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Mental models: concepts for human–computer interaction research

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In interacting with the world, people form internal representations or mental models of themselves and the objects with which they interact (Norman, 1983*a*). According to Norman, mental models provide predictive and explanatory powers for understanding the interaction. More abstractly, Gentner and Stevens (1983) propose that mental models focus on the way people understand a specific knowledge domain. More concretely, Carroll (1984) views mental models as information that is input into cognitive structures and processes. What are mental models? Are they always formed? When formed, what are their characteristics? What are the functional consequences of having no model (if that is possible), an immature model, or a mature model? This paper intends to explore these questions.

1. Conceptual definition of a mental model

Although Johnson-Laird (1989) is generally credited with coining the term mental model, the history of the concept may be traced to Craik's (1943) work entitled *The Nature of Explanation*. Craik suggests that humans translate external events into internal models. Humans are able to reason by manipulating symbolic representations and translating them back into actions or noting correspondence between the external events and their internal representations. Craik defines the term model as "any physical or chemical system which has a similar relation-structure to that of the process it imitates. By 'relation-structure' I do not mean some obscure physical entity which attends the model, but the fact that it is a physical working model which works in the same way as the processes it parallels..." (Craik, 1943: p. 51). Craik suggests that humans develop internal models through interaction (external events) and emphasizes the structural aspect of models. He says little about the construction, modification or content of models, but bases his discussion on the premise that symbolic models are used for reasoning. Since this original work, a number of terms have come into existence which are related to Craik's general view of internal models.

1.1. MENTAL MODELS, CONCEPTUAL MODELS, AND RELATED MODELS

The notion of users' mental models is a widely accepted concept in the human–computer interaction literature; however, authors use various terms to describe this notion, such as: mental models, conceptual models, cognitive models, mental models of discourse, component models and causal models.

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Various researchers use these terms interchangeably, especially the terms conceptual and mental model. For example, Young (1981, 1983) views the term conceptual model as a hazy notion with a central assumption that users create mental representations of a system to help guide their actions and interpret the system's behavior. He uses the terms conceptual model and mental model synonymously to refer to users' mental representations of their interactions with complex devices. Moran (1981) refers to users' mental representations as their conceptual model of the system while Norman (1983*a*) titles the same concept mental model. Norman calls the designer's mental model a conceptual model. Moran distinguishes between the designer's and user's model but consistently uses the term conceptual model. Bayman and Mayer (1984) suggest that the term mental model refers to the user's conception of the "invisible" information processing states and transformations that occur between input and output. Clarke (1986) creates what he calls a conceptual model of the human–computer interface. Others use the term conceptual model to refer to an instructional device for learning the system, as in Borgman (1984, 1986). In contrast, Halasz (1984) uses the term mental model to refer to both the machine and the user's models. No wonder readers become confused with the lack of verbal clarity among the various terminologies!

Farooq and Dominick (1988), apparently exasperated with the variety of terminology, believe the term user model has become almost meaningless. But rather than being meaningless, models are almost too meaningful. The problem is, without precise definitions, the terms are meaningful on intuitive appeal, because they mean whatever readers want them to mean. The only basic requirement is that readers adopt the premise of the mind operating in a symbolic fashion. Perhaps partially because of the ambiguity of definitions, the elusive notion of mental models has a large following. Fortunately, authors contributing to the growing body of work on the subject are beginning to sort through the conceptual confusion created by the use of assorted terminologies.

Norman (1983*a*) offers some distinctions between the terms conceptual and mental models. In appraising mental models, he suggests several considerations:

(a) the target system,
(b) the conceptual model of the target system,
(c) the system image,
(d) the user's mental model of the target system and
(e) the scientist's conceptualization of the mental model.

The target system is the system a user is learning or using. A conceptual model is invented by teachers, designers or scientists as an accurate, consistent and complete representation of the target system. These entities are useful tools for understanding and teaching about systems. The system image is the impression the device portrays to the users. The conceptual model of the system may or may not be consistent with the system image. Mental models, on the other hand, are created by users as they interact with target systems/system images and may not be equivalent to conceptual models. These are "what people really have in their heads and guide their use of things" (Norman, 1983*a*: p. 12). Finally, the scientist's conceptualization of a mental model is a model of a model.

The first three terms are certainly clear, but the last is less so. How does a scientist's conceptual model differ from a scientist's conceptualization of a mental model? Perhaps Norman means that the scientist's conceptual model relates to the model of the *target* system while the conceptualization of a mental model is related to the scientist's attempt to describe attributes of the *user's* mental model. Farooq and Dominick (1988) use the term cognitive model to mean a model, usually formulated by a cognitive psychologist, which attempts to describe the mental processes by which humans complete a task. This concept seems to correspond to Norman's notion of a scientist's conceptualization of a mental model. At any rate, the term conceptual model relates to the system designer or instructor's model and is not created (or necessarily adopted) by users. The term mental model refers to an internal mental representation created by system users. These distinctions are adopted by some authors, for example Borgman (1984, 1986), Moran (1981) and Farooq and Dominick (1988). A cognitive model is, then, a researcher's conception of a user's model.

An alternative view is proposed by Johnson-Laird (1989) who considers mental models as a method of representing knowledge and the manipulation of models a form of reasoning. In his discussion, Johnson-Laird argues that some authors draw distinctions among various concepts of mental models when they likely represent "the same underlying reality". He suggests one reason for believing that humans construct mental models is that the mental models theory can explain the comprehension of discourse (written text). While the comprehension of text is certainly related to users' formation models about computer systems, our discussion here is less concerned with mental models of discourse and more concerned with the mental representations formed through computer instruction and experience.

Certainly Johnson-Laird's position about artificial distinctions among mental model concepts is well taken. Perhaps all models are based on the same reality, but to avoid confusion, this discussion adopts the definitions created by Norman (1983*a*) and Farooq and Dominick (1988).

1.2. COMPONENT AND CAUSAL MODELS

De Kleer and Brown (1983) use the terms component and causal models. Component models concern the process of determining the function of a device by describing the behavior of various components independent of the context in which the component is embedded. That is, the functioning of a device is determined by "gluing together" the specific behaviors of all its components. While interesting, this conception of a mental model speaks more to the construction and content of a model than to the formation of a mental model. The end result, however, is still a mental model.

Causal models are the end result of trial runs of the component model. That is, with each application or run of the component model, various cause and effect relationships are created; at its conclusion, a causal model of a functioning device is developed. Again this concept, while plausible, addresses the process by which mental models are used or created. At least for the sake of this discussion, the term causal model is equivalent to a user's mental model.

For this discussion, the term mental model refers to users' own mental representations of their interactions with devices. Conceptual models refer to the system designers', instructors' or scientist's invented model of a system created for design or instruction purposes. Cognitive models are researchers' various conceptions about the structure, process and content of users' mental models. Component and causal models were not thought to be distinct entities for users' mental models. Perhaps, as Johnson-Laird (1989) suggested, these are synthetic distinctions since they may represent the same reality; however, for the sake of clarity in this discussion, the differences will be retained.

2. Characteristics of mental models

Do mental models even exist? Most cognitive psychologists are comfortable with the theory of mental models, but only indirect evidence is available for their existence. Most of the research in the area infers the existence of mental models either by observing differences in problem-solving abilities of novices and experts within a particular domain or by comparing users' performance on a system when they are, or are not, given a conceptual model. Research is, in any case, difficult since the measurement of internal models is indirect and problematic.

Text editor and hand calculator users provide much of the early data about mental models. Text editors are used so much, in fact, that one author calls them the "white rat" of human–computer interaction research (Foss, 1989). Other studies use individuals interacting with on-line card catalogues. Overall, studies find computer users perform better when they are given a conceptual model before using a system (Borgman, 1984; Halasz, 1984; Mayer, 1981; Moran, 1981; Young, 1981).

Mayer (1981) reports a model that helps students learn the computer language BASIC. Apparently, conceptual models serve as an organizer for users' knowledge representation. This implies the existence of user mental models, with Mayer's caveat that the model works only if it is presented specifically before system instruction. In a related study, Gilfoil (1982) reports findings from observing users as they learn to use a text editor. Gilfoil suggests users develop a cognitive structure for their interactions with the text editor.

Janosky, Smith and Hildreth (1986) describe a study that examined on-line card catalog users. As part of their analysis of the errors users made, Janosky, Smith and Hildreth report that users substituted concrete terms for the abstract meaning of categories. For example, users tend to enter their own names rather than an author's when prompted by "enter name". Janosky, Smith and Hildreth suggest these actions suggest the existence of some form of mental representation of the system.

2.1. CONSTRUCTION OF MENTAL MODELS

No one, of course, knows exactly how mental models are formed. One notion is that analogies or metaphors function as tools of thought which help structure unfamiliar domains (Gentner & Gentner, 1983).

2.1.1. Metaphors and analogies

Douglas (1982) and Lewis and Mack (1982) report subjects spontaneously generating a typewriter model as they learned to use a text editor. In fact, the type of errors and misconceptions about text editor behavior are consistent with this analogy. Apparently, subjects attempt to transfer old knowledge into a new domain given the similarities of physical attributes.

(1983) and Gentner and Gentner (1983) propose an analogy hypothesis: nderstanding is structured in the form of analogies that are in part rom a base domain of knowledge, for example the analogy of electricity water. Imported or induced analogies (as in teaching) imply structural mong objects but not necessarily the objects' characteristics. Gentner and ll these analogies structure-mapping; structural relations between old and are deemed identical. The authors offer a series of experiments to support sal. Generative analogy might be one way in which individuals form a structure for their mental model; analogies define relational structures jects. Greeno has a similar opinion about analogies that are used to and perform procedures. Altogether, these studies seem to indicate dels are a very visual, structured proposition that rely on identified between known and unknown systems.

nd Mack (1985) criticize the generative analogies concept. They consider t a type of structural theory of models. They propose using the linguistic phor (X is Y). Carroll and Thomas (1982) argue that the act of learning to uter is structured by metaphoric comparisons, such as the statement that ter is a typewriter. These authors contend that interface designs succeed ed on the learnability of the metaphor. Metaphors, according to Carroll apply not only to similarities between objects but also to dissimilarities. open-ended, incomplete by definition. Carroll and Mack contend that ps, rather than being static and formal as proposed by Gentner and are generated by users actively working through the metaphor and their experiences with the proposed metaphor. Metaphors are more than ural resemblances to new entities but are like a crystal seed which is used crystal.

discussion, Carroll and Mack address the experiential creation of models. jects actively search for dissimilarities between their current mental models s on experiences. They are given metaphors to help create new mental n contrast to Carroll and Mack, Gentner and Gentner focus on mental tions that are more passive and theoretical. Perhaps these experiences are alent.

er one calls entities analogies or metaphors seems less important than the otion that these entities serve as model construction devices. Instead of ct entities by themselves, these smaller objects may serve as the genesis for mental model of a new domain of knowledge. Users may transfer e about familiar systems to new systems in the form of visual phenomena either analogies or metaphors. At times dissimilarities may be the impetus onstruction of new relations or structures; however, users may not reject or metaphors even given the presence of dissimilarities as we shall see

ucture and content of mental models

l, many authors think mental models are organized structures consisting of nd their relationships (Gentner & Gentner, 1983; Greeno, 1983; Lee, 1988; Hollan & Stevens, 1983). Johnson-Laird (1989) expands this idea to include notions as well. Objects in mental models are related to perceptual entities, and the structure of mental models is correlated with the structure of the situation or interaction it represents. Although not explicitly stated, this type of explanation does not mean to imply the lack of rich relational structures and details. Depending on the individual, some mental models are very rich sources of information indeed.

Moray (1987) views users' mental models as homomorphic decompositions of large, complex systems. By this he means most systems can be decomposed into smaller, independently functioning systems which decrease users' mental processing loads. If designers can discover these homomorphs, better systems must necessarily result. According to Moray's theory, many users develop small working models of subcomponents of complex systems.

Many authors agree that experts' mental models are more abstract than those of novices (DiSessa, 1983; Doane, 1986; Greeno, 1983; Larkin, 1983). Doane (1986) reports that experts' models of a UNIX system are more abstract, entail semantically-bound information and represent higher functioning levels of UNIX. Novices' models represent more concrete levels of knowledge. According to Larkin (1983) novices have a naive problem representation in that they represent objects in real time. Experts, on the other hand, use physical representations with imagined entities as well as real ones. Experts' models are richer and more abstract, what DiSessa (1983) terms a "macro-model".

2.1.3. Types of mental models

Young (1983) proposes eight "suggestions" or tentative types of mental models: (a) strong analogy, (b) surrogate, (c) mapping, (d) coherence, (e) vocabulary, (f) problem space, (g) psychological grammar and (h) commonality.

Young states that these types are not intended to be mutually exclusive categories. He critiques two types of models, surrogates and mapping, against four criteria: performance, learning, reasoning and design. According to Young, the surrogate model is deficient in the performance, learning and design criteria. Mappings fare better, being deficient in learning and somewhat in reasoning. Perhaps because of limited space, Young does not mention either the origin of the model types nor the evaluation criteria. These distinctions, with the brief exception of mapping, are not widely adopted by others, perhaps because mental models may be combinations of these types. It seems unlikely that the mind constructs such parsimonious models that are definable in categories. One is reminded of Johnson-Laird's (1989) caution that all model distinctions may be artificial for they may represent the same reality.

2.1.4. The process of running the model

"Running" the model is the process of manipulating the mental model in one's head to test hypotheses about the reality the model represents. One example is provided by DiSessa (1983) who describes the process in relation to the concept of springiness. People have, in DeSessa's view, a visual image in their heads of hands pushing against both ends of a spring. By using rules and structural relationships among objects, the model is run in a qualitative sense (William, Hollan & Stevens, 1983) as well as in a more cause-and-effect mode (DiSessa, 1983; Gentner & Stevens, 1983). Williams, Holland and Stevens call the sense of running the model "omnipresent" although they admit that how the behavior occurs is not known.

The dynamic nature of mental models presents an interesting question. In measuring mental models, is one measuring a process or an outcome? Clearly, learning a system and running mental models point toward describing the concept as a process, but the result is an outcome. If the term mental model is conceptualized as a process, then measuring it in a cross-sectional study may not capture its essence. Perhaps multiple measurement periods and multiple measures of key variables is preferable. For example, one might need to capture variables such as the complexity and abstractness as well as the effectiveness of the model. In addition, researchers should be clear, if at all possible, which dimension of the model they are studying: *process, content* and/or the *structure* of the model. Johnson–Laird (1989) puts an intriguing twist into this notion when he notes that there is no evidence for differences in structure or process, only content.

2.2. MULTIPLE MODELS

Although some authors discuss mental models as if they were single entities, others admit the possible existence of multiple mental models (Borgman, 1984; DeKleer & Brown, 1983; Williams, Hollan, & Stevens, 1983; Johnson-Laird, 1989; Moray, 1987). Perhaps these are in the form of metaphors, subcomponents, homomorphs or partial models, but nevertheless, multiple entities all the same. One example of this notion is described by Williams, Hollan and Stevens (1983) who present protocols of a subject using multiple models for a heat exchanger.

The use of multiple models seems to depend on two items: the task, as well as the expert level of the user. Williams, Hollan and Stevens suggest individuals considered a heat exchanger as both a temperature and a heat flow model when neither model individually could fully explain anticipated device behavior. In this case, the complexity of the task may drive the use of multiple models. In addition, as users grow in expertise, their ability to manipulate or call into action multiple models also expands. This notion is consistent with the ideas expressed by Gick and Holyoak (1980), Moran (1981) and Young (1983). These authors stressed matching the complexity or abstractness of a model to users' levels.

Again the suggestion of multiple models is intuitively appealing. In this case, there is a small amount of evidence for their existence, and authors generally accept the notion of multiple models. Williams, Hollan and Stevens, in fact, consider the use of mental models crucial for human reasoning but admit the lack of conclusive evidence for this idea.

3. Learning, performance and system design

Mental models are related to system learning, performance and design. Humans also use mental models for reasoning about systems, but for this discussion, reasoning about systems is subsumed under the performance category and discussed as reasoning about complex tasks and problem solving.

3.1. LEARNING

Many authors suggest that giving individuals a conceptual model of a system before instruction enhances user learning (Bayman & Mayer, 1984; Borgman, 1986; Carroll & Mack, 1985; Moran, 1981; Rumelhart & Norman, 1981). Several studies expand this idea to define types of successful training. The common opinion is that giving users a conceptual model, or more than one model, during training is superior to giving only procedural instructions. Apparently the model serves as a knowledge organizer to prevent user confusion and promote understanding of the system. A typical study compared the performance of subjects when they were given a conceptual model during training vs. those who were given only procedural instructions, for example Borgman (1984) or Halasz (1984). Conceptual model learners apparently understood the system better and, depending on the task complexity (to be discussed shortly), they also performed better.

3.1.1. *Inferring mental models*

Moran (1981), Norman (1986) and Young (1981) distinguish between giving users a model, as in the above studies, vs. having subjects induce or infer models. Overall, these studies conclude that users more easily incorporate given models than they induce new ones. However, authors do not agree about whether subjects induce models if they are not given them. Norman (1986) suggests that users infer mental models of devices with which they interact. Moran (1981) proposes the opposite: Users, if not given a model, do not induce one.

Certainly, inducing models depends on a number of factors; some might be: (a) the motivation of the user, (b) the complexity of the system and (c) the complexity of the task. Users might be motivated to induce a model because of the perceived need for information in the system or their interest in the device. The complexity of the system and task may, on the other hand, inhibit mental model construction.

3.2. PERFORMANCE

If one forms a mental model of a system, how is user performance affected? Baecker and Buxton (1987) propose users' mental models and performance are "intimately linked". Young (1981) suggests models guide users' behavior during routine performance. In Halasz's (1984) and Borgman's (1984) studies, model and non-model users perform no differently on routine, simple tasks, but model users perform better on complex tasks. Halasz and Moran (1983) and Bayman and Mayer (1981) also provide evidence which supports this outcome. As Johnson-Laird (1989) states, it is a pedagogical precept to present information to students in a way that enables them to cope with novel problems. The construction of a mental model should help users solve novel problems such as debugging programs.

3.2.1. *Problem solving*

Trouble-shooting errors or problem solving can be viewed as a complex task. DeKleer and Brown (1983) point out that the theory of mental models should be useful for trouble-shooting. Individuals associate actions or patterns with causes to correct problems. Therefore, individuals with more advanced models should be better problem solvers.

3.2.2. *Efficiency*

One might reasonably assume that users with more developed mental models are more efficient computer users. With an understanding of the system, users should be able to debug more quickly and move from option to option without having to spend time eliciting help from documentation or personnel. Speed for routine tasks may or may not be affected. This notion, although plausible, has not been extensively studied.

3.2.3. Accuracy

Mental models are useful for predicting system behavior. Therefore, users with well-developed mental models should be able to produce more accurate results when interacting with systems. This issue is, again, not well studied. In the studies which compared experts and novices, experts were, by definition, individuals who have much experience and make fewer errors (e.g. Larkin, 1983). Whether this is due to the richness of their mental models or other factors is not completely clear.

More important than the number of errors committed is the seriousness of errors. Norman (1983*b*) divided errors into two categories: mistakes and slips, with mistakes being more serious. Certainly mental models theory predicts that naive users not only commit mistakes more often but also commit more serious mistakes than experts.

3.3. SYSTEM DESIGN

Moran (1981) uses Command Language Grammar as an example of a mental model of the user and a conceptual model for design. He divides a system into a conceptual, a communication, and a physical component. In this manner, he provides the basis for a general theses: conceptual and mental models should be congruent. Norman (1986: p. 46–47) outlines the general thesis about the relationship between mental models and system design in this way:

> "...The problem is to design a system so that, first, it follows a consistent, coherent conceptualization—a design model and, second so that the user can develop a mental model of that system—a user model—consistent with the design model... The user model is not formed from the design model: it results from the way the user interprets the system image. Thus, in many ways, the primary task of the designer is to construct an appropriate system image, realizing that everything the user interacts with helps to form that image..."

Designers must create a clear design model in order to enhance users' abilities to create appropriate mental models. Janosky, Smith and Hildreth (1986) added that designers must also anticipate users' models so that errors can be reduced. The point is clear: *designers must be aware of users' mental models.*

4. Problems and consequences of mental models

Many researchers have found a number of interesting problems with mental models. Norman (1983*a*: p. 8) reports his observations after observing subjects using hand calculators. He concludes mental models are fragmentary and worse.

(a) Mental models are incomplete.
(b) People's abilities to "run" their models are severely limited.
(c) Models are unstable. People forget the details of the system.
(d) Mental models do not have firm boundaries: similar devices and operations get confused with one another.

(e) Mental models are "unscientific": people maintain "superstitious" behavior patterns even when they know they are not needed because they cost little in physical effort and save mental effort.
(f) Mental models are parsimonious: often people do extra physical operations rather than the mental planning that would allow them to avoid those actions; they are willing to trade-off extra physical action for reduced mental complexity. This is especially true where the extra actions allow one simplified rule to apply to a variety of devices, thus minimizing the chances for confusions.

4.1. INCOMPLETE AND INACCURATE MODELS

Many authors acknowledge that models are often simple, inaccurate or incomplete (Borgman, 1986; Johnson-Laird, 1989; Moran, 1981; Moray, 1987; Norman, 1983*a*; Williams, Hollan & Stevens, 1983). But what are the consequences of incomplete and inaccurate models? Janosky, Smith and Hildreth (1986) report the serious consequences of incorrect mental representations by studying on-line card catalogue users. Some users actually ignore new information and continue interpreting errors in light of their formed but incorrect mental models. At times, this leads to erroneous conclusions overall, such as that a particular book is not in the library when, in fact, it actually is. Moray (1987) noticed users' tendencies to become rigidly stuck in one mode and not update their model in the face of new information. This he called "cognitive lock-up".

In this same vein, anomalies may not aid learning. Rather than using anomalies as an impetus to construct new, more accurate models, users may instead try desperately to rationalize strange system outcomes. Actions may be interpreted in unintended ways, according to Lewis and Mack (1982). They use the term, "creative comprehension" to describe this phenomenon. Other researchers depict a related notion. They claim that new concepts may map inconsistently into models (Carroll & Mack, 1985; Gentner & Gentner, 1983; Young, 1981). Gentner and Gentner suggest this incorrect concept mapping might be widespread. At first reading, one might interpret Norman's earlier comments to be consistent with the above findings, that incomplete models promote inaccuracies and are a hindrance to users. However, Moran (1981), Norman (1983) and Johnson-Laird (1989) maintain even incomplete or partial models may be useful.

Individuals may import models into new knowledge domains and over-generalize or overmap them (Borgman, 1984; Halasz & Moran, 1983; Young, 1981). Individuals may use old models to generalize inappropriately to new interactions, such as generalizing all typewriter behavior to computer keyboards. Also, as Borgman (1984) noted, there may be interference among multiple mental models. An example of this problem would be transferring commands from one software package to another. Mental models, then, have no shortage of difficulties.

5. Exploratory mental models research: observations of SPSSX users

Some exploratory interviews were conducted to determine whether nurses develop a mental model during their interactions with the statistics package SPSSX. The concept of mental models provided a framework for the interviews and observations of SPSSX users. Five doctoral nursing students were interviewed and observed interacting with SPSSX. In addition, one computer programmer was interviewed because she provided help to students in the school computer center and had a broad perspective of how the class functioned as a whole. The students were selected in a purposive manner to represent novice and expert users among doctoral students. All students had taken the same 2 h introductory course which familiarized them with the use of the CMS editor and basic functions of SPSSX such as how to set up a program file. Also, all students had successfully passed a sampling and survey course, an inferential, and a multivariate statistics course which all required computer exercises as part of the coursework. The students used SPSSX for at least a year.

The interviewing technique was semi-structured and lasted an average of 1 h each, although the range of times was 45 min to 2–2·5 h. The students were asked about their perceptions of their interactions with SPSSX, and specific questions about (1) their previous computer experience and knowledge, (2) how they would rate their knowledge of SPSSX on a scale of 1–10, (3) their strategies for debugging, (4) to describe various system components such as the CMS editor and (5) to describe their conception or mental picture of the system. Notes were taken during the interviews and additional observations by the investigator were added immediately following the session. Students were observed interacting with the system to determine patterns of interaction, for example whether or not they created hand-written programs before logging onto the system. The results were synthesized into novice or expert user groups.

5.1. FINDINGS

5.1.1. Evidence for mental model existence

Novice users had very immature mental models because they denied their existence and made major conceptual errors during their interactions with the computer. In defense of this, mental models may be difficult to articulate even if they are present. Only one student was able to articulate a model of the system. She had a rich, visual image of the computer, its file and her interaction with both. Her detailed image even included a mental picture of where her files were located on a disk. "Oh", she said, "what you want to know is my conceptual model of the system". The other expert user, by her actions, certainly understood the organization of the system but denied having any sort of mental representation of it. The novice users flatly denied having any kind of mental image of their interactions with the system. "I don't have one", was a typical response. Another user stated, "I have no concept of how the system is put together". For her to try to describe it would be like "a 2-year-old trying to draw the human body".

Do these preliminary findings indicate that users have no mental model or that they are just unable to articulate one? Certainly doctoral students have little difficulty with either conceptualization or verbalization in general, but articulating an internal model may be another thing altogether.

In her dissertation research, Borgman (1984) found on-line card catalog users had trouble articulating a model of the system they used. Some could articulate a problem-solving framework, though. She attributed this, in part, to the manner in which her question about mental models was asked. Perhaps models, especially in novices, are innate or so immature they cannot be identified by their owners. Clearly, *something* must exist for the students to have successfully used SPSSX for three difficult courses. Perhaps users' actions speak differently than their words, or perhaps mental models defy words.

5.1.2. Inferring mental models

Several factors, such as user motivation, system and task complexity, can inspire subjects to infer a model, as discussed in Section 3.1.1. In this work, students were very motivated to learn the system (their grades depended on it) but were not given a conceptual model of the complex system. Their 2 h class consisted of procedural instructions about how to logon, set up a data and a program file. SPSSX is a very complex and technical program and not easy to learn quickly. Its accompanying computer manual is very complicated, with a lot of computer and statistical jargon. The students began by running very simple statistical programs, calculating ANOVAs, but gradually moved to more complex functions. Some of the course assignments were to design a study and carry out appropriate statistical tests on a large database.

Despite this level of activity, the three novice users induced very immature to non-existent mental models as evidenced by their inability to articulate differences in system components and their observed interactions with the system. Perhaps this was due to the complexity of the system, but even small working models of the system seemed to be absent. Novice students relied heavily on very specific notes detailing steps from logon to logoff. "I just couldn't remember any sequence of steps, and I still have my index cards [outlining the steps] even though I haven't used the computer for two semesters". Another subject stated, "I never went in without a complete, written program on a FORTRAN sheet. I had to have everything exact, including the spaces". Without an understanding of the system, these students had to rely on precise procedures.

The expert users induced, or at least had, system models, one of them rich in detailed, visual imagery. They relied much less on exact written programs, saying that they might write a major command or two but never the entire program. Another difference between the novices and experts is that the novices became very goal-oriented, nearly at the survival level. The experts were willing to experiment with the system and system commands while the novices wanted only to complete an assignment as quickly as possible.

Without a conceptual model to help organize learning, students, especially ones fairly new to computing, had no organizing framework on which to store new knowledge. In fact, one student lamented she retained nothing from the introductory computer class because it made no sense. Therefore, the class was a source of anxiety, not of help with the system. During interviews, novices were asked to explain the term CMS, the computer operating system and editor function, and none could. Two subjects answered, "I don't know", and the third, "CM Read" without elaboration. (CM Read is the message line text when one is in CMS.) The experts, however, understood its function and gave a working definition without hesitation. Novices, even after three courses and a year's interaction with CMS and SPSSX, still did not understand program differences or CMS's basic function.

5.1.3. Accuracy and problem-solving abilities

Users with developed mental models are likely to commit fewer errors. The exploratory research corroborated this notion. Naive computer users committed mistakes which demonstrated their lack of basic understanding of the system. For example, the computer centre programmer stated she found novice users inputting data into their program files (they are separate in our SPSSX interactions) which created fatal errors. These users combined the files so that the computer would "know" where the data are. Some users never did understand the differences in file types, but were at the "now you push this button" stage of understanding.

Subjects with mental models should be better problem solvers. This theory holds true in this study. Novices were paralyzed by their inability to solve problems. One subject stated she used her detailed, exacting, hand-written programs as insurance against committing errors while running the input computer program. If she got errors, she was unable to solve them independently. Another novice just stopped when she made errors and "never asked for help". She then did statistical calculations by hand.

Expert users had several strategies for problem solving. First of all, they expected errors and were surprised if the program ran cleanly the first time. They knew to look immediately for small syntax errors in the program. If that failed, they attempted various trial-and-error methods of problem solving and tried to interpret the error message using the manual. In fact, it was this trial-and-error strategy that differentiated expert from novice problem solving. The experts would try various corrections before expending much energy at analysis. As one expert said during an interaction, "It won't work, but let's try it anyway". Novices, on the other hand, had an impoverished repertoire of strategies, and tried few trial-and-error attempts as remedies.

Novices all agreed the manual was of little help in problem solving, especially at first, because they had no idea in which section to look for guidance. Was the problem with the data file or the program file, (assuming they knew there was a difference between the two)? Was the problem a matter of typing errors or command errors? They had no idea. Over time, novice users learned most errors were syntactic, a missing space or parenthesis, but they discovered this only after enlisting help many times from the computer center personnel and other more skilled students. Some committed very basic errors, such as one subject who sat for about 15 min working at a personal computer terminal in the computer center when she needed to be using a mainframe terminal. Only after one of the computer personnel noticed her struggles did the problem become clear.

5.1.4. Efficiency

In this research, there is evidence for experts being more efficient SPSSX users. Novices were very deliberate typists, and one complained that the whole process, "took so long". Since students were at the extreme poles of the continuum of

novice
to expert, the drastic differences may have been more apparent. However, other studies note differences in performance even among computer professionals (Borgman, 1986; Borgman, 1989; Coombs, Gibson & Alty, 1982). More work is needed in this variable before firm conclusions are made.

5.1.5. Problems with mental models

Many common problems with mental models were observed in this research as well. Although the novice users frequently wrote detailed SPSSX programs before entering the computer center, they were not motivated to create more useful mental models of the system. Somehow, the novices remained procedurally based users rather than developing sophisticated models that would help understanding and probably speed interactions with the system. Novices used comfortable old methods rather than learn new, quicker ones. For example, one student could have reduced substantially file processing and printing time for her lengthy dissertation data analysis by creating a system file. Even though she knew about the existence of system files and was given explicit instructions on how create one, she continued to use the more lengthy but comfortable old method for data analysis.

Why users developed nearly non-existent or immature models after multiple interactions is not known. Intellect was not a problem among doctoral students; obviously, they had no problems learning concepts in other fields. Users' comments point to a lack of interest in learning about computers, at least for two of the novices. According to one, "I need computers to survive, but I'm not crazy about them. In fact, I never liked dealing with the machine at all". This student found dealing with computers "an exercise in pure frustration". That is why, she said, she developed no interest in learning more than she absolutely had to about both computers and SPSSX. Experts, on the other hand, were interested in computers and what they could accomplish for users. As one said, "Computers are my friends".

Despite the lack of interest and the immature models for novices, they persevered. Therefore, even incomplete mental models may be useful as Norman (1983*a*), Moran (1981) and Johnson-Laird (1989) propose. Perhaps this view helps explain how the novice SPSSX students managed. Even though they used procedurally based survival strategies, these may have been very simple but effective enough for students to pass required courses. Beyond that, novices users apparently had no motivation to build more complete, accurate models.

Some authors propose multiple model interference. In this study, transference among models was not a problem since SPSSX commands were fairly unique compared to other programs students used. One student described learning SPSSX as "learning a foreign language". She had no knowledge of the "foreign language" since her word-processing program had no similar vocabulary.

5.1.6. Consequences of immature models

One of the differences between novice and expert SPSSX users was the way they approached entering programs. Novices created detailed programs before going to the computer center. Experts wrote only brief notes which involved new commands or general ideas. They, in fact, used varied and advanced commands in their independent work and were able to interpret new commands by reading the manual. Novices used much more limited data analysis techniques. The most striking difference, however, was the absolute paralysis novices exhibited when programs did not run correctly. Without a mental model or understanding of the system, they had no problem-solving skills and had to depend on others to help them. One user commented, "SPSSX was a nightmare for me". Experts expected error messages and had a repertoire of problem-solving strageties that included some trial-and-error attempts at first. Experts thought dealing with the computer was "fun, like hitting pay dirt". Their interactions with the computer involved humor and tolerance.

Social support was a major strategy novices used to cope with the frustration of SPSSX. They wrote computer programs together after class and then went as a group to the computer center to run them. When one student could not get her program to run, another would help. If students were unable to help, then computer center personnel were enlisted to debug. Novices learned only enough about the system to survive their statistics courses. They had little interest or motivation in pursuing further information. Experts, on the other hand, worked independently and searched for ways to improve and speed their interactions with the system. The findings of this exploratory research might be summarized by one student's statements:

> "Using the computer is just this mystery... When I get errors I experiment with changes, and eventually it works, but I have no idea why... A mental representation of how I interact with the machine? I don't have one... I'm inductive. I guess that's why I have trouble, but I make the computer work anyway. It's a challenge, and when it works I think, 'I have beaten the deductive system".

6. Summary

Many cognitive psychologists and human factors researchers believe humans use mental models to interact with devices. During the 1980s, authors created a number of terms which refer to the notion of mental models. Rather than being meaningless, these interrelated terms have intuitive appeal, which may be a partial reason for the extensive adoption of the notion of user mental models.

There is agreement among authors about several issues. Mental models are internal representations of systems in particular knowledge domain. These internal representations are formed through knowledge (instruction) or experience or a combination of the two. Last, the resulting model is a private enterprise, an individualist phenomenon.

Some evidence for the existence of mental models has been generated from studies primarily using text editors and hand calculators. The measurement methodology in these studies was frequently protocol analysis, and device users were often given like tasks or problems to complete during the course of the study. Much of the work to date has compared the models of novice and expert users.

How mental models are constructed is not known. Some authors, however, think that humans construct models by using analogies or metaphors of past represented objects or interactions. In general, authors think models are composed of both concrete and abstract objects in a relational structure which emulates the actual situation. Humans have the ability to "run" models in their heads for both descriptive and causal hypothesis testing. In this way, models may be modified and constructed. Mental models seem to be more process than outcome entities because of their dynamic and changing nature. Also, there is some evidence that humans use multiple mental models for reasoning and for modeling complex systems; although this notion is logical and appealing, there is only a small amount of evidence to support it.

Mental models are related to user learning, performance and system design. If users are given conceptual models during training, they understand the system better and outperform others in complex task actions. Giving users a conceptual model may serve as a knowledge framework in which new knowledge may be organized. Authors generally agree that it was easier to give users a conceptual model than have them infer one. Authors agree that designers' conceptual models should be congruent with the users' mental models. At least, designers must be aware of what type of image the system gives users. Users with developed mental models may be more efficient computer users, but little research has been carried out to support this idea. Another area needing research is the relationship between mental models and types of errors. One might assume the presence of a mental model would reduce the number and kinds of errors commited. However, this assumes that mental models are accurate, which is not necessarily the case, as we have seen.

6.1. MENTAL MODEL ISSUES

Mental models research has only just begun, and a number of issues remain to be solved. First, more work is needed to clarify definitions. What exactly are mental models? Are conceptual, cognitive and mental models one and the same? If they are different, how are they different? How are mental models different from any knowledge stored in the human brain? Perhaps the difference is in content or organization, as proposed by some authors, but this is, as yet, a mental model of a mental model conjecture. Certainly conceptual models help users assimilate information, but do they differ from any organized information presentation?

The research may have begun with too broad a concept. There is the possibility that mental models may be a general term which is a manifestation of smaller brain processes. In that light, one might find information processing or "chunking" to be a more fruitful beginning point. How mental models are related to general concepts in learning might be explored. What learning concepts might help explain the phenomenon of mental models? Perhaps mental models are just the result of a learning style or a combination of intelligence, interest and perceived need for the device.

Are mental models transitory or more permanent? Perhaps the brain has the ability to link smaller pieces of knowledge stored in long-term memory into temporary networks which differ from interaction to interaction. Rather than being a permanent structure, as one might surmise in mental models theory, one might find different links from day to day which might explain some of the inconsistencies and errors observed, and this might explain some of the notions about multiple mental models.

At a more particulate level, how does mental models research relate to the current thinking in brain physiology or neural networks? Are instructional knowledge and psychomotor experiential knowledge coded into separate models or are they combined into a larger, more complex one? Perhaps we are thinking too rigidly and simplistically about mental models. They may be much more complex than we can currently measure.

6.1.1. Mental models measurement

Authors have been writing about mental models for less than 10 years, so these works depict only the beginning of needed research. Most of the research to date has been qualitative using protocol analysis to describe interactions between humans and text editors, calculators, and on-line card catalogs. The use of protocol analysis raised some reliability and validity issues; however, the obtained data have been rich, although riddled with problems and mysteries.

Interesting measurement issues persist. What behaviors did researchers choose to analyse? What information was ignored? Were categories of behaviors identified? Little of the methodology is reported in most studies, and this information might assist other researchers. How were the results synthesized? Maybe qualitative research techniques and tools might help mental models researchers; for example, using one of the qualitative data analysis software packages could be useful. Did more than one researcher examine data? Was inter-rater and/or intra-rater reliability done? Does user performance remain stable over several interactions? Or is there little reliability from time to time? If researchers are using observational data, perhaps videotaping might help researchers develop coding schemes. Also, it would capture the effective component of human–computer interactions, an aspect not discussed in mental models literature as yet.

When researchers conducted experiments using conceptual models, how did they know they were implementing mental models vs. another concept, such as organized information? Are observed results an individual characteristic, a computer characteristic or an interaction effect? One must be careful to measure and combine data from a consistent unit of analysis. For example, are observed errors to be defined as a user characteristic (a faulty mental model) or an interaction characteristic (a combination of mental model and conceptual model difficulty). Most research treated errors as if they were the result of a user problem, when, in fact, it may be an interaction effect of design and user. Likewise, is a particular study measuring results from the users' mental model, the users' perception of the conceptual model or the researcher's cognitive model as they observed the users? One is not always sure.

The concept of mental models is an alluring one, representing some fascinating thinking about how individuals manage interactions with computers as well as with other domains of knowledge. Mental models may be useful to improve computer user efficiency, accuracy and performance, expecially with complex problem solving, but basic questions about concept definition and measurement issues remain. The concept is problematic. Mental models can be incomplete, inaccurate and parsimonious. Individuals can over-generalize or over-map if they import existing models or use multiple mental models. Measuring mental models also presents a major challenge to researchers. While these problems appearing discouraging, they should serve as the impetus for interesting research in the future.

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