LEVEL $\overline{I\!I}$

FINAL REPORT FOR CONTRACT N00014-78-C-0022 FOR THE PERIOD
1 OCTOBER 1977 - 30 SEPTEMBER 1980

James G. Greeno
University of Pittsburgh

January 26, 1981

Technical Report No. 7

DTIC
SELECTE
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81 2 17 187

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
Technical Report No. 7	AD-A095 138	14 TR - 7

4. TITLE (and Subtitle)

FINAL REPORT FOR CONTRACT N00014-78-C-0022 FOR THE PERIOD 1 OCTOBER 1977 - 30 SEPTEMBER 1980

5. TYPE OF REPORT & PERIOD COVERED

Technical Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

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8. CONTRACT OR GRANT NUMBER(s)

N00014-78-C-0022

9. PERFORMING ORGANIZATION NAME AND ADDRESS

University of Pittsburgh
Learning Research & Development Center
Pittsburgh, PA 15260

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

Prog. Ele.: 61153N
Proj.: RR 042-06
Task Area: RR042-06-02
Work Unit: NR 157-408

11. CONTROLLING OFFICE NAME AND ADDRESS

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

12. REPORT DATE

26 January 1981

13. NUMBER OF PAGES

18

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

RR 04246
RR 042.0205

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/ DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

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

18. SUPPLEMENTARY NOTES

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

reasoning
problem solving
understanding
cognitive skill

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

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DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102- LF- 014- 6601

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1.0

OVERVIEW

This is the final report for Contract N00014-78-0022, for the period 1
October 1977 - 30 September 1980. The research examined processes of
informal reasoning in problem solving and relationships between informal
and formal reasoning.

In an important tradition in cognitive theory, correct thinking is
characterized as a set of formal principles to be followed. In modern
cognitive science, thinking is characterized as a set of cognitive
processes and structures, and cognitive theory consists of analyses of
these and their relationships to formal principles.

Informal reasoning includes thinking processes of two kinds: procedural knowledge and tacit conceptual knowledge. We have analyzed relationships between cognitive procedures and general conceptual knowledge in the form of schemata, resulting in clearer conceptualization of the role of understanding in planning, constructions, problem-solving set, and transfer related to meaningful learning.

In studies of relationships between formal principles and informal reasoning, a theory of procedural planning has been developed, providing a framework for analyzing relationships between procedures and general principles in the form of constraints, and an analysis of flawed or "buggy" procedures has been developed. An analysis was developed involving procedural knowledge for solving proof problems and the formal principle of deductive consequence; a theoretical analysis and an instructional experiment were conducted to specify the cognitive processes that constitute understanding of the principle underlying the procedural knowledge.

2.0

BACKGROUND

The purpose of this research was to contribute to a cognitive theory of reasoning and problem solving. Such a theory will identify the kinds of knowledge that are required for someone to reason successfully and solve problems.

One starting point for a theory of reasoning is in formal systems. In a tradition that includes, among others, Aristotle, Descartes (1637/1980), and Boole (1854), knowledge required for correct reasoning is characterized as a set of rules codified in a formal language. If one wishes to reason correctly in logic or science, one should learn the rules of thinking in the field, and with correct understanding of the rules, correct reasoning will follow. The way in which students are most often instructed in scientific fields seems to agree with this formalistic idea. Students are taught the formulas that describe relationships among quantitative properties--say, in electronic circuits or in mechanical systems. Examples are shown in which the formulas are used in solving problems, but if a student does not succeed in solving problems it is not unusual to say that the student failed because the formula was not "really" learned or understood.

Cognitive science provides a different view. Knowledge required for correct reasoning is characterized as a set of cognitive processes and information structures that can produce correct performance on reasoning and problem-solving tasks. Knowledge of formal principles may be included in the cognitive requirements for successful reasoning and problem solving. Such knowledge, however, may be in tacit, rather than explicit, form. Furthermore, formal knowledge is always incomplete; it does not provide a sufficient cognitive system for performance. As Ryle (1949) noted, knowledge of propositions, which includes explicit knowledge of formal principles, must be supplemented by knowledge of procedures which Ryle referred to as "knowing how." Another form of knowledge required for

successful reasoning was called "tacit knowledge" by Polanyi (1967), referring to conceptual ability that is not formulated explicitly.

In the psychological literature, the best-known discussion of the relationship between formal knowledge and informal conceptual processes was provided by Wertheimer (1945/1959). Along with other Gestalt theorists (e.g., Duncker, 1945; Kohler, 1927; Luchins, 1942), Wertheimer considered achievement of structural understanding as the primary requirement for successful reasoning and problem solving. Wertheimer explicitly distinguished between problem solving with understanding and problem solving in which solutions are obtained using a rote, mechanical procedure. In many of Wertheimer's examples, the mechanical procedure was an item of formal knowledge, and the cognitive process required for structural understanding was identified informally, often as a set of spatial relationships.

Most psychological studies of problem solving during the 1950's and 1960's were conducted in the framework of behaviorism or associationism, and theoretical analyses (e.g., Maltzman, 1955) were focused on factors influencing performance. In the 1970's, analyses of performance in problem solving have become more rigorous and more detailed with the development of information-processing concepts and theories largely stimulated by Newell and Simon's (1972) important studies.

In psychological studies of reasoning, a major concern has been to identify ways in which thinking is discrepant from rules of formal logic;

well known studies include those of Chapman and Chapman (1959), Henle (1962), Wason and Johnson-Laird (1972), and Woodworth and Sells (1935) Recent investigations have provided more specific hypotheses about the nature of cognitive procedures involved in performance of syllogistic reasoning tasks (e.g., Braine, 1978; Guyote & Sternberg, 1978; Johnson-Laird & Steedman, 1978; Osherson, 1975).

In addition to the major advances that have been made in understanding the procedural aspects of informal reasoning, some significant beginnings have been made toward analysis of conceptual aspects. Studies conducted thus far have considered knowledge required for intelligent representation of problems, especially in physics (McDermott & Larkin, 1978; Novak, 1976), and the nature of qualitative reasoning in solving problems in physics and electronics (Bundy, 1978; deKleer, 1975, 1979; Simon & Simon, 1978).

3.0

SUMMARY OF RESEARCH FINDINGS

Results of research in this project have been in two general groups. One set of results involves relationships between two kinds of informal knowledge in problem solving. We have completed three analyses of relationships between general conceptual knowledge, in the form of schemata, and problem-solving procedures. The other set of results involves relationships between general formal principles and cognitive procedures. These analyses investigated ways in which knowledge of formal

principles, in the form of constraints on problem solutions, can influence generation and understanding of procedures for solution of problems.

3.1

Schemata and Problem-Solving Procedures

Our analyses of interactions between conceptual schemata and cognitive procedures were developed in three studies. First, we analyzed schematic structures involved in planning geometry proof problems. This analysis provided a plausible hypothesis about the way in which simple constructions are produced in problem solving. The hypothesis also gives an explanation of one kind of problem-solving set.

A second analysis dealt with the problem of meaningful learning. A hypothesis was developed regarding the role of conceptual schemata in the acquisition of new problem-solving procedures. The hypothesis provides an explanation of the way in which meaningful learning results in knowledge that can be transfered more successfully to new kinds of problems, as well as a form of understanding of the cognitive procedures that are learned.

The third analysis investigated relationships between task demands and cognitive procedures that are used in solving problems. We conducted an experimental study of a task in which subjects retrieved information about a spatial display. Interpretations of previous findings had hypothesized different forms of information used to represent locations of objects. We replicated previous empirical findings by varying the phrasing of questions

about a single spatial display, and proposed an interpretation in which performance differences result from differences in cognitive procedures for retrieving information and making inferences.

3.1.1 - Schema-Based Planning

The theoretical problem addressed in this study was the problem of constructions. In well structured problems, the materials presented in the problem situation are sufficient for solution of the problem. One way for a problem to have weak structure is to present an incomplete set of materials, so that the problem solver has to augment the problem space in order to find a solution.

Problems with incomplete initial problem spaces occur in the domain of geometry proofs in a form that turned out to be quite manageable for theoretical analysis. The incomplete problems are those in which the diagram presented in the problem must be augmented by the addition of an auxiliary line.

A computational model that simulates solution of problems requiring constructions was developed. Knowledge for problem solving is organized in the model in a way similar to that developed by Sacerdoti (1977), with knowledge about actions of varying degrees of generality. Knowledge of general actions used in planning includes patterns of problem features that constitute prerequisites for using the plans. These schematic patterns provide the basis for constructions when their components are partially but

not completely matched by features of the problem situation.

In addition to explaining the occurrence of constructions, the model also provided an explanation of a form of problem-solving set that has been studied extensively, notably by Luchins (1942). Problem-solving set occurs, according to this analysis, when global features of the problem situation are used to choose a plan for solving the problem, and then further activity takes place in the context of the goals and requirements of that plan.

The results of this study, including data from a few protocols and some experiments on set, were reported in Greeno, Magone & Chaiklin (1979). Further documentation, consisting of protocols from several problems involving constructions, was provided in Greeno (1979). Briefer summary reports of these results were included in two other papers (Greeno, 1980b; in press).

3.1.2   - Meaningful Learning

The analysis of meaningful learning was undertaken as part of a collaborative project with John Anderson, studying processes of learning problem-solving skills in geometry. A model was developed that simulates learning in two forms: one in which new cognitive procedures are simply associated to stimuli in the problem situation and one in which new material is connected to general conceptual schemata. The latter provides a hypothesis about the nature of meaningful learning.

Learning that was simulated was based on solutions of three example problems. In one problem, the meaningful learning system learned to apply a schema that was already known in a situation where it was not previously applicable. In a second problem, new procedural knowledge was added to a schema. And in a third problem, the learner formed a new schematic structure with previously existing schemata as subschemata of the new structure. In all three cases, the rote learner simply learned to do what was done in the example problem, forming productions with relatively specific problem features as the conditions.

The model seems to provide a plausible hypothesis about the nature of meaningful learning. It also shows how schemata that incorporate general conceptual knowledge can provide a basis for transfer to new kinds of problems. When a new kind of problem can be schematized using a conceptual structure that was learned previously, then problem-solving procedures associated with that schema are available for use in the new situation. Data in the form of thinking-aloud protocols on a transfer problem in geometry provided evidence that was generally consistent with the model's account of transfer.

Reports of our analysis of meaningful learning are in Anderson, Greeno, Kline, and Neves (in press) and in Greeno (1980a).

3.1.3 - Retrieval of Schematized Information

In previous experiments, Lea (1975) and Hintzman, O'Dell & Arndt

(1979) obtained evidence that led to quite different interpretations about the cognitive representation of spatial information. Lea's conclusion, based on reaction times to report objects displaced varying distances from a specified object, was that information about locations is stored as a circular list. Hintzman et al's conclusion, based on reaction times to move a stylus in the direction of a specified object, was that the spatial representation includes information about relative directions and distances between objects.

An experiment was conducted in which all subjects answered questions of the form, "What object is at X," where X was a location relative to a specified object, thus avoiding a substantial difference between the tasks used by Lea and by Hintzman et al. However, in one condition relative location was specified by displacement on the circumference of a circular display, and in the other condition location was specified by compass directions. In the data we obtained, Lea's findings were replicated in the displacement condition, and Hintzman et al's were replicated in the direction condition.

We propose an interpretation in which information about locations is stored in a spatial schema, and different retrieval procedures are induced by the different forms of questions used in the two tasks. This interpretation extends ideas about forms of cognitive representation in linear arrays, used for storing information about ordered sequences (e.g., Banks, 1977; Bower, 1971). Our empirical findings provide further documentation, along with Hintzman et al's results, for cognitive

representations that are distinctively spatial in their directional characteristics. In previous empirical demonstrations (e.g., Kosslyn & Pomerantz, 1977), support for spatial representation was related to consequences of information about distances.

Our findings are reported in Greeno, Magone, Siegel, and Mokwa (in press).

3.2

Formal Principles and Informal Procedural Knowledge

Three studies have been completed investigating relationships between knowledge of formal principles and cognitive procedures. In one analysis, general principles in the form of constraints were used as the basis of a theory of procedural planning. The result of the analysis is a theoretical framework that is generally applicable for analyzing the consequences of prescriptive principles that relate to cognitive procedures.

A second study analyzed processes of applying incomplete knowledge and creating new procedures by extending existing knowledge to new circumstances. The theory that resulted from this analysis explains the occurrence of flawed procedures on the basis of informal methods of patching existing procedural knowledge when conditions are inappropriate for use of the existing procedures.

In a third study we examined the understanding of formal principles

that are relevant to a set of problem-solving procedures. We found that students typically lack understanding of an important general principle, and developed a hypothesis about knowledge that would constitute at least implicit understanding of the principle. In a training study, we had some success in instructing student subjects in the procedure that was identified in our theoretical analysis.

3.2.1 – Formal Constraints in Planning

A theory was developed for analyzing relationships between a set of prescriptive principles, in the form of constraints, and a cognitive procedure that conforms to the constraints. The theory consists of a process that generates a data structure, called a planning net, that represents the steps in synthesizing a procedure based on the constraints. The analysis shows which components of a procedure are needed to conform to specific principles. Therefore, human performance that is faulty in specific ways can be taken as diagnostic evidence that the person lacks knowledge or understanding of specific principles that are violated by the performance flaws.

The analysis worked out in developing the theory involved a series of procedures involving a spatial model of arithmetic. Constraints were analyzed for performing subtraction using concrete objects. An important result of the analysis is a distinction between constraints that are essential in the goal of a procedure and constraints that are useful in making the procedure more efficient. Distinguishing between essential and

inessential constraints can provide a first step in the analysis of robustness of procedural knowledge, when circumstances make it impossible to conform to all the constraints of a normal procedure, and the adjustment that is made should sacrifice constraints that do not cause the major goal of the procedure to be violated.

The theory of planning nets is described in VanLehn and Brown (in press).

3.2.2 - Misapplication of Procedures and Generation of "Bugs"

Many cognitive procedures are not strongly grounded in a set of prescriptive principles that are known by the individual who can perform the procedures. When an individual encounters a situation in which existing procedures cannot be executed normally, some extension or modification of the procedures often occurs. This can lead to erroneous performance, and if the modification is stored in memory, a systematically flawed procedure may result.

An analysis of procedural misapplication has been completed and given the name "Repair Theory." The theory provides an explanation for an extensively compiled set of procedural flaws that occur in the domain of elementary arithmetic (Brown & Burton, 1978). We believe that the principles identified in this analysis contribute to an understanding of the importance of understanding the constraints that must be honored in modifying proceaural knowledge, and also provide an important beginning for

a principled theory of procedural learning.

The theoretical analysis is reported in Brown and VanLehn (in press).

3.2.3 - Understanding of a Formal Principle About a Procedure

An analysis was performed of understanding of an important general principle that has to be honored for correct performance of a cognitive task, and often is not appreciated by individuals who learn to perform the task correctly. The principle studied was the concept of deductive consequence, which is the critical idea involved in construction of formal proofs. It is widely believed--and data that we collected in interviews of students supported the belief--that although students in geometry become quite skilled in constructing proofs, they do not acquire a deep understanding of the concept of proof.

Our main focus in studying the concept of formal proof was on a task of proof checking. In this task, a proof problem is presented with what is purported to be a solution. The subject's task is to evaluate the alleged proof, to determine whether it is valid, and to identify any error that may be present in it. This task tests a student's knowledge of the principle of deductive consequence in a way that is similar to the traditional experimental test of a subject's knowledge of a categorical concept, in which candidate examples are presented and the subject's task is to identify which are positive and which are negative examples.

We found that students in a geometry class performed poorly in tasks of checking proofs, especially when the error to be detected involved an omission of needed information. This suggested that their knowledge about proof was deficient in the important characteristic of deductive arguments; namely, that for each step there have been sufficient prior assertions to make the next step follow necessarily. A model of knowledge required for checking proofs was developed as a computer program, modifying an earlier model of proof construction (Greeno, 1978). The model provided a clear characterization of knowledge that would constitute implicit understanding of the principle of deductive consequence that is not required for constructing proofs. We designed training materials, based on the computational model, and succeeded in producing significant improvement in proof-checking performance by presenting this instruction to student subjects.

A brief report of our study of proof checking was included in Greeno (1980a), and a more complete report is in preparation.

4.0

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