DOCUMENT RESUME

ED 272 982 EA 018 709

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TITLE	Center for the Study of Learning. Final Report.
INSTITUTION	Northern Illinois Univ., De Kalb.
SPONS AGENCY	National Inst. of Education (ED), Washington, DC.
PUB DATE	7 Oct 85
GRANT	NIE-G-85-7114
NOTE	32p.
PUB TYPE	Reports - Descriptive (141)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	Higher Education; Information Dissemination; Learning; *Learning Theories; *Program Development; *Research and Development Centers
IDENTIFIERS	*Center for the Study of Learning IL; Northern Illinois University

ABSTRACT

This report describes the conceptualization and planning for the Center for the Study of Learning at Northern Illinois University. The center's mission is to provide an institutional setting for the discovery, synthesis, and dissemination of knowledge about learning in three subject areas: mathematics, sciences, and social studies. The report first describes the original planning for the project. The paper then outlines 13 specific research and development projects designed to further construction and application of a theory of knowledge representation in the 3 subject areas. The activities, governance, resources, and evaluation plan for the center are covered next. The report then clarifies the center's eight project goals: (1) studying the learning process, (2) involving practitioners, (3) developing instructional materials, (4) influencing policy, (5) considering the needs of handicapped learners, (6) studying learning issues affecting minorities, (7) collaborating with other centers, and (8) disseminating research results and materials. The report concludes with a review of the center's program; its strategies for research, development, dissemination, and collaboration; and its long range plans. Appended to the report is "Knowledge Representation: A Foundation for Educational Research and Practice," a paper clarifying the theoretical base for the center's work. Twenty-eight references are cited. (PGD)

Final Report

CENTER FOR THE STUDY OF LEARNING

NIE-G-85-7114

Merlyn J. Behr

Northern Illinois University

October 7, 1985

SUMMARY

Planning Process

Planning for the institutional proposal from Northern Illinois University for a Center for the Study of Learning consisted of several major activities. The planning process was begun with a "retreat" planning conference held at Northern's Lorado Taft Campus. The 1 1/2 day Conference at which 18 NIU faculty members were present had two objectives: a) To reach a consensus on a definition of the scope and mission of the Center for the Study of Learning at Northern Illinois University; and b) To obtain writing commitments from faculty for the description of certain R & D projects and for the development of certain sections of the proposal.

The planning conference was preceded by a lengthy discussion between co-directors of the planning grant Drs. Judith Threadgill-Sowder and Merlyn Behr and the University's acting provost Dr. James Norris. This discussion resulted in identification of Dr. Merlyn Behr as coordinator for the development of the institutional proposal and as project director for the proposed Center.

Following these two activities, Behr held numerous conferences with individuals and small groups of scholars on Northern's campus to discuss research programs and how these programs might contribute to the mission of the Center. As a result of the Taft Conference and these individual conferences, 13 individuals or groups of collaborators developed R & D proposals; 8 were included in the institutional proposal.

The Taft Conference also lead to a strategy to incorporate collaborative research relationships with other universities to add strength to the existing strong research areas at Northern. Collaborations were defined with Cornell University in Science learning, and in mathematics learning with Rutgers University, The University of Minnesota, and the University of Illinois at Chicago. Writers of R & D proposals from these institutions in the order listed were: Dr. Joseph Novak, Dr. Gerald Goldin, Dr. Thomas Post, and Dr. Mitchell Rabinowitz.

Some authors of R & D projects also contributed to other sections of the proposal. In addition Dr. Carol Goldin and Ms. Arlene Neher of the College of Continuing Education contributed substantially to development of strategies and plans for dissemination. Dr. Jeri Nowakowski an expect in evalution developed the plan for evaluation for the Center.

During the planning process, two outside consultants were employed: Dr. Robert Davis, Professor, University of Illinois at Urbana, and Dr. Peter Martorella, Professor and Head, North Carolina State University. Professor Davis' research field is mathematical cognition and Professor Martorella's expertise is in the area of social studies. These two consultants visited on two occasions: once in mid July which was mid stream in our planning and proposal writing and again in late July when R & D proposal selection and refinement were in the final stages.

This process lead to formulation of a research, development, dissemination, and evaluation plan submitted as an institutional proposal to NIE for a Center for the Study of Learning summarized in the following synopsis.

Mission and Strategy

The Center's mission is to provide an institutional setting for the discovery, synthesis, and dissemination of knowledge about learning. Programs to study learning in three areas of school content--mathematics, sciences, and social studies are included. Collaborative projects are described with Cornell University in science and with the following universities in mathematics: Minnesota, Rutgers, and Illinois at Chicago.

We recognize a need to study learning processes among minority and handicapped populations, as well as among middle and upper socioeconomic populations and normal learners. Project goals that address this need include (a) having special education experts among the research staff, (b) providing equal opportunity employment for research faculty and research associates, and (c) involving experts on handicapped and minority learners as members of the National Advisory Board and among consulting scholars.

It concerns us that much research on learning mathematics, science, and social studies has not been interpreted into usable information for the practicing educator or the policy maker in government and education. The research has had little impact on instruction in schools or on published instructional materials. To address this need, Center goals assure that educational practitioners, text writers and publishers will have input into projects and activities of the Center. Practitioners will be included in all aspects of the research process: setting research agendas, conceptualizing research, conducting research and also interpreting, reporting, and disseminating results. Practitioners will be involved as members of the National Advisory Board, as full- or part-time research associates, as teacher experiementers, and as conductors of dissemination workshops.

Another need is to disseminate research in usuable form to appropriate audiences. Scholarly journal papers, monographs, and technical reports will serve the research community. Less formal means will communicate to practitioners, policy makers, and lay persons. Newsletter, articles in the popular press, and pamphlets of experimental instructional materials are but a few examples. Conferences will be held for scholars and practitioners; workshops and meetings will be held to inform and interact with practitioners.

Plan of Operation

One goal of the project is to construct a theory of knowledge representation and interpret this theory for application to educational practice. A theory of knowledge representation is concerned with the question of how learners represent and use knowledge in problem solving and other forms of higher order thinking and how external representations (e.g., pictures, diagrams, graphs) of problems and situation affect the mental or internal representation learners form. Distinct projects within program areas will investigate how learners represent knowledge and how instruction affects the formation and use of these representations.

1. The Mathematics Program Area.

The specific R & D projects in the mathematics program area fit into three subareas: number and number sense, function and variable, and problem solving. The subarea of number and number sense includes four distinct projects.

R & D Project No. 1, The Part-Whole Schema and Number Development, will investigate, in the context of instruction based on a theory of a part-whole schema, children's ability to learn and demonstrate understanding of (a) strategies for processing basic addition and subtraction facts and (b) algorithms for multi-digit addition and subtraction problems. The methodology will be that of a teaching experiment resulting in protocol data. The beneficiaries of the work will be children and teachers of grades K through 3.

R & D Project No. 2, The Development of Computational Estimation Skill and its Influence on Number Sense, is concerned with the question of what strategies children have or can be taught to estimate number size and results of number operations. Teaching experiments reflecting instruction based on a neo Piagetion theory of development will give rise to protocol data. The work will involve and benefit children and teachers in grades 4 through 8.

R & D Project No. 4, Rational Number Concept and Proportional Reasoning, continues 6-7 years of collaboration between investigators of three institutions (Northern Illinois University, University of Minnesota, and WICAT Systems, Inc.). This work investigates: (a) The relationship between children's understanding rational number concepts and their ability to do proportional reasoning, (b) the effect of context and numerical content on children's solution performance, and (c) the extension of children's part-whole schema to facilitate their proportional reasoning skills. Status testing of large populations will result in data for statistical analyses and teaching experiments will result in protocol data. Beneficiaries of the work will include children in grade 4-9 and teachers of mathematics and science in these grades.

R & D Project No. 6, Manipulatives and Technology: EMR and LD Handicaps, a Special Concern, will address the question of the differential effect on learning mathematics concepts when instruction presents icons of manipulative aids via a computer-managed video device as compared to actual use of the manipulative aid. Protocol data will be obtained from handicapped and normal students in grades K through 3. Beneficiaries of this work will be normal, EMR, and LD students in these repective grades and their teachers.

The subarea of function and variable will include two distinct projects.

R & D Project No. 3, The Variable Concept and Algorithmic Thinking, has two main thrusts: (a) children's concept of variable is consistent or inconsistent with the different notions of variable for algebra and computer programming and how situations presented via a computer can facilitate children's algorithmic thinking will be investigated. Protocol data will be the main data source. Beneficiaries will be children in grades 4 through 5, high school students, and their teachers.

R & D Project No. 7, Investigation of Conceptual and Affective Factors Influencing Minority Students' Learning of Mathematics, will be conducted at the Center as a collaboration with Northern Illinois University with funding anticipated from the State of Illinois. The study will use clinical methods to acquire protocol data from disadvantaged college subjects from tasks designed to provide a window into their conceptions of mathematics. Course development in response to these findings will follow. Beneficiaries of this work will be disadvantaged mathematics students throughout the country and instructors of college developmental mathematics courses for disadvantaged and minority populations.

The subarea of problem solving will include the following two distinct projects.

R & D Project No. 5, External and Internal Representations for Word Problems, deals with learners' ability to solve typical mathematics verbal problems. The issue is whether providing different external problem representations to students will effect the mental problem representations they form and improve their problem-solving skill. The methodology of a teaching experiment will result in protocol data; generalizations from the work will benefit a wide age range of children and their teachers. The first two years of the project will be funded through the National Science Foundation.

R & D Project No. 8, Heuristic Processes for Problem Solving in Mathematics, to be carried out at Rutgers University, involves construction and verification of a model for competency in mathematical problem solving. It concerns the question of how five different representational systems interact in developing problem-solving competence. The methodology is that of clinical interviews and teaching experiments providing protocol data. Subjects include gifted and normal children in grade 6, 7, 8; they and their teachers are the beneficiaries.

R & D Project No. 9, A Representative of Simple Addition Knowledge, to be carried out at the University of Illinois at Chicago, is concerned with the development and verification of a theory for children's processing of basic addition and subtraction facts. A computer simulation will represent addition knowledge within a theory of a spreading activation memory system. The study will involve subjects from various levels, including adults. The benefits will be in improved understanding of the cognitive processes involved in learning basic addition facts.

2. The Social Studies Program Area consists of three distinct research and development projects.

R & D Project No. 10, Cognitive Intergration in Social and Moral Judgment, continues the investigator's program of research concerning how children process information in forming social and moral judgments. Individual differences in processing due to developmental and instructional influences will be investigated using classical methods. Research subjects will be high school students and college freshman.

R & D Project No. 11, Concept Training Using a Direct Instruction Model, within the discipline of history, will consider the question of learners' understanding of historical phenomena as a result of direct concept instruction. Direct concept instruction singles out a concept (e.g., civil war) for direct instructional attention before children are expected to demonstrate understanding of events of the American Civil War. Classical experimental methods for instructional effect will involve high school subjects. The project results will have implications for instruction in high school social studies.

R & D Project No. 12, Correspondence Between Career Development Representational Systems Derived From School Programs and Family/Ethnic

Backgrounds, centers on the learner's perceptions of the cognitive skills and strategies needed for career development. The study will use interview methods and the beneficiaries will be high school age students.

3. The Science Program Area.

The Science Program will be directed by Joseph Novack of Cornell University, and the major portion of the project will be undertaken at Cornell. This program of research represents the continuation of a three-decade programmatic effort to study problems associated with students' acquisition and use of science knowledge and their understanding of the scientific enterprise. The major research questions to be addressed are:

(a) How do students prior knowledge and misconceptions influence student's acquisition of new knowledge?

(b) How can learning styles be modified toward more meaningful, functional strategies?

(c) What heuristics and other approaches can be effective in changing student's learning strategies? (d) How can feelings and values be utilized in more functional learning approaches?

(e) How can teachers be more efficiently helped to facilitate meaningful learning and positive attitudes development?

(f) How can subject matter be better organized to facilitate meaningful learning and better understanding of how humans produce new knowledge?

(g) What learning heuristics can function to aid students to understand better the nature of knowledge and knowledge production?

(h) What new evluation resources can be used to encourage more meaningful learning and more validly measured "higher order thinking skills"?

(i) What are valid ways to measure attitude and value changes?

(j) What school organization patterns are cost effective for encouraging more meaningful learning and positive affective growth?

(k) What patterns of pre-service and in-service teacher education programs most cost-effectively achieve goals of teacher enhancement?

(l) What practices show promises for meeting the challenge of the growing shortages of qualified math and science teachers?

The major beneficiaries will be the students in upper elementary and high school, and the science teachers at these levels.

In addition to the science program at Cornell University, the following study will be conducted at the Center at Northern Illinois University.

R & D Project No. 13, Children's Scientific Question-Asking, continues the investigator's program of research concerning scientific question-asking skills among preschoolers and how these skills can be facilitated with intervention activity. Clinical research methodology will give rise to substantcial protocol data; results will benefit preschool children and their parents.

Center Activites

Significant Center activities will exert leadership in the study of learning. One such activity is a total of five conferences. Conferences in years 1 and 5, entitled Knowledge Representation: Theory and Practice, will address the major theoretical thrust of the Center. A conference in each intervening year will concern learning issues within each of the three program areas. These conferences will involve approximately ten paper presentations from Center and international scholars in the given area. Additional scholars and practitioners will participate. Proceedings will be published in book form.

Numerous workshops will be conducted at the Center or in surrounding school districts and states for educational practitioners. Findings from the Center will be made available to other institutions from practitioner workshops in various formats. Communication in various media will be made through professional journals, newsletters, computer networks, as well as through the popular press.

Syntheses of research will be conducted at the Center and will be made available to scholars and practitioners in appropriate form and through appropriate media.

Institutional Capacity, Adequacy of Resources, and Evaluation Plan

Governance. The governance structure for the Center includes the director, administative director, and program area directors. The director is responsible for the administration of the project, with responsibility for day-to-day operations delegated to the administrative director. Program area directors will assist in scholarly leadership and personnel management. Subcontract sites will have a designated site director responsible for the project operations at that site. Assistance from a technical writer will be provided for regular reports. Carful attention has been given to evaluation of project activity and Center personnel.

Program coherence will be guaranteed through careful assignment of Center personnel to work groups which are responsible for the various components of a distinct project, its design, methods of data collection, data interpretation, and dissemination of results. Various mechanisms will be used to provide for regular interaction among Center personnel: overlapping membership on work groups, weekly seminars, regular progress reports, and visiting speakers and consultants.

Resources. Northern Illinois University has excellent library, computer, technical and service facilities to support the Center. A long standing reputation as a quality teacher education institution gives the University close ties with school districts, schools, and school personnel; this will facilitate school-based research and development, as well as dissemination work. Appropriate space, equipment, and facilities will be provided for a centrally located Center.

The University has close ties with regional schools and industries though an organization called the Corridor Partnership for Excellence in Education.

(Collaboration between the University and Fermi and Argonne National Laboratories, for example, has resulted in projects for improving learning of science and mathematics in regional schools.) Many of the researchers of the Center have successful histories of collaborative work. Communication with other proposers has taken place to define a point of departure for collaboration with the following NIE Centers: Reading, Technology, Student Testing, Evaluation and Standards, and Effective Elementary Schools and with the existing North Central Regional Educational Laboratory.

Careful composition of the National Advisory Panel will give representation to a cross section of research and disciplinary specialists, as well as to experts on minority and handicapped learners.

Evaluation. A plan for evaluation of the Center's activities, based on the evaluation model of an internationally recognized expert, will be implemented. Evaluations conducted by an internal evaluator will be corraborated by an external evaluator. Results of evaluations will become part of the Director's reports to NIE and the National Advisory Panel, and will play an important role in administrative decisions.

TECHNICAL REPORT ON R & D MISSION: RESULTS OF PLANNING

The general mission of the proposed Center for the Study of Learning at Northern Illinois University was to provide an institutional setting for the discovery, accumulation and dissemination of knowledge about learning. This institution will provide mechanisms to facilitate work by resident, visiting, and adjunct scholars. The institution, while having definite geographic locations, will extend conceptually to all interested and qualified national and international scholars. The institution will foster all aspects of research on learning: conceptualization, scholarly interaction, synthesis, experimentation, preparation of publications and prototypical instructional materials, and dissemination. In its role of promoting and conducting research on learning, the institution will take cognizance of the interplay among societal, theoretical, and practical issues. In achieving and main taining this institutional status, the Center will provide leadership and direction for the study of learning, as well as for interpreting research to delineate the implications for teaching practice and educational policy decisions.

To fulfill its mission as an institution for the study of learning, the Center will direct its efforts toward the attainment of eight project goals. The project goals will be achieved by careful selection and design of distinct projects, as well as through the interpretation and dissemination of results within the Center's three program areas—the study of learning in (a) mathematics, (b) science, and (c) social studies.

Project Goals

The eight project goals address the need to: (a) study and clarify the learning process; (b) involve and impact on practitioners; (c) develop prototypical instructional materials; (d) influence educational policy; (e) consider the special needs of handicapped learners; (f) discover and study learning and instructional issues for minority students; (g) collaborate with other centers, laboratories, and other institutions; (h) disseminate research results and prototypical materials.

GOAL 1: Advance our understanding of the learning process to provide a theoretical foundation for educational practice. Particularly targeted will be the study of the acquisition of higher order thinking skills and instructional processes which promote this acquisition.

We intend to attain this goal primarily through continued contributions to the construction of a theory of knowledge representation. Various representational systems are used by learners to represent knowledge, both internally (e.g., imagistic models) and externally (e.g., mathematical symbols). These representations vary within and across learners and within and across content domains. One of the primary purposes of instruction is to choose appropriate external representations which will assist students in modifying their internal representations so as to expand their critical thinking capabilities.

We therefore propose to discover and study

- informal strategies, skills, algorithms, etc., which children possess for critical thinking and problem solving,

- informal strategies children possess for creating, internalizing, transforming, externalizing, and elaborating problem representations,

  and

- effects of theory based instruction on the formation and improvement of these strategies

within and across

- populations,
- content domains,
- contextual settings,
- representational systems, and
- theoretical paradigms

to advance the knowledge base concerning

- the mechanisms by which learners create internal and external representations of knowledge,

- the mechanisms by which learners transform knowledge representations,

  and

- how learners use representations in problem solving and critical thinking.

Work toward the attainment of Goal 1 directs the Center's attention to a "broad spectrum of higher order skills" (RFP, P35) and to broad guiding questions such as (a) What is the nature of these cognitive skills? (b) How are these skills acquired? and (c) What characterizes instruction which facilitates this skill acquisition?

The remaining goals direct attention to concerns about populations from which this research knowledge is obtained and for whom it is applicable, strategies to optimize the impact of accumulated knowledge on instruction, instructional materials, and educational policy, and how research activity will include minority populations and handicapped and special learners.

GOAL 2: Enable practicing school teachers, administrators and other policy makers to have a voice in the selection of research agendas of the Center to ensure that the research conducted at the Center has an impact on instructional practice.

Efforts to meet this goal will include the following plans: (a) The National Advisory Panel will have representatives who are practicing teachers, administrators, and policy makers, (b) Center personnel will have frequent interaction with personnel of the North Central Regional Educational Laboratory who are working with school personnel, (c) The Center will employ practicing teachers as part- or full-time research associates; and in choosing graduate student assistants for the Center qualified students with school teaching or administrative experience will be given preference. These Center personnel will participate in seminars and work groups where research planning takes place. Also, research associates will play an important role in dissemination activities of the Center. In this way people who are in close contact with educational practice will have input into development of research agendas and also will be able to advise and participate in dissemination of findings.

GOAL 3: Conduct and synthesize research at the Center so that the design and use of instructional materials will be improved.

Attainment of this goal involves several considerations: (a) As knowledge accumulates through research conducted and synthesized at the Center, this knowledge will be interpretated to point out implications for the development of instructional materials; (b) this knowledge will be communicated in a form that is accessible to practitioners, curriculum developers, text writers, and publishers; and (c) prototypical materials developed at the Center for experimentation will be made available to teachers, curriculum developers, text writers, and text publishers.

Various activities of the Center will facilitate attainment of this goal. Part of our overall research agenda is to synthesize the research of the Center, as well as related research in the field. These syntheses will be written in several forms to reach various audiences. The Center will host on a timely basis workshops and conferences for audiences such as teachers, text writers, and publishers who have a responsibility for and interest in the development of instructional materials. The information presented would have implications for the content of instructional materials, as well as for pedagogical considerations.

GOAL 4: Disseminate knowledge gained through research conducted, accumulated, and synthesized at the Center so it will have an impact on educational policy.

Various individuals and interest groups influence school policy. These include parents, teachers, and administrators as individuals and as organized groups, and it includes school boards as well as state and federal appointed and elected officials. Textbook selection procedures and selection committees at state and local school levels are affected by educational policy. The need to have these individuals and groups aware of current research findings is addressed by activities to meet this goal.

Attainment of this goal places a responsibility within the Center to provide information relevant to school policy considerations; such as questions of the cost effectiveness of suggested instructional changes, the impact of anticipated change on class size and organization, and guidelines regarding how changes might enhance opportunities for minority and handicapped populations.

These considerations will be addressed in the syntheses of research which are conducted by the Center. Most of the interest groups will be represented at workshops and other conferences hosted by the Center. Announcements to the popular press and "popularized" scientific periodicals will reach another group of individuals. Personnel from the Center will have frequent interaction with the personnel of NCREL. These interactions will facilitate interpretation of research findings for policy implications and also their dissemination to school officials across a seven-state area. As indicated in the description of the National Advisory Panel many of the interest groups will be represented on the Panel.

GOAL 5: <u>Investigations at the Center will be designed so that findings about learning will derive from, and implications of the findings will be appropriate for, selected handicapped populations.</u>

We have in mind a model for ensuring that the design of our R & D projects are appropriate for meeting the need to obtain findings about learning among handicapped learners. The basic mechanism to accomplish this is through appropriate assignment of personnel to work groups. As proposed, R & D Project No. 8, Manipulatives and Technology: EMR and LD handicaps, a Special Concern, exemplifies a model for collaboration which meets this concern for a handicapped population. In this case, an expert from the Special Education faculty of NIU is a collaborating coprincipal investigator with, an expert in Mathematics Education. The expert from Special Education will aid in developing prototypical instructional materials, conducting the experiment, and interpreting results for application to the special population.

Refinement of this collaboration model will facilitate development of the component of the Center for the Study of Learning among handicapped learners. While development of this component of the Center is under way, we will use experts in special education to advise on the design of many other R & D projects. Thus, as the development of prototypical instructional materials and testing instruments proceeds, concern for selected handicapped populations can be dealt with.

The National Advisory Panel will include an expert in special education; advice from this Panel member will prove helpful in development of specific policy to guide this important component of the Center's activities.

GOAL 6: <u>Distinct projects in the Center will be designed so that information about learning and teaching practices will have valid implications for policy decisions affecting minority students.</u>

This goal if concerned with special needs and issues for the study of learning among minority students. To attain it we will (a) appoint research associates to the Center to represent a cross section of minority groups, (b) employ principal investigators at the Center and make assignment to work groups without prejudice, (c) choose classrooms as research sites that reflect an appropriate distribution of minority learners, (d) have a national leader of at least one recognized minority group on the National Advisory Panel.

We plan to do some studies with small groups of students (as few as 6), as well as studies with large groups (multiple classes). Small groups will be chosen without prejudice to any minority group and large groups will be chosen so that minority groups are appropriately represented.

GOAL 7: Collaborate with other NIE Centers and Laboratories and other institutions to help attain the other goals of the Center and to add leverage to NIE's total national research effort.

This goal will help achieve the other goals of the Center for the Study of Learning, as well as contribute to the achievement of the goals of other NIE Centers and Laboratories, in the most cost effective manner possible. The issues with respect to collaboration are not only to expedite the activities of individual laboratories and centers, but also to contribute to the total NIE national research effort.

We have already established several collaborative links between the proposed Center and other universities. These collaborative efforts were established explicitly to define a Center for the Study of Learning with expertise of sufficient breadth and depth to immediately have nationally recognized leadership capacity for the study of learning in the areas of mathematics and science and for a developing program in social studies and humanities. These collaborations are between the Center and Northern Illinois University, The University of Minnesota, Rutgers University, The University of Illinois-Chicago and with Cornell University.

We have suggested potential collaborations between the proposed Center and other existing and proposed Centers. Brief statements about the basis for such collaborations are given elsewhere. We see potential for collaboration between the proposed Center for the Study of Learning and Centers for Teacher Education; Technology; Student Testing, Evaluation and Standards; and Effective Elementary Schools. In each case, we have established communication with the director or proposed director which corroborates our suggestions for bases for collaboration. The same has been done for NCREL and the WICAT Research Institute.

GOAL 8: Disseminate research findings, research syntheses, and prototypical material emanating at the Center in appropriate depth, format, and media to reach all appropriate audiences, including research scholars, developing researchers, teacher and administrative practitioners, educational policy makers, and text writers and publishers.

This goal addresses the very important need to have research findings, research syntheses, and prototypical materials have an effect on what goes on in American schools. These products can influence education practice only to the extent that they reach the appropriate audiences in a form that is comprehensible or useable by that audience.

To achieve this goal we will have dissemination activities in various forms: (a) Conferences will be held for scholars, practitioners, policy makers, text writers, and publishers; (b) Workshops will be conducted for teachers and administrative practitioners; (c) Written reports will be distributed as professional journal articles, professional monographs, Center technical reports, newsletters, newsletter contributions, news releases, "popularized" scientific journal articles, etc. We will also make products from the Center available as content for workshops conducted by collaborating labs or other institutions.

The Program of Work and Contribution to Theory

The proposed Center for the Study of Learning will conduct a program of work which is conceptualized into three program areas--the study of learning in mathematics, in science, and in social studies. Each program area will investigate learning within that content domain. The concern of the project is to discover aspects of learning which are common among or different across these domains. The thrust of the project is to contribute to a developing theory of knowledge representation.

The proposed program of work within each of the three program areas is defined in terms of distinct projects. While these projects are written as separate R & D projects, there are important overlaps and interfaces between studies within a program area and in some cases between studies across program areas. Each study within all three program areas will contribute information about one or more concern of the nature of cognitive skills, the effect of instruction on acquisition and development of cognitive skills, and individual differences in acquisition and development of cognitive skills.

The total proposed program of research is projected in 13 separate R & D projects: 9 in the mathematics program area, 1 in the science area, and 3 in the social studies area. Separate R & D projects in the Center will study learning in children ranging from pre-school age through high school, and in one collaborative project with disadvantaged college students. Every age within this range is represented in at least one study.

The research program of the Center will contribute to the theory of knowledge representation. We will seek to clarify issues about how learners form and use representations of knowledge to solve problems and accomplish other higher order thinking tasks. The long term aim is to understand issues of knowledge representation in a way that enables us to positively influence educational practice.

Potential to Advance Practice

The advancement of educational practice will be of major concern to the Center. This concern implies the obligation to deduce practical implications of research conducted at the Center and elsewhere. This is true about research conducted at abstract and theoretical levels as well as for more action oriented research. The working arrangements to be developed within the Center, and between the Center and other groups in educational practice, are consistent with this concern.

Strategies for Research

Methodology. Our method of operation will be to develop research teams, or work groups. A work group will be under the direction and leadership of a Principal Investigator. A work group will normally develop in response to an announcement by a particular PI that exploration of issues concerning an identified R & D project or other educational problem will begin. Other PIs and research associates will self-select or be appointed to participate in the work group. Self-selection into a work group will likely reflect the interest and expertise of these individuals. Appointments to work groups will be made so that an adequate distribution of expertise and professional background is reflected. In many cases, it will be appropriate for a work group to include the leading PI whose expertise is in the given content domain (mathematics learning, for example), a specialist in education of handicapped learners, a psychologist, and at least one person from the relevant practitioner area, for example, a middle school or elementary school teacher or supervisor. Members of the work group will conceptualize the research as equal partners with due regard for the expertise of each. The PI leader will ensure the subject area integrity of the study, the psychologist will ensure that the basic learning or development issues are considered, the expert in special education will address adaptation of the study to investigate questions of concern to handicapped learners, and the practitioner will ensure that the deliberations lead to a research design and investigation of questions which are of interest in a classroom or school setting.

Normally, membership on work groups will overlap. The purpose of this is to increase the synergistic effect of the work groups and to increase the likelihood that outcomes of the research contribute to the broad goals of the Center.

There will be variation among program areas and among individual R & D projects with respect to research methodology. For some studies a classical experimental design will be appropriate. It is expected, however, that many R & D projects will use the paradigms of research in cognitive science. Our interpretation of these paradigms for research at the Center concerned with learning in the complex domains of school content suggests three phases of research for most projects.

Phase I: Status Studies. In the first phase, status studies will be conducted to determine the cognitive structures and thinking strategies which learners are able to bring to bear on tasks from a content domain. This type of investigation is similar to what the Soviet educational research literature refers to as an ascertaining experiment. Emphasis is on conducting research in naturalistic settings such as the school or home (Kantowski, 1979). The purpose of an ascertaining experiment is " . . . to examine a knowledge state or pattern of behavior as it exists in some population. It is most often undertaken to gather information about the status of a skill or ability or to determine error patterns as a prelude to diagnosing reasons for such errors. The clinical method is generally employed" (Kantowksi, 1979). This type of experiment is similar to the identification-type clinical interview described by Ginsberg (1981), in which cognitive processes underlying intellectual phenomena are identified and described. For some areas of research proposed herein, considerable knowledge from such studies already exists from prior work of the investigator or from the research literature in the area.

Phase II: Teaching Experiments. The second phase of the research will often involve a teaching experiment. Teaching experiments have been carried out frequently enough in this country that their approach may be familiar. In contrast to the usual experimental design, with clear specification of treatments, control of as many extraneous variables as possible, and carefully developed instrumentation, the usual teaching experiment has a different objective: to study "processes in their development and to determine how instruction can optimally influence these processes" (Kantowksi, 1978, p. 45). The teaching experiment is often a longer-term undertaking, involves relatively few students, and maintains a great deal of flexibility in that occurrences on one day might lead to a great modification of the intended lesson for the next day. When processes (e.g., the strategies used in solving story problems) are the focus, the students are usually probingly questioned to ascertain their use of processes. Most often, regular interviews of individual students are used for this purpose. Analyses of interview data give information for revision of the prototypical materials for a third phase.

Phase III. The third phase of the research will involve a classical experimental design and will investigate learning in the context of the prototypical materials as revised. The revision will be assisted by experts in instructional science. In this phase of the research, the prototypical materials will be used experimentally in regular classes being taught by regular teachers. In this component of the research we will benefit from collaborative arrangements with the North Central Regional Educational Laboratory.

Individual projects will vary according to which phase of the three-phase research process is appropriate. For some studies, adequate knowledge exists to start at phase two or three. For other studies, only phase one or phases one and two may accomplish the objectives of the project. Still other projects will include only phase 3.

While subjects for ascertaining experiments and the small group teaching experiments will be chosen without discrimination, it is at this third phase of experimentation where particular attention will be given to appropriate minority group distribution. Most experimentation at this phase will include careful experimental design and instruments to produce data appropriate for statistical analysis; nevertheless, the research emphasis on probing individual learner's thinking will remain an important focus. As in the teaching experiment, this probing will take place through one-on-one interviews with learners, followed by careful analysis of the protocol data.

Strategies for Development

It is important to distinguish between development of prototypical instructional and evaluational materials for research and the usual notion of curriculum development. Our use of the term "development" refers to the production of instructional and evaluational materials to provide a basis for investigating cognitive structures learners employ in an environment determined by these materials. We intend that those materials which are developed will be used in experimental settings and will serve as a prototype, a point of departure possibly, for further curriculum development. We do expect that the materials themselves, as well as the findings from their use, will have important applications to classroom practice. Frequently, materials will be suitable for submission to a commercial publisher. Normally, additional development, refinement of the "packaging," further commercial editing, development of companion teacher manuals, and other supplementary materials will be needed prior to broad distribution.

The development of prototypical materials will be an important aspect of the research process for most projects at the Center. Generally, materials development for teaching experiments will be done under the close supervision of a PI. In fact, development for teaching experiments will frequently be on a day-to-day basis responding to observations about the learners. Teaching experiments will result with a set of prototypical instructional materials.

Materials development for larger scale experiments which involve multiple classes and multiple teachers will involve the expertise of specialists in instructional science from Northern Illinois University's Faculty of Instructional Technology, Department of Leadership and Educational Policy Studies.

Working in a team headed by the R & D project PI, specialists in instructional design will provide support for the development of a delivery system for the prototypical instructional materials. An instructional designer will provide an overall framework for the instruction while the content expert (PI) will provide the content material. The instructional designer will have knowledge of appropriate technology. The final criterion for a satisfactory instructional package will be that it reflects the theory base for its development, is accurate from the content perspective, and is useable by classroom teachers.

Strategies for Dissemination

There will be two major strategies of dissemination. The first strategy is to integrate the dissemination function into all other aspects of the Center's work, including the setting of research agendas, applications, and evaluation. The second strategy is to choose from a range of dissemination activities those activities which are most appropriate to the specific research and development projects. Among the criteria for choosing appropriate dissemination media and forms will be: the nature of the research findings, the external demands for technical assistance, the demonstrated utility of prototypical materials, the relevance of the projects to current trends in curriculum development, and the applicability to professional development goals in schools.

Dissemination is an integral part of the Center's mission. The Center will not only distribute information to researchers, policy makers, teachers, and the general public, it will use dissemination as a tool in its formative evaluations. Feedback on disseminated materials from research colleagues, policy makers, and practitioners will be solicited and integrated into the evaluation process and will help to shape subsequent research and development projects at the Center.

The first major aspect of the Center's dissemination strategy will be the integrating of dissemination into the research activities of the Center. The Center's principal investigators and research associates will keep the dissemination function in mind as they formulate research agendas, deliberate on appropriate methodology, and designate schools and classrooms as research sites. Plans regarding the appropriate media, methods and intensity of dissemination activities on a given research and development project will all be made in a tentative fashion as research plans are being formulated and will be reevaluated as the research proceeds. The work of the Center will be informed and guided by the concerns and needs of dissemination.

At the outset of each research and development project a practitioner research associate will be designated to be responsible for coordinating dissemination activities. The principal investigator and other researchers involved will work with the dissemination research associate as part of the team. Research teams will conduct their work so that research, formative evaluations, interpretations of research, and dissemination of results becomes an integrated process. The strategy of integrating the dissemination function into the planning, research and evaluation aspects of the Center's work will also be implemented at the Project or Center level; naming several practi tioners to the National Advisory Panel with special concern for this will facilitate this strategy.

Practitioner research associates will be involved in many aspects of the Center's work. Practitioners will aid in interpreting research findings and translating them into materials useful to other practitioners. The linkages they will provide to other teachers, curriculum specialists and school administrators, as well as the direct contacts they have with learners, will provide a continual check on whether or not scholars in the Center are doing work that is relevant in educational practice.

The second major strategy of the Center's dissemination plan will be to tailor dissemination activities to the specific research and development project. There will be a range of activities; some research and development projects will have minimal dissemination activities associated with them; others will have multiple, elaborate activities. The range of activities will include: traditional academic publications, Center sponsored publications, scholarly conferences, computer network communications, teacher inservice workshops, application and evaluation of prototypical materials, development of classroom materials for publication, and introduction of the Center's findings to the general public through articles and other media activities.

To maximize the Center's impact on theory development and educational practice, dissemination activities will be appropriately matched to specific research and development projects and to the demands of the relevant publics. Well designed and well chosen dissemination activities will ensure both cost-effectiveness and project utility. While the major function of the Center will be the advancement of theoretical knowledge about learning, the function of dissemination will not be neglected. The aim of dissemination will be that new knowledge about learning becomes integrated into teacher inservice programs and into classroom instruction.

Establishment of Working Relationships with Other Organizations

We expect extensive collaboration with the North Central Regional Educational Laboratory (NCREL), located in Elmhurst, Illinois (45 minutes from DeKalb). A major thrust of this NIE laboratory is to provide professional development opportunities for educational practitioners, especially from rural and urban areas. The Lab will promote teacher workshops and conferences which emphasize improvement of instruction. The Lab will give special attention to dissemination of instructional strategies and instructional materials which promote problem solving and other higher order and critical thinking skills. The Lab will disseminate recent research findings and help teachers and administrators incorporate this information into textbook selection.

In many cases, findings from the Center, research syntheses conducted at the Center, and prototypical instructional materials developed at the Center will provide appropriate content for the activities of the Lab. We expect personnel at the Center to be frequent workshop leaders and conference speakers. In this way the Lab will provide an important dissemination function for the Center.

The Laboratory personnel will have constant contact with teachers and other practitioners. These contacts will enable them to identify practicing teachers who are competent and interested to collaborate with the Center on research projects. This will be an important means for identifying teachers to serve as Center research associates. This close contact with practitioners will also make Lab personnel extremely sensitive to issues about learning. We at the Center expect to use Lab personnel as frequent consultants in our deliberations of research agendas and directions for research. Interaction between Center and Laboratory personnel will give a continuous check that research at the Center has implications for educational practice.

The Laboratory has an extensive communication network across seven states. Through this network the Lab will provide information for newsletters, and serves as a clearinghouse for research information. Close collaboration between the Center and the Laboratory will make it possible for the Center to utilize this network. This will provide a means for dissemination of information from the Center; equally important is that information exchanged in the network will help the Center keep abreast of practical issues which bear on research agendas.

The Laboratory is also committed to work with state level educational policy makers. This is possible through a governance structure which includes the chief educational officer from the seven-state network. Here we see the possibility of a close collaboration with the Laboratory affording the Center the opportunity to directly impact school policy matters, especially on issues of learning.

Long Range Plans

The long range plans for the Center are for its domain of influence to extend exponentially in magnitude over what would be expected to result from the basic fundings from NIE. A major strength of the Institution will be the synergistic effects from the Center's activity. A group of scholars and practitioners producing exciting research which has an impact on teaching practice and school policy will invite others to associate with the Center and to look to it for leadership. The collegial benefits and relationships which develop will result in even stronger and wider research, development, and dissemination collaborations. An important long term effect of this will be the attraction of additional external funding.

The long term operation of a Center for the Study of Learning at Northern Illinois University will make further strides in the direction of investigating learning among handicapped learners. Initially, three experts from NIU's faculty of Special Education will be involved. We see their role as collaborators with other PIs on specific R & D projects and as members of work groups which conceptualize and carry out research projects to ensure that the experimental design, prototypical instructional and testing materials are appropriate for a particular handicap. As experience is gained from the work arrangement and findings about the cognitive structures handicapped learners develop in the learning of mathematics, science, and social studies and humanities begin to accumulate, we will design more studies aimed specifically for studying learning among handicapped learners. This may require addition of a faculty level person in special education with special expertise in cognitive science.

A major first-year project with long range implications is a project to establish extensive annotated bibliographies in several of the Center's research areas. These bibliographies will be updated annually; the initial and annual additions will be made available to the research community. In selected areas, extensive literature reviews will be written. Both the bibliographic work and reviews will be accomplished on a commission basis.

Knowledge Representation: A Foundtion for Educational Research and Practice

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Research on the learning of school content such as mathematics, science, and social studies has been characterized by a reliance on diverse theoretical perspectives. Until well into the sixties, curricula and teaching practices were dominated by behaviorism. Later, other psychological perspectives, developed in an attempt to understand the nature of mental structures, came to play an important role in theorizing about learning and schooling. Piaget's theory of intellectual development has greatly affected educational thinking about school programs, particularly in science and mathematics. The explanatory nature of Piaget's work proved to be attractive to educators seeking to understand how development influences intellectual functioning, and how instruction should be planned to accommodate this growth. In more recent years, advances have been made in unifying our knowledge about school learning from research based on paradigms arising from cognitive science. As cognitive psychologists and cognitive scientists move from the limited domains of laboratory tasks to study learning in complex settings (i.e., school learning), we can expect even more significant advances.

As the field of cognitive psychology develops and matures, some psychologists are attempting to blend behavioral and developmental theories with information processing theories. Gagne's updating of behaviorism and Case's melding of Piagetian theory with cognitive psychology are but two examples. It is this blending of theories, with its rich promise of influencing learning through effective educational change, which is particularly attractive to us. The freedom to draw from different perspectives helps to alleviate the dangers incumbent in strict adherence to one perspective. Past school failures, such as the overuse of behavioral objectives to the extent that teaching for discovery was discouraged, the excessive reliance on stage theory to delineate the structuring of school content, or the "new math" with its emphasis on curricular change without regard for the needs of students and teachers, can all be blamed on too narrow a theoretical focus. Therefore, although current research should borrow extensively from the knowledge base, theory, and method ology of cognitive science, the overriding consideration for the choice of a paradigm for a given project or activity must be the question of how best to achieve the mission and goals of educational research and practice. Research on learning among the handicapped already has a successful tradition based on behavioral theory. Moreover, the work in educational R & D needs to deal not only with research but also with the development of prototypical instructional and testing materials, as well as dissemination. Work in development should reflect information acquired about learning based on the deep analyses of cognitive science. On the other hand, development for broad based experimentation, as well as organization of materials for dissemination, should call upon theory and practice from instructional science, an area which is eclectic in its theoretical foundation.

An important issue for research, and one which allows a natural entry point to these diverse theoretical perspectives, is that of in knowledge representations and representational systems. It is our belief that research on how individuals represent knowledge and how such representations can be modified can lead to real improvement of instructional materials and techniques, and therefore ultimately result in desired school change. We expect to make substantial contributions to the understanding of knowledge representations and how this affects learning, problem solving, and other higher order thinking processes. For this reason, we address the following questions at length under separate headings in this section.

1. What is a representation? And what is a representational system?

2. What are some examples of representational systems?

3. What is the role of representational systems in educational practice?

4. What is the role of representational systems in research on learning?

5. What are issues addressed by research and knowledge representation?

6. What are the implications to teaching practice?

7. What are some models for research on knowledge representation?

8. How will individual R & D projects contribute to the Study of Knowledge Representation?

What is a Representation?/System?

We begin by listing components of a representation (Kaput, 1983) and then elaborate on each component: (a) a represented world, including entities, relations, and operations which are represented; (b) a representing world, including entities, relations, and operations which do the representing, and (c) a correspondence.

We use the term representational system to mean the representing world. First, a representational system must contain entities. Entities (Greeno, 1983) are objects that the organism can reason about in a relatively direct way. Entities are distinguished from attributes and relations. Attributes and relations can be reasoned about indirectly based on cues from the entities. Second, a representational system must contain configurations of entities and rules for forming them. The rules also give criteria for determining when a configuration is "well-formed." For example, in base ten numeration 1, 4, 6, and 7 are entities; 74 is a well-formed configuration for seventy four, 614 is not, except in special cases. Relations and attributes are dependent upon the nature of the entities. For example, one representational system for representing number has rods as entities with an attribute of length. A trichotomous relation of interest in that system is longer-than, same-length-as, or shorter-than. The roles of represented and representing world are interchangeable. A rod of a given length, in the example above, can be used to represent a number; that number can also represent all rods or combinations of rods with that length.

It is important to observe that a representational system need not represent anything. Even the very familiar system of numerals 0, 1, 2, . . ., 9 does not represent anything without a rule for determining what each numeral represents. Thus, a rule of correspondence between the representational system (representing world) and the represented world is needed. We call this correspondence a symbolization. An example of such a correspondence is a rule which maps each numeral onto the quantity it represents. An often-heard complaint from teachers is that children manipulate numerals without meaning. This suggests that children are operating in the numeral representational system without demonstrating knowledge of the rule of correspondence.

In short, a representational system consists of entities, rules to form new entities (configurations of entities), and relationships among the entities. A representation, or symbolization, is a rule of correspondence between the representing world and the represented world.

Examples of Representational Systems and Representations

The notion of representational system is quite diverse, and includes, for example, mathematical and linguistic symbols, measurement devices, problem state-space and manipulatives. Some illustrations follow.

The symbols p, q, r, . . . in symbolic logic can stand for (i.e., symbolize) declarative statements in a natural language; the symbol $\wedge$ can stand for "and," the symbol $\rightarrow$ for "implies," and so forth. Assigning truth values to natural language statements provides us with a "model" (a "represented world") for the system of logic. The symbolization gives an imperfect model, since the semantics of natural language is often at variance with formal logic. In formal logic, $p \wedge q$ is equivalent to $q \wedge p$, but in ordinary usage, "He ran into the road and he was hit by a car," is not equivalent to, "He was hit by a car and he ran into the road." Such imperfections in this symbolization of "everyday" English by symbolic logic probably account for some of the difficulties students have in learning the subject of symbolic logic.

A measuring device, such as the thermometer, "represents" one physical property of the system whose temperature is being measured. The correspondence between physical states and instrument readings constitutes the symbolization. Conversely, one might take the more unusual perspective and say that the physical property "represents" the thermometer.

Another representational system, a problem state-space, can be considered to "symbolize" certain features of any of the following representational systems external to it (Goldin, 1985): (a) a system of problems posed verbally, iconically, by means of a concrete apparatus, or some other way, (b) a system of algorithms, strategies, or heuristic processes which can generate paths or sets of possible paths within the state-space, (c) a system of overt behaviors of problem solvers.

A system of multibase blocks consists of entities called units, longs, flats, and cubes. Rules indicate how these entities are joined to form new entities. A rule of correspondence which associates the unit with the number 1, the long with the number 10, etc., and joining of blocks with addition of numbers is a representational system for addition of whole numbers.

Davis (1984) suggests two representational systems for the names of the states of the U.S. If a person has an alphabetic representational system, a request for a listing might result with Alabama, Arkansas, Alaska, ... A representational system based on geographic location might result in Maine, New Hampshire, Vermont, Massachusetts . . . .

In physics a collection of forces can be represented quite precisely and usefully with a vector diagram. Moreover, the relationships between forces and combined effects can be represented in the vector diagram. Of course, the vector diagrams are useful only after appropriate interpretations about the vectors in the diagram are learned.

What is the Role of Representational Systems in Educational Practice?

The objective in educational practice is to aid children in acquiring knowledge in various content domains. That is, there is a domain of knowledge (the represented world) and an objective that the child acquire knowledge of that domain. Because of a learner's background knowledge or cognitive development, a teacher has reason to believe that a child knows or can more easily learn a related but different domain (a representing world). What can be done in educational practice to use the learner's knowledge of the representing world to facilitate the understanding of the represented world? The notion of representational system is appropriate here. First, the learner must know several things about the representing world: What are the entities, and what are relations and operations on the entities? Second, the learner must know what the entities of the represented world are and the correspondence between entities in the representing and represented worlds. Learning in the represented world then involves inferring relationships between entities in the represented world from the relationships between corresponding entities in the representing world, or inferring the results of operations on entities in the represented world from results of operations in the representing world. To the extent that relations between, and operations on, entities in the represented world are easily observed based on the corresponding ones in the representing world, learning is expected to occur. That is, the more easily the correspondence between entities of the two domains "carries" with it the relationships between entities, the more useful the representational system is for learning in the new domain.

A check on knowledge of the content domain could be based on tasks which investigate the extent to which the learner is able to reverse the role of representing and represented worlds. That is, given a relationship between entities in the represented world, can the learner infer the corresponding relationship between entities in the representing world?

In an educational setting we might expect to find three "stages" in the evolution of learning where instruction is based on the notions of a representation and representational system (Goldin, 1985).

1. First is the act of symbolization, where entities of a represented world symbolize or stand for entities of a previously known, or more easily learned, representing world.

2. This is followed by a period of learning of the structure of the represented world (i.e, what are relations and operations on the entities?) in the form of patterning the structure of the representing world.

3. Finally, the new system (the represented world) can be separated from the originally symbolized system (the representing world) because it is seen that there is no necessity for the original symbolization, and that alternative symbolic relationships with other representing worlds are possible.

The role of the teacher is to determine the learner's perception and understanding of entities, relations and operations in both worlds and to facilitate the development of suitable representation.

What is the Role of Representational Systems in Research on Learning?

Various representational systems are used by learners to represent knowledge, both internally (e.g., imagistic models) and externally (e.g., mathematical symbols, diagrams, technical vocabulary, . . .). These representations vary within and across learners and within and across content domains. Skillful and naive problem solvers, for example, attend to different features of an external problem representation (e.g., graphs, written sentences) in forming an internal representation. Internal representations can be processed mentally to form a transformed internal representation, and may in turn be externalized to produce a transformation of the original external representation (e.g., a written sentence is transformed to a symbolic algebraic expression). There are several questions concerning the manner in which learners form representations of knowledge and problems. How do different external representations affect internal representations? How do internal representations change over time due to instructional intervention? How do different external representations interact and how do they facilitate or inhibit learning and the development of internal representations? How do problem representations differ between experts and novices in a content domain? How do learners acquire knowledge of the rules that govern a representation? How can instruction facilitate this rule acquisition and transfer to rules of another representational system? How do external representations of knowledge facilitate development of quantitative and qualitative problem representation? Do different external representations help learners acquire schema driven problem-solving strategies? How do teachers' representations of problems differ from students? How do expert problem solvers' representations differ from novices? What affective variables are related to the construction or use of the representations? How can instruction encourage learners to use external representations? How can instruction encourage formation of mental representations? How can external representational systems facilitate novice problem solvers' ability to use qualitative reasoning to guide appropriate quantitative procedures? Individual R & D projects which are described later in this section of the proposal address many of these questions.

What Issues are Addressed by Research on Representation of Knowledge?

Gestalt theorists, in the 1930's and 1940's, recognized that a learner's understanding of a problem is central to solving it, and that understanding is based on one's mental representation of the problem. In more recent discussions of a problem-solver's state-space, these same principles have been reiterated.

Some of the early work based on an information-processing paradigm emphasized "direct" translation from a representation of the verbal problem statement in a text or lecture to a formal or mathematical representation (Bobrow, 1968; Hayes & Simon, 1974). But there is now overwhelming empirical evidence that insightful problem solving by children and adults, particularly in mathematics and physics, involves the construction of coherent intermediate internal representations (Briars & Larkin, 1984; Caldwell & Goldin, 1979, 1984; deKleer, 1975; diSessa, 1982, 1983; Greeno, 1980a; McDermott & Larkin, 1978).

More recently, Kintsch and Greeno (1985) have developed a model which simulates construction of cognitive representations that include information that is appropriate for problem-solving procedures that children use. The verbal problem input is transformed into a conceptual representation of its meaning as a list of propositions organized to highlight the relations that are mentioned in the text.

A number of researchers have discussed the notion of representational system as a schema. Learners and problem solvers develop schemas to represent large sets of organized knowledge. A schema has a number of specified slots, correponding to the entities and rules in a representing world. Some schemas, such as the "textbook" schemas of practiced readers, are hierarchical, and the superordinate slots are generally more readily filled and remembered for texts that conform to such schemas. Schemas may include representations of two kinds of knowledge--propositions representing declarative knowledge about facts, and productions representing rules for procedures involved in skills. Production rules take the form of condition-action pairs. Greeno (1980b) discusses evidence for the existence of schemata for problem representation. A feature of Greeno's theory is that procedures for problem solutions exist in the form of subschemata. A schema representation of a problem then instantiates appropriate procedures.

Experts have been found to have better organized schemas than do novices. Chi, Feltovich, and Glaser (1981) explain that a problem representation is a cognitive structure constructed by the problem solver, which reflects his/her domain-related knowledge and its organization. Chi and Glaser (1982) indicate that expert problem solvers recognize problems as belonging to classes based on relational aspects represented in a schema. Representations for a specific problem then activates higher levels of a schema. After this, the problem solution is directed by a top-down activation of other levels in the schema. A novice problem-solver's problem representation, on the other hand, is based on surface features of the problem which activate the lower levels, and solution attempts are a bottom-up process.

Davis (1984) makes the point that the mind once having constructed a problem representation does not easily change to a new representation. He discusses a problem from a preliminary form of a standardized test; the answer keyed as correct--the experts' consensus--was incorrect. A highly plausible representation leading to this incorrect solution was compared to that constructed by an examinee (a novice) who obtained the correct answer. Davis goes on to say that a problem will be easy to solve if the appropriate representation is constructed; if not, it will be difficult or impossible to solve.

VanLehn and Brown (1980) introduce the concept of a planning net for representation of competence for a complex procedural task. A planning net incorporates the semantic knowledge of the task, as well as the syntactic constraints of the procedure, and results in the hierarchical goal structure used by experts.

Representation of problems in qualitative vs. quantitative terms has emerged as a significant variable from the expert-novice research paradigm. Research has shown that expert problem solvers are likely to apply qualitative analysis to the relationships among the problem components while novices' qualitative thinking is directed to the surface features of problems (Chi & Glaser, 1982). Chi, Glaser, and Rees (1981) suggest that qualitative analysis involves construction of a problem representation that has some external concrete referents.

There are other ways, as well, to differentiate cognitive representational systems used by experts from those of novices. Larkin (1979) discusses experts' use of condition-action units. DiSessa's procedural epistemology examines the process of learning in relation to students' prior experiences (diSessa, 1979, esp. p. 246). Greeno (1983) discusses the entities available for representing problem situations, which allow for a more precise distinction between the "naive representation" of a physics problem (in which the entities are direct representations of familiar objects), and an expert's "physical representation," in which entities are constructs such as force or energy (Larkin, 1983).

Procedures used by expert (or competent) problem solvers have been described in a variety of analyses. Greeno, Riley, and Gelman (1984) incorporate three types of competence—conceptual, procedural, and utilizational—in a planning analysis of children's counting. A similar planning analysis by Behr et al. (1985) represents competence for multidigit subtraction. Goldin (1982, 1983) has suggested that a realistic model for competence in mathematical problem solving should be based on four kinds of internal cognitive representational systems: (a) a system for verbal and syntactic processing of "natural" language, (b) systems for non-verbal spatial, kinesthetic, or auditory processing ("imagistic" representations), (c) formal notational systems of representation, and (d) a system for heuristic planning and executive control.

The development of some cognitive representations used by experts has been described by Johnson-Laird (1982), who outlined a theory of psychological semantics that postulates two stages in interpretation of sentences, an initial and superficial propositional representation and a more articulated and integrated mental model. Both representations have advantages; propositional representations facilitate retention of information while an important feature of articulated mental models is that they enable us to make inferences without knowledge of rules of logic.

What are the Implications for Teaching Practice?

Practitioners in education have long advocated the use of concrete real-world experience, or simulations, to facilitate learning. Yet, very little is known about what the characteristics of such an experience should be. Educators advocate the use of concrete aids, pictorial representations, graphical representations, etc., to facilitate understanding of concepts and relationships. Again, little is known about what constitutes an effective concrete or graphical aid or what mental representations learners make from them. Novak and Gowin (1984) use two representational systems in research and teaching. Concept mapping is a way to help students see the meaning of learning materials and a knowledge vee diagram represents knowledge about a concept which helps students penetrate the structure and meaning of the knowledge they seek to understand.

Much of the research at the Center will investigate questions of learning in the context of theory-based instructional materials. Many of these prototypical instructional materials will incorporate representational systems. Part of the research process will be a careful analysis of the representational systems to be used. The analysis will clarify what entities and relationships between the entities must be clearly understood by the learner so that the representational system will facilitate learning.

The findings from the research will lead to discovery of a set of principles which guide the construction of representational systems and how they can be used in education to facilitate learning. The prototypical instructional materials will be instantiations of these principles in the disciplines of mathematics, science, and social studies. Both the principles and the prototypical materials will be products for dissemination and in this way will lead to improved teaching practice.

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