Operationalizing Mental Models: Strategies for Assessing Mental Models to Support Meaningful Learning and Design-Supportive Learning Environments

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Abstract

Mental models are the conceptual and operational representations that humans develop while interacting with complex systems. Being able to reliably and validly operationalize users' mental models will help us to assess advanced knowledge and problem solving skills acquired while interacting with constructivist learning environments. Additionally, understanding effective and ineffective models will provide us advice for designing the kinds of scaffolding, modeling, and coaching that should be included in learning environments to support effective mental model deveelpment. This paper describes an initial study assessing the mental models of novice and experienced refrigeration technicians.

Keywords — mental models, advanced knowledge acquisition, problem solving and transfer, designing constructivist learning environments.

1. Introduction

Most constructivist learning environments, including cognitive flexibility hypertexts (Spiro & Jeng, 1990), anchored instruction (Cogniton & Technology Group, 1992), goal-based scenarios (Schank (1993/1994), causally modeled diagnostic cases (Jonassen, Mann, & Ambruso,in press), share a common goal: the construction of advanced knowledge by learners that will support complex performance, such as problem solving and transfer of learning. These environments stress situated problem solving tasks, because those are the nature of tasks that are called on and rewarded in the real world. In most professions, people are paid to solve problems, not to memorize information.

While advanced knowledge, higher order thinking, problem solving, and transfer of learning evoke common associations and expectations in most of us, there remains an operational inexactitude in these constructs. Just how do we know when leaners have constructed advanced knowledge? How advanced or higher order does that knowledge have to be? How do we assess it? In this paper, I argue that these learning outcomes can best be operationalized and predicted by assessing and understanding learners' mental models of the problem or content domain being learned. Why? Because solving situated, ill-structured problems in different settings requires the solver to use complex and diverse mental representations. Problem solving performance can be at least partially explained by the quality of the mental models of the problem solvers (Gott, Benett, & Gillet, 1988).

The purpose of this paper is to begin to explore the utility of mental models as learning outcomes from using complex and situated learning environments. In order to provide useful recommendations, it is necessary to formulate clear and operationalizable representations of mental models and then to assess changes in those models that may result from complex interactions with constructivist learning environments. If that is possible, then it will be potentially useful to reverse engineer appropriate types of structures in those environments to support the various kinds of mental model development that can be expected from those environments. This paper seeks to develop and asses an operational definition of mental models which can be used to assess advanced knowledge acquisition and transferable learning.

2. Mental Models

The construct, mental models, emerged from the human computer interaction field as a mental metaphor for describing the conceptions that humans develop for internally describing the location, function, and structure of objects and phenomena in computer systems. The facility with which users apply and exploit the functionality of computer systems depends, mental model theorists argue, on their conceptual models for describing the components and interactions of those systems. Are mental models merely conceptual? Mental models have been distinguished from other types of models that are also used to aid the development of user interfaces (Farooq & Dominick, 1988):

- **Cognitive Models.** Cognitive models are typically developed by cognitive psychologists, using information processing conceptions of skills and propositions, to describe the processes that humans use to perform some tasks such as solving problems, using a computer system, programming computers, etc. Among the most prominent cognitive models is the GOMS Model (Card, Moran, & Newell, 1983) that conceives of system-using activities in terms of Goals, Operators, Methods, and Selection rules (GOMS). Such models are task-specific and are often used to design interfaces and intelligent tutoring systems. They describe the goals, operators (processing activities), and methods needed to accomplish the goal state in terms of expert performance. Cognitive models, unlike conceptual or mental models, are not concerned with how users or learners actually conceive of tasks or systems.

- **Conceptual Models.** System designers often construct conceptual models of a system to show the users how they should conceive of the system. Mayer (1989) reviewed several of his own studies on the provision of conceptual models in learning BASIC, the camera, database systems, physics, and other content domains. He concluded that providing concrete, conceptual models for learners improves conceptual retention, reduces verbatim recall, and improves problem solving transfer. Showing learners how ideas are interconnected in the form of concrete models enhances the learners' mental models of the content being studied.

- **Mental Models.** Mental models are the conceptions of a system that develop in the mind of the user. Mental models possess representations of objects or events in systems and the structural relationships between those objects and events. Mental models evolve inductively as the user interacts with the system, often resulting in analogical, incomplete, or even fragmentary representations of how the system works (Farooq & Dominick, 1988). Unlike cognitive and conceptual models that describe how users should represent a domain or system, mental models describe how users or learners actually conceive of the system or domain. Moran (1981) expresses the belief of many designers that the design of the system controls the mental model that is developed by the user, so an ideal user's mental model would be congruent with the conceptual model of the interface as developed by the designers. However, Moray (1987) makes the argument that mental models evolve instead as homomorphs of the system's structure rather than isomorphs. Users' mental models usually vary, often significantly, from the cognitive or conceptual model promoted by the designers because of varying prior knowledge, individual abilities, and different beliefs about the purpose and functions of the system.

Although some claim that the term mental models relates only to conceptions of computer systems that users evolve, we agree with many psychologists that the concept is generalizable to most content domains and processes as well as general world knowledge. Mental models, according to Norman (1983), are the internal representations that humans develop of themselves and the objects they interact with in the world. Johnson-Laird (1983) believes that "human beings understand the world by constructing models of it in their minds." Building mental models is an important component in accommodating to the world, and to use a Piagetian construct, equilibrating differences between what is "in the world" and what is understood by the knower. That belief is institutionalized in the learning taxonomy developed by Kyllonen and Shute (1989), which contends that rote, didactic, deductive, and inductive learning methods result in the development of propositions and skills which form the basis for mental models. The construction of mental models "requires the concerted exercise of multiple skills applied to elaborate schemata" (p. 132). Like all taxonomies of learning, propositions are prerequisite to the acquisitions of related schemas and skills, which in turn are prerequisite to mental models.

3. Operationalizing Mental Models

Mental models are theoretical constructs, so we do not know where and how they develop? A common theory for describing mental model development is analogical or metaphorical reasoning (Staggers & Norcio, 1993). That is, learners generalize existing models to new phenomena through a process known as structure-mapping, that is, mapping the old structural relations onto new (Gentner & Gentner, 1983). For example, flowing water helps most people develop a mental model for electricity. Most theories believe that mental models consist of objects and their relationships (Gentner & Gentner, 1983; Carley & Palmquist, 1992). The objects are concepts or nodes, and the relationships are links or verbs that state the nature of the relationships between objects. The node-link combinations are combined into networks or maps of relationships that describe the domain of knowledge represented by a mental model. All of these conceptions of mental models are based on a set of assumptions stated by Carley and Palmquist (1992):

(1) Mental models are internal representations.

(2) Language is the key to understanding mental models; i.e.. they are linguistically mediated.

(3) Mental models can be represented as networks of concepts.

(4) The meanings for the concepts are embedded in their relationships to other concepts.

(5) The social meaning of concepts is derived from the intersection of different individuals' mental models.

These assumptions, we believe, are probably necessary but not sufficient for defining mental models.

3.1. Components of Mental Models

Generally, mental models are thought to consist of an awareness of the structural components of the system and their descriptions and functions, knowledge of the structural interrelatedness of those components, a causal model describing and predicting the performance of the system (often formalized by production rules), and a runnable model of how the system functions (Gott, Benett, & Gillet, 1988; deKleer & Brown, 1988).

Mental models have been assessed using a variety of methods, including think-alouds and verbal protocols, online protocols (audit trails), problem solving and troubleshooting performance, information retention over time, observations of system use, users' explanations of systems, and users' predictions about system preformance (Sasse, 1991). These data are often collected while users interact with experimental versions of systems, causing Sasse to conclude that such findigs are often flawed because the experimental scenarios are too restrictive and artificial, an insufficient range of information is collected, and samples are too small and too often reflect only novice users.

Mental models are more than structural maps of components. They are dynamic constructions. They are multimodal as well as multi-dimensional. Mental models are complex and inherently epistemic, that is, they form the basis for expressing how we know what we know. Because mental models are epistemic, they are not readily known to others and, in fact, not necessarily comprehended by the knower. Mental models, like all knowledge, must be inferred from performance of some sort.

3.2. Method

In this initial study, we will be studying the mental models of refrigeration technicians. We have selected a group of six novices (students in the final semester of a two-year, technical college program in refrigeration technology, and at least three experts (refrigeration technicians who have worked for six or more years for a major supermarket chain). All of the participants are male, between 20 and 38 years of age. For each paticipant, we will present him with the description of a complex refrigeration problem. In the contextof that problem, we will collect the following kinds of data:

- **Structural knowledge.** Structural knowledge is the knowledge of the structure of concepts in a knowledge domain and can be measured in a variety of ways (Jonassen et al, 1993). A number of researchers have used structural knowledge methods to develop representations of mental models. For example, Pathfinder nets generated from relatedness data were generated to depict mental model (Kraiger & Salas, 1993). Carley and Palmquist (1992) use their own software for constructing interlinked concept circles (maps) based upon text analysis or interviews. These methods all rest on the assumptions that cognitive structure can modeled using symbols (Carley & Palmquist, 1992) and that semantic proximity can be represented in terms of geometric space (Jonassen et al, 1993). Using structural knowledge methods to model mental models further assumes that they can be represented as networks. In this study, we will use Pathfinder nets to analyze the structural knowledgeusig a constrained setof 20 refrigeration systems concepts. While we believe that networks of interconnected knowledge underlay mental models, they cannot function adequately as the sole means of representation.

- **Performance/Procedual Knowledge** It is essential that learners be required to perform problem solving tasks. Kyllonen and Shute (1989) recommend process outcome predictions for assessing mental models, that is, performing some task, such as troubleshooting a simulated task or "walking through" a performance test. "Running" the model has received limited investigation of simple concepts to qualitatively test the visual images in their heads (diSessa, 1983). These will be assessed using think-aloud protocol analysis while solving the problem provided. In addition to providing performance problems that need to be solved, learners should be required to articulate their plan for solving the problem, and they should be observed on how well they adhere to the plan, what stratgies they use for dealing with discrepant data and events, and finally what kinds of generalizable conclusion they can draw from the solution. These data can probaby best be gathered by having learners think aloud while solving the problem. We propose to intervene and prompt the learner at various stages with questions requiring them to explain or infer why certain results occurred and to make predictions about what will happen next.

- **Reflective procedural knowledge.** An increasingly common method for assessing mental models is the teach-back procedure, in which learners or users are asked to teach another learner (typically a novice) how to perform certain tasks or how to use a system. Students often produce a variety of representations, such as a list of commands, verbal descriptions of task components, flow charts of semantic components, descriptions of keystrokes (van der Veer, 1989).

- **Image of system.** Wittgenstein (1922) described propositions as imaginal models of reality. Most humans generate mental images of verbal representations. The statement, "The stone gained speed as it rolled down the steep slope" is meaningful only when an image of a mountain with a stone descending along its side is generated. Mental models definitely include mental images of the application of domain knowledge. So, it is important to elicit the learner's mental image of a prototype of the system s/he is constructing. Some learning environents accommodate this need by providing an "envisioning machine" that displays system objects in different views (Roschelle, 1987). However, such envisioning tools map representations or views of the world that may not be consonant with the learners'. So, in this study,we require learners to articulate and visualize their "runnable" physical models or the physical devices or processes (Gott et al, 1986) using interviews

- **Metaphors.** In addition to imaginal representations, humans naturally tend to relate new systems to exisiting knowledge, often by associating them with other physical objects. A recent interview with an engineer produced a "marshmallow" metaphor for molecules. While most metaphors are not as distinctive, they are important means for uunderstanding peoples' mental models. We will therefore require the participants to generate metaphors or analogies of the system involved in the performance,asking them to explain the similarities between the efrigeration system and the metaphor.

- **Executive knowledge.** It is not enough to have a runnable model of a domain or process, but in order to solve ill-structured problems it is essential to know when to run which model. Knowing when to activate mental models allows the learner to allocate and apply necessary cognitive resources to various applications. This can only be assessed by presenting a variety of problems to solve. That is not possible in this initial study.

These data are currently being collected, and exerpts of these interviews will be used to illustrate this model in the conference presentation. The mental models of the participants will be evaluated using the following criteria.

3.3. Criteria for Evaluating Mental Models

Since mental models are process-oriented and relatively intangible, and since they need to be assessed using multiple data sources, an important goal of this research is to identify potentially useful criteria for assessing the quality and utility of individual mental models. A rational analysis of the construct suggests the following criteria:

CHARACTERISTIC	MEASURE
Coherence	Structural knowledge, Think-aloud
Purpose/ Personal Relevance	Self-report, Cognitive interview
Integration	Cognitive simulation
Fidelity with Real World	Comparison to expert
Imagery	Generating metaphors, analogies
Complexity	Structural knowledge
Applicability/ Transferability	Teach back, think aloud
Inferential/ Implicational Ability	Running the model

4. Implications of Mental Models for Design Practice

We expect that these interviews will show that situated experience will be positively related to richer, more structurally coherent, and efficient mental models. We are currently negotiating contracts to design and develop case-based learning environments to support the refrigeration technology curriculum. The findings from this study, comparing the mental models of experts and novices, should provide directly relevant information about the nature of the scaffolding, modeling, and coaching that needs to be embedded in these environments, as well as providing us with measurement devices for assessing the advanced knowledge that we hope they will help learners to construct.

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