large number of the important rules for written calculation: the digit structure is respected, there is only a single digit per column, all columns are filled, there are crossed out and rewritten digits, and so forth. In the sense of being an orderly and reasonable response to a new situation, the buggy algorithms look quite sensible. However, each buggy algorithm violates a fundamental rule of the arithmetic system--the necessity of maintaining the value of the top quantity no matter what particular transformations or "exchanges" of quantities may be made between the columns in the written number. This points to a pervasive feature of learning and cognitive performance: People try to make sense of the world, and to create rules for acting in it, even with only limited data. They do not wait until they have all the necessary information before they construct a theory to account for what they perceive. In the case of buggy subtraction algorithms, children seem to construct a "theory of allowable operations" that respects the information they do have while ignoring some mathematically important constraints that apparently are not stressed adequately in primary school arithmetic teaching.

1. Smaller-From-Larger. The student subtracts the smaller digit in a column from the larger digit regardless of which one is on top.

$$\begin{array}{r} 326 \\ -117 \\ \hline 211 \end{array} \qquad \begin{array}{r} 542 \\ -389 \\ \hline 247 \end{array}$$

2. Borrow-From-Zero. When borrowing from a column whose top digit is 0, the student writes 9 but does not continue borrowing from the column to the left of the 0.

$$\begin{array}{r} 6\overset{9}{\cancel{0}}{}^{1}2 \\ -437 \\ \hline 265 \end{array} \qquad \begin{array}{r} 8\overset{9}{\cancel{0}}{}^{1}2 \\ -396 \\ \hline 506 \end{array}$$

3. Borrow-Across-Zero. When the student needs to borrow from a column whose top digit is 0, he skips that column and borrows from the next one. (Note: This bug must be combined with either bug 5 or bug 6.)

$$\begin{array}{r} \overset{5}{\cancel{6}}0{}^{1}2 \\ -327 \\ \hline 225 \end{array} \qquad \begin{array}{r} \overset{7}{\cancel{8}}0{}^{1}4 \\ -456 \\ \hline 308 \end{array}$$

4. Stops-Borrow-At-Zero. The student fails to decrement 0, although he adds 10 correctly to the top digit of the active column. (Note: This bug must be combined with either bug 5 or bug 6.)

$$\begin{array}{r} 70{}^{1}3 \\ -678 \\ \hline 175 \end{array} \qquad \begin{array}{r} 60{}^{1}4 \\ -387 \\ \hline 307 \end{array}$$

5. 0 – N = N. Whenever there is 0 on top, the digit on the bottom is written as the answer.

$$\begin{array}{r} 709 \\ -352 \\ \hline 457 \end{array} \qquad \begin{array}{r} 6008 \\ -\ 327 \\ \hline 6321 \end{array}$$

6. 0 – N = 0. Whenever there is 0 on top, 0 is written as the answer.

$$\begin{array}{r} 804 \\ -462 \\ \hline 402 \end{array} \qquad \begin{array}{r} 3050 \\ -\ 621 \\ \hline 3030 \end{array}$$

7. N – 0 = 0. Whenever there is 0 on the bottom, 0 is written as the answer.

$$\begin{array}{r} 976 \\ -302 \\ \hline 604 \end{array} \qquad \begin{array}{r} 8\overset{4}{\cancel{5}}{}^{1}6 \\ -409 \\ \hline 407 \end{array}$$

8. Don't-Decrement-Zero. When borrowing from a column in which the top digit is 0, the student rewrites the 0 as 10, but does not change the 10 to 9 when incrementing the active column.

$$\begin{array}{r} \overset{6}{\cancel{7}}0{}^{1}2 \\ -368 \\ \hline 344 \end{array} \qquad \begin{array}{r} \overset{1}{\cancel{2}}{}^{1}0{}^{1}5 \\ -\quad 9 \\ \hline 1106 \end{array}$$

9. Zero-Instead-Of-Borrow. The student writes 0 as the answer in any column in which the bottom digit is larger than the top.

$$\begin{array}{r} 326 \\ -117 \\ \hline 210 \end{array} \qquad \begin{array}{r} 542 \\ -389 \\ \hline 200 \end{array}$$

10. Borrow-From-Bottom-Instead-Of-Zero. If the top digit in the column being borrowed from is 0, the student borrows from the bottom digit instead. (Note. This bug must be combined with either bug 5 or bug 6.)

$$\begin{array}{r} 70{}^{1}2 \\ -3\overset{5}{\cancel{6}}8 \\ \hline 454 \end{array} \qquad \begin{array}{r} 50{}^{1}8 \\ -4\overset{7}{\cancel{8}}9 \\ \hline 109 \end{array}$$

Figure 7

Samples of buggy subtraction algorithms invented by children, adapted from Brown and Burton (1978).

A closer consideration of the origins of buggy arithmetic algorithms highlights this point. Brown and VanLehn (1980, 1982) have developed a formal theory in the form of a computer-based simulation program that invents the same subtraction bugs and therefore makes substantially the same errors as do children. According to their "repair theory," buggy algorithms arise when an arithmetic problem is encountered for which the child's current algorithms are incomplete or inappropriate. In trying to respond, the child eventually reaches an impasse—a situation for which no action is available given the procedures learned up to that time. At this point the child tries to fix the procedure, calling on a list of *repairs*—actions to try when the standard action cannot be used. The repair list includes strategies such as performing the action in a different column, skipping the action, swapping top and bottom numbers in a column, and substituting an operation (such as incrementing for decrementing). The outcome generated through this repair process is then checked by a set of "critics" that inspect the resulting solution for conformity to some basic criteria such as no empty columns, only one digit per column in the answer, only one decrement per column, and the like.

Together, the repair and critic lists constitute the key elements in a "generate and test" problem-solving routine. This is the same kind of "intelligent" problem solving that characterizes many successful performances in other domains (cf. Simon, 1976). With buggy algorithms, the trouble seems to lie not in the reasoning processes but in the inadequate data base applied. In particular, the critic list does not contain criteria that would reject repairs that violate the principle of maintaining quantity equivalence. The invented algorithm is a sensible construction, but on a data base that is incomplete. It therefore turns out to be a buggy rather than a successful invention.

Repair theory is, in fact, a detailed theory of acquisition for a small domain of arithmetic. Its broader implications for cognitive theories of acquisition are that these theories must recognize people's tendency to organize and structure whatever information they have, even though the information may be grossly incomplete or downright inaccurate. People do not simply acquire information passively until there is enough of it for correct rules and explanations to emerge. Instead, they construct explanations and rules of procedure continuously, either out of intellectual curiosity or the need to function in the practical world. This tendency to construct ordered explanations and routines even in the absence of adequate information can account at least partly for the phenomenon, discussed above in the context of physics learning, of robust naive theories that are resistant to change even when instruction (and thus better information) does come along. The naive theories have been constructed to help the individual make sense of the natural world. Like buggy algorithms, they are partly correct, sensible interpretations of available evidence, and they have--outside the classroom--a relatively large and reliable field of application. To give them up in order to accommodate the principles of Newtonian mechanics is to give up a reliable and long-held system of knowledge, with many interrelated schemata and domains of application, for an as yet "incoherent" (because unconnected either to other schemata or to practical experience) new theory. It is not surprising that many students simply reserve their classroom-acquired theories for classroom situations, and do not try to apply them outside.

Self-Monitoring and Learning

Another theme that emerges from an inspection of recent cognitive task analyses is the central role that self-monitoring of one's own cognitive states seems to play in learning. I use the term self-*monitoring* rather than self-*awareness*, because the kind of monitoring that seems to be important in learning is not always conscious and open to overt observation or verbal self-report. Yet several sources of evidence suggest that successful learning nearly always involves some form of inspection and evaluation of one's own mental processes or mental states.

First, we can consider recent developments in artificial intelligence. There now exist several systems that "learn" (e.g., Anderson, 1981)--that is, they modify their own procedures in the course of performing a class of tasks. Current learning systems vary in many important respects. However, all share a crucial feature: They maintain a record, for at least a brief time, of the actions they have taken and the results produced, and they use this record to change their rules for future actions. An illustrative case comes from work by Neches (1981), who has developed a system that invents the "count-on-from-the-larger-addend" addition procedure described above.

The program begins, as do children, with a procedure in which both addends are counted out and the resulting sets combined and recounted. As it works on successive problems, the system retains a record of what it has done most recently. When it notices that certain conditions have been met in this record, it transforms its rules of procedure using a specified set of transformation heuristics. Table 1 lists a few of the transformation rules that can be used by learning systems of this kind. None of the rules appears to depend upon understanding the total situation or upon extensive reflection. Each heuristic is applied when its local conditions are met.

A. Reduction to a rule: replacing a procedure with an induced rule for generating its results.

1. Effort difference: If a difference in expended effort is observed when the same goal is operating on the same input(s) at different times, THEN set up a goal to find a difference between the methods used, and try to produce the circumstances which evoked the more efficient method.

B. Replacement with another method: substituting an equivalent procedure obtained by noting analogies.

1. Side-costs: IF the effort of set-up and clean-up operations are not small compared to costs of mainstep operations, THEN try to find the major factor dealt with by those operations, and look for a method in which that factor is not present.

C. Unit building: grouping operations into a set accessible as a single unit.

1. Co-occurring procedures (composition): IF a procedure, P_1, is frequently followed by another procedure, P_2, and the result of P_1 is used by P_2, THEN try to merger of the two as a new single procedure.

D. Deletion of unnecessary parts: eliminating redundant or extraneous operations.

1. Untouched results: IF a procedure produces an output, but no other procedure receives that result as input, then try deleting the procedure.

2. Over-determined tests: IF a procedure contains two tests as part of a decision, call them T_1 and T_2, and it is observed that the tests agree (i.e., T_1 is observed to succeed on several occasions, with T_2 also succeeding on all of those occasions, and is observed to fail on several other occasions, with T_2 also failing on all of those occasions), THEN try deleting one of the two tests.

E. Saving partial results: retaining intermediate results which would otherwise have to be recomputed later in a procedure.

1. Result still available: IF a procedure is about to be executed with a certain input, but the result of that procedure with the same input is recorded in working memory, THEN try to borrow that result now and in the future.

TABLE 1

Sample heuristics for transforming procedures.

F. Re-ordering: changing the sequence in which operations are performed.

1. Crowding: A large number of items are in working memory which have not been used, THEN set up a goal to change the sequence of operations.

2. Waiting: IF a result is generated, but many operations intervene before any use of it is made, THEN set up a goal to change the sequence of operations so that the operation producing a result and the operation using it are performed closer in time.

3. Non-optimal state utilization: IF a state which appeared previously must be restored in order to satisfy the enabling conditions of a planned operation, THEN set up a goal to find the action which changed the state, and to place the planned operation ahead of that action.

TABLE 1 Cont.

The result is learning that proceeds by many small and local changes in procedure. There is no single moment that would correspond to a moment of "restructuring" or of "insight", and thus nothing that would seem to qualify as a moment in which the system became consciously aware of its transformation. Nevertheless, each rule can be applied only when the system recognizes that its condition of application has been met; for this to happen, the system must retain and scan its immediately preceding actions and their results. If the system acted without maintaining and using such a record, it could not apply its transformation heuristics and could not "learn." Thus even this very automatic learning, which does not appear to be based on any effort to understand the situation, depends on self-monitoring.

Other evidence of self-monitoring comes from the entire recent history of research on reading processes. This work also supports the idea that self-monitoring and self-regulating processes must be at work as people try to understand and learn from texts. Various studies have shown that people adapt their reading processes to features of the text and to their own purposes in reading. For example, reading rates are slower and there is more "checking back" at points in a text where ambiguous or inconsistent information is encountered, or where information from important clauses must be integrated and inferences made (Just & Carpenter, 1981; Kieras, 1977). Such demonstrations basically reflect the additional time and work that is needed to build coherent representations under certain difficult conditions. However, they also point to the fact that readers are sensitive to their own states of knowledge, that they in some sense know when they have built a coherent representation. If they lacked such sensitivity, we would expect people simply to read along at a regular rate and conclude their reading with differences in the extent to which easy and hard material had been integrated. In other words, why work harder at certain points in a text if one is not, at some level, cognizant of whether or not one has completed the work of building an adequate representation of the text?

Indeed, research on children and on various groups of weak readers or individuals who are generally poor in learning suggests that inability to assess one's own state of knowledge is a hallmark of those who do not comprehend or learn skillfully. For example, Markman (1977) has shown that six-year-old children were unaware that they had not understood game instructions, as shown by their failure to request more information when incomplete instructions were given. These children needed to try to carry out the instructions before they became aware that more information was needed. Young children also have been shown to be less able than older children and adults: (a) to assess problem difficulty and thus allocate study time and effort efficiently, (b) to assess their own readiness for tests, (c) to judge which parts of a text are most important and thus should be studied most carefully, and (d) generally to engage in systematic efforts to increase their memory or comprehension (see Brown, 1978, 1980, for a review of this research on "metacognition"). The same kinds of difficulties are also characteristic of retarded and other poor learners. These individuals not only lack strategies for effectively processing information, they also lack the ability to decide for themselves when to use these strategies.

A confirmation of the central role of self-monitoring in learning comes from a few recent studies that have begun to show success in improving the memory or comprehension skills of weak learners. Earlier investigators had been able to show good immediate gains in performance on memory tasks by simply instructing individuals to rehearse items on memory lists or to engage in various kinds of verbal elaboration (e.g., Brown & Barclay 1976; Butterfield, Wambold, & Belmont, 1973; Engle & Nagle, 1979; Turnure, Bulum, & Thurlow, 1976). In these studies, however, there was almost complete lack of transfer--even to only slightly modified tasks. In other words, the subjects learned to process the material in the way they were told, but they showed no evidence of being able to judge for themselves when the processing strategies they had acquired would be useful. In recent studies (e.g., Belmont, Butterfield, & Borkowski, 1978; Borkowski & Cavanaugh, 1979; Brown & Campione, 1977; Kendall, Borkowski, & Cavanaugh, 1980; students have been taught skills such as assessing their own readiness for a test and deciding when to use rehearsal or imagery, and strategies for formulating questions about a text they have read. Transfer and retention of improved learning have been much greater in these studies. I will reconsider this line of work below in the context of a theory of instructional intervention.

Toward a Cognitive Theory of Intervention

We come now to the question that is at the heart of a prescriptive theory of instruction: how to intervene in people's processes of acquisition in ways that will facilitate these processes and lead more often to correct than to incorrect procedures and concepts. The theory of intervention is, at present, the least well-developed aspect of a cognitive theory of instruction. It is the domain, therefore, in which the greatest leaps of inference and conjecture must be tolerated. Nevertheless, a careful consideration of emerging evidence concerning the nature of acquisition processes, together with results of a few early cognitive instructional experiments, points to the kinds of questions a cognitive theory of intervention will have to address.

Before proceeding to more specific points, it is well to note once again that the fundamental thrust of cognitive science is to press us toward a *constructivist theory of instruction*. By this I mean that the task now facing psychologists concerned with instruction is to develop a theory of intervention that places the learner's active mental construction at the heart of the instructional exchange. We can no longer conceive of instruction as a process of directly putting knowledge or skill into people. Instead, effective instruction must aim to place learners in situations where the constructions that they naturally make as they think about the events and information that impinge on them are maximally likely to be correct and efficient. A constructivist theory of intervention escapes none of the traditional concerns of an instructional theory. We will still need principles for presenting new information to students, for organizing and sequencing topics in a curriculum, for providing feedback, for organizing practice, and for providing feedback and direction to the learner's efforts. But each of these traditional concerns of instructional intervention, many of which have been carefully addressed in behavioral theories of learning, takes on a fresh aspect and poses new difficulties in the context of a constructivist theory of knowledge acquisition. Let us consider the implications for intervention of what we have been learning about acquisition.

Adapting Instruction to Limited-Capacity Learners

Demonstrations of the limited memory and attentional capacity of humans have several important implications for cognitive theories of instructional intervention. Perhaps most obvious is that automation of skill must, in many domains of learning, be recognized as one of the important objectives of instruction. This means that effective methods of helping people to automate complex skills, or their key components, must be sought. Alternatively, limited capacity can be accommodated by simplifying tasks during the acquisition phase, when demands on attention and memory are particularly great. These two modes of adapting instruction to learners' information processing capacities suggest two of the questions to which a cognitive theory of intervention must eventually respond: (1) How should practice be organized? (2) How can task demands be effectively reduced during learning?

A new theory of practice in learning. Let us begin with what may be the oldest of instructional questions, the role of practice in learning. It is interesting to contrast our current position with that of E. L. Thorndike, the prominent associationist psychologist who in the 1920s developed an extensive theory of instruction based on the learning of "bonds"—that is, stimulus-response associations (Thorndike, 1922). For Thorndike, the role of practice in learning was straightforward and self-evident. It "stamped in" correct associations through reward. The assumption, maintained in subsequent associationist and behavioral instructional theories, was that competencies did not change in any fundamental or qualitative way as a result of practice; they merely became stronger, faster, and more reliable. At one level of analysis, recent cognitive research underlines a role for practice not unlike the one proposed by Thorndike and his successors. Practice is the primary means of automating skills or components of skills. But at another level of analysis, recent work on the acquisition of cognitive skill strongly suggests that practice does not simply strengthen skills or procedures in their original forms; instead, it provides the occasion for transformations of procedures that make them more efficient instruments of performance. This is apparently true not only when an obviously new procedure is invented--as, for example, when preschoolers invent new addition algorithms (Groen & Resnick, 1977)--but also when the only overt performance change is a "smoothing out" and speeding up of execution (see Anderson, 1981).

This propensity of people to change the form of their skills as they practice complicates the task of those who seek principles for instructional intervention. On the one hand, it allows us to depend on people's procedure construction and modification capacities as a way of building new levels of skill. On the other hand, it forces us to recognize the fact that these constructions have certain built-in costs. A recent analysis of geometry learning (Anderson, Greeno, Kline, & Neves, 1981) suggests that the same mechanisms that account for the acquisition of skill in constructing high school geometry proofs may also explain people's inability to recognize more efficient performance options when new situations arise. We do not know how general such a "trade-off" between the benefits of smooth and skillful performance and the disadvantages of rigid performance sequences may be. Anderson and colleagues' theory accounts nicely for data on the developing abilities of a group of high school students in a traditional geometry course in which daily practice in proving theorems of a fairly standard type is provided. However, this does not preclude the potential for developing forms of instruction and practice that would foster skill acquisition without promoting inflexibility. To build these, we will need to develop theories of practice that take account of how attention is distributed and how new units of processing are built during practice. Such an agenda for instructional research is likely to carry us far from the concerns and formulations of Thorndike and other associationists.

Evidence that practice provides the occasion, and perhaps the motivation, for the invention and testing of new procedures points to another kind of modification in our theories of instruction as well: The traditional distinction between skill acquisition and understanding may need to be modified substantially. Practice leading to skillful performance may turn out to be necessary to the development of deep understanding, at least in certain domains of learning. Piaget's theory of reflexive abstraction and his demonstration that successful performance often precedes understanding of certain phenomena (Piaget 1974/1973) suggest such a possibility, as do our own demonstrations of procedural inventions by children (Groen & Resnick, 1977; Resnick, 1980). Surely the *kinds* of practice afforded by instruction and the ways in which procedural practice is interspersed with invitations to reflect and construct explanations will influence the development of understanding. Here, then, is another set of questions about practice that a constructivist theory of intervention will have to address.

Reducing task demand. The idea that attentional and memory demands of complex tasks can be reduced to help learners, especially in the early stages of acquiring a new competence, is an old one, although it has not always been expressed in the present cognitive terms of adapting to limited capacity. For example, when teaching a procedure that has many steps, it is a common strategy for the instructor to perform some steps and have the student perform the others. The student gradually takes control of more and more of the procedure. This allows the student to deal with only parts of the task at the beginning. Once those parts are mastered—that is, to some degree automated so that they require less attention—the student can take on other parts. Various systems of prompting and hinting that are used when texts are to be learned also have the effect of initially reducing memory demands for the learner. These traditional techniques, which are known to work but are not very well understood, may eventually take their place in a more elaborated theory of the role of demand reduction in instruction.

For the moment, the bes eveloped theory of this approach to adapting to limited capacity is that of Case (1978). Case suggests that restricted memory capacity is the reason why preschool and primary grade children are unable, under normal untutored conditions, to learn certain tasks that require the coordination of several "schemas" (or chunks of knowledge). He further proposes that it is possible to build a capacity for performing some of these tasks via instruction that organizes tasks in ways that reduce memory load. Case's assumption is that acquisition processes themselves use up some of the available capacity. Therefore, if memory demands are reduced during learning, then *performance* of the task—which requires less memory capacity--should thereafter be possible. This assumption accords well with what we can induce by examining various self-modifying computer programs, which typically require the search of more memory nodes when a procedure is being acquired than when it is simply being performed (see Resnick & Neches, in press).

However, close inspection of the kinds of instruction designed by Case with the intention of reducing memory load suggests that his successful instruction may be due not only to memory reduction but to the fact that his simplified tasks in effect teach the child a new schema for interpreting the problems. Thus it may be that it was acquisition of this schema rather than simple memory-load reduction that improved children's performance in Case's experiments. This interpretation would accord well with a growing body of evidence that memory itself—as measured by such traditional tasks as repeating in reverse order a string of words that has been read to one, or reconstructing a visual display that one has viewed briefly—is increased by greater knowledge of the domain from which the items are drawn (Chi, 1978). Greater familiarity with the domain seems to improve memory by allowing the information to be coded in larger chunks of related items.

This close link between memory capacity and the chunking of knowledge suggests that instruction intended to adapt to memory limitations will also need to take into account the broader evidence that learning is vitally dependent on prior knowledge. I turn now to several of the instructional questions that emerge from this observation.

Schemata for Learning: The Question of Instructional Representations

Several lines of evidence reviewed earlier in this chapter point toward a major goal of instruction. Schema-theoretic accounts of reading comprehension and research on story grammars both suggest the important role of prior knowledge in learning from text, and research in physics and mathematics problem solving shows that qualitative differences in the schemata possessed by novices and experts in a field affects the nature of their reasoning processes. These findings suggest that a continuing objective of instruction must be the teaching of schemata that learners can use to organize subsequent knowledge acquisition.

The teaching of organizing schemata and concepts is not a new concern for instructional theory. However, it takes on a new form and perhaps renewed urgency in the context of a constructivist theory of intervention. It is often assumed that a task analysis that specifies the performance or knowledge of experts in a domain will automatically yield not only "objectives" for instruction in that domain but an outline of the form in which information should be presented to learners. Implicit in this assumption is the notion that instruction should communicate as directly as possible the final or expert form of a concept or skill. Research of the kind discussed in this chapter, however, makes it clear that this assumption does not adequately recognize the work of the learner in *constructing* the mature form of knowledge. Novice-expert contrastive studies have shown that the mental representations of beginners differ qualitatively from those of people more experienced in a domain of knowledge. Furthermore, there are hints that novices may not be able to assimilate or use the categories and representations of experts when these are presented directly. Yet we know that extensive practice allows people who begin as novices to discover the representations and skillful performances of experts. If this is so, then the task of the instructor is not necessarily to search for ways of presenting information that directly match the thought or performance patterns of experts. Rather, it is to find instructional representations that allow learners to construct those expert representations gradually for themselves.

Until quite recently, the question of representations for instruction has been the concern almost exclusively of curriculum developers and pedagogical subject-matter specialists. Only recently have psychologists begun to analyze these materials and their function in the learning process. Resnick (1976) has suggested that instructional representations must (a) represent the concept or idea to be acquired in a veridical, if simplified, way; (b) be "transparent" to the learner--that is, represent relationships in an easily apprehended form or decompose procedures into manageable units; and (c) map well onto expert modes of understanding and skill. The special role of analogies as a way of helping students to construct scientific explanations and to learn scientific and other concepts also has begun to receive attention (Gentner, 1980). A similar concern has emerged in work on mathematics (e.g., Resnick, 1982) and understanding computer functions (Rumelhart & Norman, 1981). In the domain of language, the same interest in teaching powerful schemata is reflected in a renewed interest in the possibilities of teaching fundamental forms of discourse and rhetoric in connection with both writing skills and reading comprehension (e.g., Bereiter & Scardamalia, 1982; Stein & Trabasso, 1982).

The Problem of Coherence: Taking Learner's Theories of the World into Account

Our emerging conception of learning as the construction of coherence between prior knowledge and new information also poses special challenges for a cognitive theory of intervention. On the one hand, the demonstrated power of certain schemata in making new situations interpretable leads to the kind of emphasis just discussed--that is, on the teaching of powerful organizing schemata and the use of representations that facilitate links between known and new phenomena. On the other hand, evidence that people's naive theories are sometimes incompatible with the theories and concepts one would like to help students learn forces us to recognize that prior knowledge can also interfere with acquiring new concepts. This means that instructional interventions are needed that explicitly take this potential interference into account.

A theory of intervention quite different from the one derived from behavioral cumulative learning theory will probably be needed to guide instruction of this kind. As a point of departure, the Piagetian notion that cognitive growth occurs as the result of conflict between competing schemes might be elaborated in the context of instructional subject matters. Perhaps it also might be linked more explicitly to schema-driven theories of comprehension and acquisition of the kind now developing in cognitive science. This could provide one basis for intervention studies that explore different approaches to relating new learning to old. What is best: ignoring prior incompatible conceptions and helping students construct strong new ones, or directly confronting the conflicts between the old and the new conceptions? These kinds of questions have rarely been raised in the context of instruction, except by people exploring the educational implications of Piaget (e.g., Duckworth, 1979). They surely will have to be addressed in the constructivist instructional theory of the future.

Recognition of the ubiquity of naive theories also points to another instructional concern. Given people's tendency to construct theories and procedures even in the absence of complete information, we must ask what can be done to make it most likely that their constructions will be successful ones—that is, ones that will not produce procedural errors or conflict with scientific theories to be learned later. One possibility that comes to mind immediately is to provide more information earlier--essentially, to try to block the formation of conflicting naive theories by providing early opportunity and demand for learning the scientific ones. There is obvious logic in this suggestion. However, early intervention cannot of itself solve the problem. There is no way that all necessary information on all topics on which people form naive theories can ever be offered early enough, and it is not possible to control adequately the kinds of information and situations to which people will be exposed outside of the formal instructional environment. This means that cognitive scientists who seek to build a theory of intervention will have to pay careful attention to the kinds of information that are particularly powerful in blocking the formation of buggy procedures or naive theories that later must be given up.

It is to be expected that this powerful information will have to be identified separately for each instructional domain. Nevertheless, some general principles can be anticipated for the kinds of information likely to play a particularly important role in improving the kinds of cognitive inventions that people make. For example, analyses of buggy arithmetic algorithms and their origins (Brown & VanLehn, 1982) suggest that incorrect procedures are invented when certain *constraints* are ignored. In subtraction, for example, a wide variety of specific procedures would qualify as correct; the particular procedure taught to children in school is a cultural convention, a choice from among a number of possible, mathematically correct procedures. All of the correct procedures, however, obey certain fundamental constraints that insure that the relationships between the quantities in the problem are maintained. Most of the buggy algorithms shown previously in Figure 7 violate the constraint that the total quantity shown in the top number cannot be changed in the course of exchanges between columns (at least not without making the same quantitative change in the bottom number, a much more complex constraint that is mathematically more powerful because it allows a wider variety of specific procedures). Informal inspection of errorful procedures of other kinds and in other domains of learning suggests that these, too, can be analyzed in terms of constraint violation. Might it not therefore make sense, when introducing procedures to children, to teach quite directly the key constraints to which the procedure must conform? Such teaching not only would provide information that is key to successful rather than buggy inventions; it also might provide a more general interpretation about procedures--in terms of constraints and alternative ways of satisfying them--that might prove powerful beyond the specific domain in which it was taught.

Improving Learning Skills: Teaching Strategies for Learning

The analysis of procedures in terms of constraints and requirements is only one of a potentially large range of general strategies for constructing knowledge that cognitive science research suggests as potential objectives for instruction. The notion that general strategies for problem solving and learning may be teachable has a long history, and one can find many examples of efforts to teach people study skills, reasoning strategies, and the like. Nevertheless, despite continuing interest in the possibility of improving people's general abilities to learn, it has been difficult to demonstrate that skills taught in one context are spontaneously and successfully applied in another. In other words, the skills and strategies learned have turned out not to be so general as had been hoped. As I noted earlier, recently reported studies have had greater success in improving learning outside the situation in which the skills were taught. Such studies all involve teaching some kind of self-monitoring strategy (cf. Belmont, Butterfield, & Ferretti, 1980; Brown, 1978). Strategies such as assessing one's own readiness to take a test and deliberately planning how to apportion study time, and various routines for self-interrogation while learning have been taught to retarded people of various ages and degrees of retardation (e.g., Belmont et al., 1978; Borkowski & Cavanaugh, 1979; Brown & Campione, 1977; Kendall et al., 1980). After training, both transfer and retention on various memory and reading tasks improved. Dansereau and his colleagues (1979) have demonstrated a similar effect among college students. Their learning strategy program included training in specific strategies for understanding, remembering and retrieving information in a text; but it also included strategies for managing one's attention and concentration on the task and for setting study goals. The most promising results to date are from a study in which middle school students who were very poor readers were taught skills of summarizing, posing questions about a text, and predicting what would be said next in the text. Students who were taught these skills in a special skills laboratory also applied them in class and showed general improvement on reading comprehension tests (Palinscar & Brown, 1984).

The apparent promise of skill training that focuses on executive or self-control strategies accords well with theories of intelligence that stress general strategies rather than specific capabilities as the hallmark of those who learn more easily. There have been a number of suggestions that the source of the ability to control one's own intellectual performance lies in social interactions in which an adult serves both as external controller and prompter of the child's intellectual activity, and as a modeler of self-control strategies that the child eventually can manage alone (Brown & Campione, 1980; Feuerstein, 1979; Wertsch, 1978). Some intervention experiments with retarded learners are exploring ways of systematically providing such experiences. This view of the origins of intelligent self-monitoring also is implicit in some recent efforts to shape reasoning processes through computerized tutorial interactions (e.g., Stevens & Collins, 1980). Programs of this kind query learners in ways that force them to search their knowledge in order to answer questions for which answers are not immediately available. In the process, it is hypothesized, learners will acquire both more fully connected knowledge structures and an ability to use the query strategies on their own. One of the features of interest in this work is its focus on inference and "reasonable guessing" as a normal aspect of learning. It thus represents an extension of one of the important processes of cognitive acquisition that I noted earlier.

Conclusion

I have tried in this chapter to sketch an emerging cognitive theory of instruction. The conception of the human learner that derives from recent research in cognitive science, as well as many of the specific findings concerning learning and performance in various domains of knowledge, has profound implications for the ways in which we are likely to think about instruction in the future. As I have suggested here, the view of the learner as an active interpreter of information and constructor of knowledge forces a deep reconsideration of many of the assumptions of the instructional theories we have been living with, and raises new questions for those interested in helping others to learn. Some of the directions in which the new constructivist assumptions may lead instructional theory have been suggested in the preceding section. However, the particular questions I have addressed are but early examples of the ways in which the traditional concerns of instructional theory can be expected to take on new substance and direction as research on the cognitive science of instruction gathers momentum.

One of the more important influences on the direction of research in cognition is the cumulating evidence for the central and complicated role of prior knowledge in performance and learning. As this phenomenon has been recognized, it has had the effect of directing the efforts of many cognitive scientists toward intensive study of human performance in particular domains of skill or knowledge. Instead of searching for general laws of learning or development, many cognitive scientists are now devoting attention to the analysis of specific task domains--including many that are of direct interest to the educator. This renders large segments of basic cognitive science immediately relevant to the task of developing an instructional theory. It also makes much of the research that is directly motivated by educational concerns capable of illuminating basic questions of cognitive functioning. We are thus closer than we have ever been to a true science of education rather than a technology concerned with applying principles developed elsewhere to the problems of instruction.

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