DOCUMENT RESUME

ED 285 739 SE 048 327

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TITLE	Cognitive Principles for Instructional Design. Final Report (August 1983-February 1987).
INSTITUTION	California Univ., Berkeley.
SPONS AGENCY	Office of Naval Research, Washington, D.C. Personnel and Training Branch.
REPORT NO	CES-5
PUB DATE	Jul 87
CONTRACT	N00014-83-K-0598
NOTE	13p.; For related documents, see SE 048 323-326.
PUB TYPE	Reports - Research/Technical (143)
EDRS PRICE	MF01/PC01 Plus Postage.
DESCRIPTORS	*Cognitive Processes; Computer Assisted Instruction; Engineering; *Instructional Design; *Instructional Development; *Instructional Improvement; Mathematics Instruction; Physics; *Science Instruction; Sciences; *Scientific Concepts

ABSTRACT

This final report summarizes work done to formulate and test some cognitively-based principles useful for designing instruction in scientific or engineering fields. These principles stress the coherence and interpretability of the knowledge acquired by students. The principles were specifically applied to: (1) analyze the underlying knowledge and thought processes needed to interpret scientific concepts effectively; (2) investigate how actual experts and novice students interpret such concepts; and (3) devise and test instruction designed to teach such concepts more effectively. Attempts were also made to devise computational environments to explore and implement these instructional ideas. (Author/RH)

ED285739

July 1987

Report No. CES-5

Cognitive Principles for Instructional Design

Final Report on ONR contract # N00014-83-K-0598
(August 1983-February 1987)

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The work reported here was primarily supported by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under contract No. N00014-83-K-0598, contract authority No. NR 154-522.

Abstract

This final report summarizes briefly work done to formulate and test some cognitively-based principles useful for designing instruction in scientific or engineering fields. These principles stress particularly the coherence and interpretability of the knowledge acquired by students. The principles were specifically applied to analyze the underlying knowledge and thought processes needed to interpret scientific concepts effectively; to investigate how actual experts and novice students interpret such concepts; and to devise and test instruction designed to teach such concepts more effectively. Attempts were also made to devise computational environments to explore and implement these instructional ideas.

Introduction

The goal of this project was to formulate and test some cognitively-based principles for designing instruction in complex domains, such as science or engineering.

These instructional principles were to be based upon the following: (a) An analysis of the underlying knowledge and thought processes needed for good performance in the particular domain of interest. (b) An adequate understanding of the knowledge and thought processes of students coming to the learning situation. The instructional process would then be explicitly designed to transform a student's knowledge and thinking so as to approximate those needed for good performance.

To implement the project, it was planned to focus on a subject-matter domain which would be sufficiently limited in scope to be investigated in some detail, but which would be representative of the complexities encountered in broader realms of science or engineering. Accordingly, we chose to devote primary attention to the interpretation and learning of scientific or mathematical concepts (such as the physics concept "acceleration"). Indeed, an adequate understanding of such concepts is of fundamental importance to any scientific work and is an essential prerequisite for any problem solving in scientific domains. The learning of such concepts presents many difficulties for students and conventional teaching methods are often quite ineffective.

In carrying out our work, we were centrally interested in obtaining information sufficiently detailed to elucidate underlying thought processes and to assess the ways in which they would be affected by specific instructional interventions. Accordingly, we concentrated our efforts on detailed observations of individual subjects under controlled conditions.

General Theoretical Considerations

Analysis of desirable performance

Our basic criterion for ultimately desired intellectual performance is that a person's knowledge should be effectively usable so that it can be applied correctly and flexibly in a wide range of situations.

This performance criterion is far from trivial. Indeed, all too commonly the knowledge acquired by students as a result of ordinary instruction is merely "nominal"; i.e., it can be displayed by students on standard examination questions, but cannot be used flexibly by them to enhance their capabilities of independent thinking.

The criterion of effective usability raises the following theoretical questions: What are some of the essential characteristics needed to make knowledge about some topic effectively usable? Our analysis suggested that the following characteristics are of central importance:

(1) The topical knowledge must be accompanied by ancillary knowledge ensuring that the topical knowledge can be properly interpreted. Such interpretation knowledge must specify how to instantiate the topical knowledge in any particular case, and how to determine whether such instantiation is correct or not. (Such interpretation is clearly an essential prerequisite for more complex problem solving.)

(2) The form of the knowledge, i.e., its description and organization, is at least as important as its content to ensure that the knowledge is effectively usable. In particular, it is essential that the knowledge is adequately coherent, i.e., that knowledge elements are interconnected by possible (strict or plausible) inferences among them. Such coherence greatly facilitates ease of remembering, ease of regenerating knowledge that has been forgotten, ease of ensuring consistency, ease of debugging, and ease of extending the knowledge by generalization or new learning.

(3) Available knowledge needs to be accompanied by adequate control knowledge. (a) Such control needs to ensure proper invocation, implementation, and checking when available knowledge is applied. (Indeed, particularly in science, disciplined knowledge application is a prerequisite for accurate and flexible knowledge use.) (b) Deliberate and automatic control of knowledge must be well-integrated. Indeed, performance of a complex task would be very difficult unless some lower-level knowledge can be used nearly automatically in ways that are fast and effortless (so as to leave adequate mental capacity available.for the performance of more complex aspects of the task).

Instructional implications

The preceding considerations lead to the following general instructional implications:

(1) Instruction should be designed so as to explicitly ensure that any knowledge acquired by students have the preceding characteristics needed for good performance.

(2) Learning can be facilitated by maximizing these characteristics at any intermediate stage of the learning process. (For example, care devoted to keeping any newly acquired knowledge interpretable and coherent can appreciably facilitate extension of this knowledge by further learning.)

The following paragraphs summarize briefly how we tried to implement and investigate these general theoretical guidelines in the specific domain of scientific concepts

Analysis of Concept Interpretation

An essential task in dealing with any scientific or mathematical concept (such as "acceleration", "area", ...) involves the ability to interpret this concept so as to instantiate it properly in any specific case. This interpretation task is actually more complex than one might naively suspect.

To interpret such a concept one must retrieve from memory some knowledge stored about the concept, and then engage in information processing to apply this knowledge in the particular situation of interest. Different possible modes of concept interpretation are then possible, depending on the kind of knowledge stored in memory and the kind of processing done with it. Each of those possible modes has some distinctive characteristics, in terms of unambiguity, precision, generality, and ease of use. Correspondingly, each of them can also lead to distinctive kinds of errors.

We performed an analysis, buttressed by some observations, of various possible modes of concept interpretation and their implications. In brief, these modes of interpretation can be classified into the following two types:

(1) Some interpretation modes are "formal", i.e., deliberately designed to achieve great precision and generality. They store in memory well-specified and general definitional knowledge about the concept, knowledge which must then be explicitly processed to be applied in any specific instance. The knowledge stored may be a "declarative specification" of features characterizing the concept; the processing needed for application in particular instances may then require appreciable problem solving. Alternatively, it may be a "procedural specification" which provides a more detailed and explicit specification of how to interpret the concept in any particular instance. Such formal interpretation modes have the advantage of being reliably accurate, precise, and general. They have the disadvantage that their application is slow and requires significant mental effort.

(2) Other interpretation modes are based on a repertoire of case-based knowledge.. The knowledge stored in memory consists then of knowledge about various special cases, standard cases, and typical kinds of cases of the concept. If this knowledge has become compiled as a result of familiarity and repeated use, such knowledge can then be invoked almost automatically by recognition processes that match this knowledge with any particular instance of interest. These non-formal case-based interpretation modes have the advantage of efficiency, i.e., they can be applied quickly and effortlessly. They have the disadvantage that they can easily lead to errors or inconsistencies, and are not well suited for making general inferences.

What then is an "ideal" mode of concept interpretation which is both reliably effective and efficient? The preceding analysis suggests that such an ideal mode of concept interpretation should rely on both formal and case-based knowledge used in complementary ways. If one encounters a familiar situation, it is most efficient to use case-based knowledge, and then to rely on more

formal knowledge to check the resulting interpretation if necessary. On the other hand, if one encounters an unfamiliar situation, tries to detect or diagnose errors or inconsistencies, or needs to make general arguments, then it is most useful to rely on formal knowledge and to use case-based knowledge for possible check-points.

An account of the preceding work was published as an ONR report (Reif, 1986). An article based on this work has also been accepted for publication in the journal Cognitive Science (in press).

Comparative Studies of Good and Poor Performance

To obtain data bearing on the characteristics of usable knowledge, and more specifically on the preceding analysis of effective and efficient concept interpretation, we made some detailed observations to elucidate the nature of the underlying knowledge and thought processes used by persons who were either good or poor interpreters of scientific concepts.

To this end, we (predominantly Lisa Quinn and I) constructed two carefully designed sets of questions requiring persons to interpret the concept "acceleration" qualitatively in a variety of situations. The persons used in this experimental investigation were either physics professors who had recently taught an introductory mechanics course dealing with the concept "acceleration", or students enrolled in such a course. Each such person was individually asked to talk out loud about his or her thinking while trying to answer the questions — once without interventions by the experimenter, and a second time with requests for fuller explanations of his or her thinking. The transcript of the person's tape-recorded utterances, together with his or her written work, constituted then a protocol which was subsequently analyzed in detail.

Good experts

Those experts (i.e., physics professors) who are good at interpreting the scientific concept seem to behave in a manner similar to that proposed by our ideal model of concept interpretation. (a) They can interpret reliably the knowledge invoked by them. (b) Their knowledge is quite coherent, i.e., consistent and usable for various inferences. (c) They have both formal and case-based knowledge, and they use both these kinds of knowledge in complementary fashion.

However, even these good experts (who answer correctly more than 90% of all questions given to them) occasionally make mistakes. Many of these are due to the experts' inadequate control of their available knowledge (e.g. to failure to invoke appropriate knowledge, even when it was recently invoked in a slightly different context, or failure to check adequately application of this knowledge).

Novice students

Even when students are currently enrolled in a course where they have studied and repeatedly applied the concept "acceleration" for more than a couple of months, their ability to interpret this concept is quite poor. In our investigation, these students were unable to answer correctly about 60% of the qualitative questions about this concept.

Analysis of the protocols reveals that students' underlying knowledge about this concept has the following major characteristics:

(1) Their knowledge is quite incoherent, consisting largely of various disconnected knowledge fragments (many of them incorrect).. As a result, students are often unable to deal with situations deviating slightly from standard situations previously encountered by them; they fail to detect inconsistencies; and they encounter paradoxes which they cannot resolve.

(2) Correct concept interpretation, relying on on many such fragmentary knowledge elements, would require that each such knowledge element be accompanied by specific applicability conditions. However, not surprisingly, students often either fail to store adequately such applicability conditions, or fail to retrieve them when invoking a knowledge element.

(3) Students rarely invoke general formal knowledge and are often unable to articulate such knowledge. Furthermore, when they do invoke such knowledge, they are frequently unable to interpret it and thus cannot apply it successfully in particular instances.

In short, students' knowledge seems to lack most of the characteristics of interpretability and coherence which we have identified as essential to the effective usability of knowledge.

Nominal versus good experts

There are "nominal" experts (so designated by criteria such as title, position, degrees, or other credentials) whose actual performance is not particularly good. Hence it is important to specify whether nominal criteria or actual performance data are used to select "experts" in any comparative study of experts or novices. For example, in our experiments we found "experts" (i.e., physics faculty members at a university") who were not good at interpreting an elementary concept, like "acceleration", which they themselves had recently taught.. Indeed, their performance was partly reminiscent of that of novices. Such observations have not only sociological, but also cognitive interest. In particular, one can try to trace the performance deficiencies of such experienced persons to specific deficiencies in the form of their underlying knowledge.

Some results of these comparative studies of good and poor performance have been summarized in a recently published paper (Reif, 1987). We hope to present a more extensive account in a future publication.

Instructional Studies

The preceding theoretical ideas and observations about the essential characteristics of flexibly usable knowledge suggest some specific guidelines for the design of instruction.

Working with myself and Lisa Quinn, Peter Labudde (a postdoctoral visitor from Switzerland) carried out an instructional experiment to test some of these ideas. To be specific, we wanted to investigate the instructional efficacy of implementing merely the following two design guidelines based on our cognitive considerations: (a) Ensure explicitly the coherence and interpretability of newly acquired knowledge. (b) Ensure that this new knowledge is also coherent with students' preexisting knowledge, and can be used to debug this knowledge.

To implement these guidelines for the teaching of a new concept ("acceleration"), the instructional intervention did the following: (a) It taught students an explicit procedural specification of the concept acceleration and then gave students some practice in applying this procedure in several diverse situations. (Specification of the concept in terms of a procedure was designed to make the new knowledge interpretable. The consistent application of this single procedure to all cases was intended to make the new knowledge highly coherent) (b) It then asked students to use this procedural specification to detect, diagnose, and correct errors previously committed by themselves or errors purportedly committed by others. (By having to use their newly acquired coherent knowledge to confront their own prior notions or other common misconceptions, students were supposed to restructure their entire knowledge in coherent form. They were also thereby learning quality-control needed to detect and correct deficiencies in their new and preexisting knowledge.)

The instructional intervention in this experiment lasted about half an hour and resulted in the following main outcomes: (a) Students' abilities to interpret the concept acceleration improved markedly, from about 40% correct interpretations in a pretest before the instruction, to about 95% correct in a posttest after the instruction. (b) In their attempts to interpret the concept acceleration, students invoked many incorrect knowledge elements before the instruction, but invoked essentially no incorrect knowledge elements after the instruction. (c) Students' interpretation of the concept after the instruction was both effective and efficient. In simple situations, they relied on compiled knowledge about special cases of the acceleration; but in more complex situations, they reverted to the procedural specification to interpret the concept, or to check tentative answers based on compiled knowledge.

In both its explicitness and emphasis on the form of the knowledge acquired by students, this instructional intervention differs significantly from the common methods used to teach scientific concepts. The results of this instructional experiment were also certainly encouraging, although not definitive. In particular, this instructional experiment incorporated only a few central design principles identified by our analysis; additional tests of instructional efficacy would also be desirable.

An account of the preceding work on instruction was published as an ONR report (Labudde, Reif, & Quinn, 1987). An article based on this work has also been accepted for publication in the European Journal of Science Education (in press).

Computer-Implemented Instruction

Advantages of using computers

There are many reasons why the use of computers would be advantageous in formulating, testing, and implementing instructional design principles of the kind discussed in the preceding paragraphs. The reasons include the following:

Research on instruction can be made more rigorous by translating instructional designs into the form of instructional computer programs. (a) Such programs serve to make more explicit the assumptions incorporated in an instructional model. (b) They allow the testing of such models under controlled conditions where the successive actions of the student and the computer tutor are well-specified and well-known.

The computer has some unique advantages as a medium. (a) It can provide powerful graphical representations, including dynamic representations of physical phenomena and of the student's own thought processes. (For example, a dynamic graphical representation may be used to portray a student's own progress in carrying out a procedure.) (b) The computer can easily store and then redisplay a student's past work on an intellectual task. Thus it allows the student to reflect on his or her past thinking — and also more easily to detect, diagnose, and correct his or her previous deficiencies. (c) With careful design, computers can provide an environment where students can actively explore new concepts while being constrained to behave in disciplined ways.

Finally, computers would be very valuable for delivering practical instruction. If students are to acquire scientific knowledge that is actually usable, it is imperative that they become actively engaged in the process of constructing their own knowledge. The computer can help by providing exploratory environments and by playing the role of private individual tutor. By contrast, most usual teaching environments fail partly because they put students in passive roles where they spend most of their time merely listening or reading.

Difficulties of computer implementation

The previous appealing advantages of using computers are, however, not readily realizable because of several major difficulties — all of which became very evident in our work during this project.

Some of these difficulties involve computer hardware. The implementation of instructional designs, of the kind discussed in the previous paragraphs, requires computers which sufficiently powerful to handle text, graphics, and good student response judging. At the time when we first tried to use computers for this project, Apple Macintosh computers just became available and seemed barely adequate to satisfy our requirements. Only much later did we gain access to a few much more powerful Xerox-1108 workstations. But the software available on relatively new machines is limited. Furthermore, one quickly discovers, to one's dismay, that even expensive and powerful machines have basic software that is often remarkably "buggy"— thus making any work very frustrating and progress slow.

Even if powerful machines were readily available, with well-functioning basic software, there would still be the need for a good "authoring environment" facilitating the design and implementation of instruction. In particular, an instructional designer and producer must be able to direct his primary attention to fundamental pedagogical issues, without constantly needing to deal with details of low-level programming. The designer also needs to be able to easily edit and easily modify whatever he or she produces, preferably in an environment which is the same as that ultimately seen by the student (i.e., which is WYSIWYG, "what you see is what you get").

During the project we did not have available anything even remotely resembling such an authoring environment — and even now some such environments are only beginning to emerge. Hence we spent considerable time and programming effort trying to bring into existence something which might begin to serve our needs.

"Draw-Ed" authoring environment

David Oster, one of the programmers working on the project, responded to our needs and suggestions by constructing an authoring environment exploiting the Macintosh computer.

This environment uses available Macintosh software, "MacDraw", as an editor which can construct and modify various kinds of objects, including text, graphics, and active elements (e.g., "buttons" which can be clicked by the mouse to produce various specified responses). In this way one can readily construct and edit "frames" (i.e., complex displays ultimately presented to a student) in a way where the author can see exactly what the student will see.

This editor is then coupled to a data-management program (implmented by Oster and called "DrawEd") which consists of the following components to carry out various functions:

Information-transfer between editor and DrawEd Using "Switcher" (another standard Macintosh software), frames created in the editor can be readily transferred into DrawEd, or transferred back to the editor for easy modification.

Data base. DrawEd stores all frames in convenient pictorial form. These picture frames can be easily accessed either by name, or by browsing through a picture file where any picture can be displayed (either full-size, half-size, or quarter-size) and then visually selected with the mouse.

Interpreter of active elements. Active elements in the MacDraw editor are accompanied by some special symbols and instructions. DrawEd interprets these symbols and instructions so that the active elements actually have the specified effects when selected (e.g., so that buttons selected by the mouse actually lead to the display of specified other frames or windows).

Tutor. DrawEd has an authoring mode and a tutorial mode, and it is very easy to switch between these two. In the authoring mode, DrawEd acts like the data-manager just described. In the tutorial mode it acts as a tutor interacting with the student in the fashion specified by the instructional designer. Thus DrawEd can be used by the designer for authoring and modifying instructional programs; but it can then also be used by a student as a tutor providing instruction.

Transfer to LISP machines. Finally, DrawEd can translate all the information contained in the frames (i.e., text, graphics, and instructions) into LISP and transfer this information electronically (via RS-232 interface) to a Xerox-1108 LISP workstation. This transfer capability has the following advantages: If desired, the Macintosh can be exploited as a cheap and readily available computer acting as a kind of "scratch-pad" (or electronic story-board) where instructional designs can be laid out and perfected up to a certain point. Once this is done, the information may then be transferred electronically to the much more expensive LISP machine for further editing and refinements, so as to exploit the much greater capabilities of those machines.

Final status of computer implementation

The Draw-Ed authoring system became barely functional only near the end of our ONR project. Except for some small-scale testing, the project was thus not able to exploit this system for significant instructional research.

Continuing Work

Although the ONR project terminated last February, some of the lines of work initiated under this project are continuing under different auspices (no longer supported by the ONR). In particular, our current efforts focus more broadly on several cognitive issues involved in the learning and teaching scientific concepts. This domain of investigation seems important not only in its own right, but is also a good prototype domain within which to explore instructional principles of much wider applicability. Since Xerox LISP workstations have become more available to us, we are also increasingly trying to exploit these machines for our instructional work and to create suitable instructional authoring environments for these machines.

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