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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 4(0)

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Publication Date
1982

Peer reviewed

Generation of Useful Problem Representations in a Semantically Rich Domain: The Example of Physics

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The initial representation of a problem can crucially determine whether the subsequent search for its solution is easy, difficult, or even impossible. However, the processes used to generate initial problem representations, particularly in semantically rich domains, have been studied less extensively than those used for search. Accordingly, the study reported in this paper has aimed to formulate and test a model specifying how human problem solvers can generate effective initial descriptions of problems in a realistically complex scientific domain.

The preceding goal, which is prescriptive, is more general than one concerned with naturalistic studies of actual experts (Chi, Feltovich, & Glaser, 1981; Larkin, McDermott, Simon, & Simon, 1980). In particular, it focuses interest on procedures for generating good problem representations, without necessarily trying to simulate the behavior of experts and without making the assumption that experts behave optimally. From this general point of view, models of good problem description may thus be suggested by purely theoretical analyses as well as by observations of experts. (Indeed, protocol observations of experts reveal relatively little about the processes used to generate initial problem representations since these processes are usually carried out rapidly and almost automatically on the basis of much tacit knowledge.)

A prescriptive point of view, transcending naturalistic studies of expert performance, is also centrally important for attempts to improve human performance or for educational applications. Indeed, in instructional applications, students can not merely be taught to mimic expert performance which often relies heavily on the recognition of patterns acquired as a result of years of experience.

Our prescriptive interest has been specifically focused on human performance in generating effective problem descriptions. From a theoretical point of view, this emphasis allows us to presuppose complex human capabilities (such as natural-language understanding and pattern-recognition skills) while focusing attention on the more sophisticated cognitive skills needed to generate good problem representations. Furthermore, our interest has been in developing experimental approaches which (unlike some forms of computer simulation) allow direct validation of models of good human performance in problem solving tasks.

We chose to study the generation of problem descriptions in the particular domain of physics (especially within the subfield of mechanics) because this is a realistically complex domain representative of other quantitative sciences. On the other hand, this domain is sufficiently simple and well-defined that the generation of problem descriptions can be specified and studied in some detail.

Model of Problem Description

Our aim was to formulate a theoretical model specifying how a human problem solver can generate, for any problem in a particular scientific domain, a useful initial problem description facilitating the subsequent solution of the problem. This model decomposes the description process into two successive stages. The first stage uses mostly domain-independent knowledge to generate a problem description which summarizes and organizes relevant information about the specified situation and problem goal, introduces convenient symbolism, etc. Since the generation of this basic description is relatively straightforward, we shall not discuss it further here.

The next stage of the description procedure is more complex and involves the generation of a "theoretical description" which deliberately redescribes the problem in terms of special concepts provided by the knowledge base for the relevant domain. All the principles in the knowledge base, which are expressed in terms of these special concepts, become thus readily accessible to facilitate the subsequent solution of the problem.

The generation of the theoretical problem description is based on the following considerations. The knowledge base about any domain contains declarative knowledge specifying the particular entities of interest in this domain, the special concepts useful for describing these entities, and principles specifying relationships between these concepts. For example, in the scientific domain of mechanics, the entities of interest are particles or more complex systems consisting of such particles. The special descriptive concepts are special concepts used to describe motion (e.g., "position", "velocity", "acceleration") and special concepts used to describe the interaction between particles (e.g., "force", "potential energy",...). The principles specifying relations between these concepts are "interaction laws" (which specify how the force on one particle by another is related to the properties and positions of these particles) and "motion principles" (which specify how temporal changes of concepts describing motion are related to concepts describing interaction).

The preceding kinds of declarative knowledge in the knowledge base about a particular domain provide the basis for explicit "description rules" that specify procedures for generating a theoretical description of any situation in this domain. In particular, these description rules specify what particular kinds of entities should be described, what special concepts should be used to describe them, what properties of these concepts should be incorporated in the description, and what checks should be made to ensure that the resulting description is consistent with the principles in the knowledge base.

For example, our model for generating a theoretical description in the particular scientific domain of mechanics contains explicit rules specifying that attention is to be focused on particles or certain systems of particles (e.g., strings, solid objects, ...). The motion of each such particle is then to be described by a diagram indicating available information about its position, its velocity, and its acceleration. Similarly, the interaction of each such particle is to be described by a diagram indicating available information about all forces on this particle by other particles (with an explicit algorithm specifying how all these forces are to be identified and enumerated). Finally, the resulting description is to be checked by assessing its consistency with known motion principles (e.g., by checking that the acceleration of any particle has the same direction as the total force on it).

The preceding description procedure, specified by the model, is expected to lead to initial problem descriptions with the following properties:

(1) The resulting descriptions should be considerably more explicit than those commonly generated by actual experts. (2) Strict adherence to the description procedure should avoid most of the errors commonly committed by novices (e.g., omitting forces or introducing non-existent extraneous forces). (3) The description procedure should lead to problem reformulations which are more readily interpretable (e.g., questions about slack strings or touching objects are automatically reinterpreted as questions about forces). (4) The resulting theoretical problem descriptions should substantially facilitate the subsequent solutions of these problems.

Experimental Methods and Results

Our experimental approach for testing a prescriptive theoretical model of human performance has used the following paradigm: Design carefully controlled experimental conditions to induce individual human subjects to act in accordance with the model; then observe whether the resulting performance is effective in the predicted ways.

To implement this paradigm, we have used "external-control experiments" of the following kind. We first design a program of step-by-step directions, and associated knowledge, whereby a human subject can be guided to act in accordance with the model (e.g., directions which implement the steps of the specified description procedure). These directions are problem-independent and at an appropriate level of detail to be reliably interpretable by the subject. In the actual experiments an individual human subject is then induced to carry out a task (e.g., the description and subsequent solution of a problem) by executing the sequentially presented directions of the program implementing the model. In this process the subject is asked to talk out loud about his or her thought processes. The resulting protocol, consisting of the subject's transcribed verbal statements and written work, can then be analyzed in detail.

Figure 1 shows the experimental results obtained by such external-control experiments designed to test the proposed model for generating effective initial descriptions of mechanics problems. Each subject worked on three problems. Figure 1 shows the performance of these subjects in generating good descriptions of motions and of forces, as well as subsequently generating solutions with correct equations and correct answers. The following are the main results obtained in these experiments: (1) The proposed model for generating initial problem descriptions is sufficient to lead subjects to generate explicit descriptions that are complete and entirely correct. In turn, these descriptions greatly facilitate the subsequent problem solutions which are then almost flawless. (2) Although subjects in these experiments possess a good knowledge of basic physics concepts and principles, a knowledge sufficient to implement the individual directions contained in the model, this knowledge is not sufficient to lead to good descriptions. These results are apparent from the much poorer performance of subjects in a comparison group working without external control of the model. (3) The main features of the model are, in fact, necessary for good performance. These results follow from experiments where subjects worked under external control of a modified model that omits certain features of the proposed model (e.g., that provides a direction to enumerate all forces, but does not provide more detailed directions specifying how to enumerate them). (4) The experimental data also verify certain detailed predictions of the model (e.g., the avoidance or occurrence of particular kinds of errors).

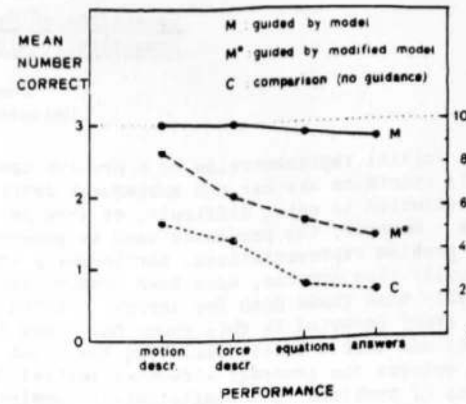

Figure 1. Results of external-control experiments.

Conclusions and Implications

The work briefly outlined in the preceding paragraphs leads to the following main conclusions.

The knowledge base for any scientifc domain implies guidelines specifying how to describe effectively any situation encountered in this domain. These guidelines can be expressed in terms of explicit rules prescribing how to generate a useful initial description of any problem in the domain.

Prescriptive models of effective human performance can be usefully tested by external-control experiments in which individual human subjects are deliberately induced to act in accordance with a model and the resulting performance is then observed in detail.

The work described in the preceding paragraphs was specifically undertaken to formulate a model for generating effective initial descriptions of problems in the particular domain of mechanics. External-control experiments show that this model, when implemented by human subjects, is very successful in leading to good initial problem descriptions that facilitate the subsequent solutions of these problems.

It should be noted that these experiments demonstrate the effectiveness of the specified description rules implemented by human subjects, but were not designed to teach description skills. (Indeed, such teaching would require that control knowledge, explicitly external in these experiments, be internalized by the subjects and made habitual.) However, such a well-validated model for generating effective initial problem descriptions can be used as a basis of explicit instructional methods to teach students effective problem-description skills and thereby enhance their problem-solving abilities.

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