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Mental models, conceptual models, and modelling[1]

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The study of mental representations constructed by students in their interactions with the world, its phenomena and artefacts, constitutes an important line of research in science education, according to what has been published in recent issues of the most important journals in the area. In this article we review what is being understood by mental model, conceptual model, and modelling, emphasizing the contributions this line of theory can bring to science education and research.

Introduction

Nowadays the contributions of cognitive psychology to the understanding of the processes of learning and instruction seem to leave no room for any doubts about its importance (Brown 1995, Gardner 1985). These contributions derive from one of the most relevant research topics, namely, the representational nature of knowledge. Vosniadou (1996) notes that they have revolutionary implications for education. They provide theoretical elements, which, with much more detail than any other psychological theory of the past, describe mental representations, and the processes that underlie expert performance in a given area of knowledge. If these processes and representations can be understood, the questions that follow have clear educative implications: are they innate or acquired (constructed)? If they are acquired, how do the students acquire them? Is it possible to design methods to facilitate this acquisition? These elements and the growing discontent with the lack of effective results (Duit 1993, Moreira 1994) from research on misconceptions and conceptual change (at least from the perspectives of Posner *et al*. 1982, Nussbaum 1989) have contributed to increase the interest of science education researchers in the theoretical constructs with which cognitive psychology describes the internal representations of people about their knowledge of the world. This interest can be seen, for instance, while reviewing the book *Research in Science*

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Education in Europe, published last year, with several important articles, in which concepts such as mental models, conceptual models and modelling are used as theoretical axes for the new trends in science education. These three terms are also quite frequently mentioned in papers in the most important journals of the area (Krapas *et al*. 1997).

What are the special characteristics of these concepts that are turning them into the new stars of science education research? First of all, we must emphasize that, as it is common in science education, these terms are not used in a univocal way; on the contrary, behind their vagueness there is also a diversification of meanings. Particularly in the case of mental models, this diversification, has led us to wonder whether they are not actually `mental muddles' (Barquero 1995), derived from cognitive psychology itself, from which they have been originally taken.

On the other hand, the words models and modelling can have a special appeal for those who work in areas related to science. Are not scientific theories `represented' by models - from physics or mathematics - for a given number of phenomena? Don't we use models to teach our students more efficiently? And, finally, don't we consider modelling - understood here as the establishment of semantic relations between theory and phenomena or objects - as the fundamental activity in the sciences, especially in physics? However, the assumption that conceptual models - because they are logically clear and often specially designed to facilitate both comprehension and learning - should be learned by students, who, besides representing reproductions of those models in their heads, should be able to use them to establish relations between the theory presented and the phenomena, is not necessarily true. Neither do mental models end up as perfect copies of conceptual models, which are generated by experts and teachers, nor is the modelling process evident to our students.

In this article we aim at providing an overview of what is being understood as mental model, conceptual model, and modelling, that is, of how they are being used in science education research. Grounded on these elements, we will attempt to explain why - although the reasoning in the last paragraph is not necessarily correct - the program of the research on mental models seems promising.

Mental models

In 1983, two books on mental models were published, one by Johnson-Laird, and the other by Genter and Stevens. According to Barquero (1995), whereas the first one represents what we could call the theoretical approach to mental models, the set of papers that appeared on the second one could be called the instructional approach. This distinction is made because the major objective, in Johnson-Laird's case, is to offer a unified and explanatory theory of distinctive cognitive phenomena, such as deductive reasoning and discourse comprehension, while the other authors focus their attention on the knowledge about physical phenomena and, particularly, about mechanical and technological devices people develop, without any attempt at representing any unified theory about it.

As Barquero points out (1995, p. 12), the notion of mental model underlying the instructional approach is

> a type of knowledge representation which is implicit, incomplete, imprecise, incoherent with normative knowledge in various domains, but it is a useful one, since it results in a powerful explicative and predictive tool for the interaction of subjects with the world, and a dependable source of knowledge, for it comes from the subjects' own perceptive and manipulative experience with this world.

Norman (1983, Gentner and Stevens 1983, p. 8) had previously noted that mental models were incomplete; unstable (people forget details of their models, or discard them); did not have well defined limits; were unscientific (they reflect the people's beliefs upon the represented system); were parsimonious (people frequently chose additional physical operations which require more energy in exchange for less mental complexity). The only commitment of mental models has to do with the functionality they have for the subject. The main role of a mental model is to allow its builder to explain and make predictions about the physical system represented by it. It has to be functional to the person who constructs it.

Several papers published in the book by Gentner and Stevens assume that to study the validity of mechanistic models, which these authors suppose people have inside their heads, they must be computationally simulatable. Thus, the models of a buzzer (de Kleer and Brown 1983), a system of fluid flux (Forbus 1983) and electric circuits (Gentner and Gentner 1983) appeared there. The relevant idea behind the requirement that those models can be implemented by a computational program is that mental models can be considered as `mental simulation' of the real situation of the problem, as `feasible' causal models for the system or mechanism they represent. In particular, de Kleer and Brown 1983 suppose these simulations, both the mental and the computationally implemented ones, involve two steps: (a) the envisioning of the system, including a topological representation of the system components, the possible states of each of the components, and the structural relations between these components; (b) the running or execution of the causal model based on basic operational rules and on general scientific principles. The structural relations between the components are defined by the relations of change of states. These relations are of the `If . . . then' type production rule, between the change of state in a component and the change of state in another component (Vosniadou and Ortony 1989). For instance, from this perspective, in order to generate a mental model of how a bicycle works, we must distinguish, in the first stage (envisioning), the system components and their relations (wheels, pedals, chain, relation between wheel size and the chain, possible states of the wheel, etc.), and in the second (running), we must establish the relation in such a way that these components will start moving and, therefore, they will allow us to ride the bicycle without falling off (establishment of the conditions of static and dynamic equilibrium conditions, relation between the force applied to the pedals and the acquired speed, etc.). Only then could the subject `run' the model based on causal rules.

The most salient characteristic of Johnson-Laird's theory is that mental models are analogical representations of reality. In face of a particular situation, models that are elected to interpret this situation, as well as the perceived or imagined relations between them to determine an internal representation that will act as a `substitute' for this situation. When these `substitutes' are internally manipulated, some of the properties of either the system or the situation, including relations that are not explicit among their components, can be `read' directly. Thus, in the bicycle example presented before, we imagine a `substitute' for the bicycle in our minds, with which we are able to predict what may happen if the chain breaks. We do not need here to specify any relations involving the chain, wheels, and pedals. Had they not been analogic representations, we would have had to determine those rules explicitly to be able to make the necessary inferences.

Johnson-Laird states that there are at least three classes of distinct mental representations: propositional representations, defined as strings of symbols, similar to natural language in the sense that they need syntactic rules (formal logic relations or production rules) in order to combine, although they cannot be confused with it; mental models, structural analogues of the world, and images, defined as views of the model. Before we elucidate any further these three representations, it might be important to emphasize that, for Johnson-Laird, mental models are working models of situations and events in/of the world, and that through their mental manipulation we are capable of understanding and explaining phenomena and are able to act accordingly to the resulting predictions.

When we say, in physics, that a phenomenon has been understood, this means that we know its causes, effects, how to start it, influence it, or how to avoid it. According to Johnson-Laird, this implies having a working model for the phenomenon. That is, though the physical phenomena are propositionally codified through verbal statements or mathematical formulations, comprehension should involve the construction of mental models for the entities or processes which they represent (Nerssesian 1992).[2]

If we hear the sentence `the cat is on the roof', its internal representation (mental), as a propositional representation, is undetermined. In fact, in order to understand the meaning of `the cat is on the roof' and, at the same time, be able to predict what might happen next, we need to represent one of the possible concretizations (for example, to have one entity that represents a cat, and another that represents a roof) being implicit in the generated mental model of the situation. This is one of the characteristics of mental models that emerges from their analogical character: the specificity of their content. If, besides forming the model, we imagine, specifically, a black cat sitting on a red tin roof, we will have built an image that, differing from mental models, in general contains more visual-spatial information, because it is the internal representation that has a higher degree of analogical approximation to reality.

These three types of representation not only distinguish themselves structurally but also functionally. Johnson-Laird makes an analogy comparing mental representations (internal) with the languages of computer programming. Whereas the computers we know nowadays function using a machine language (strings of 0 and 1), responding to a particular syntax (Boolean algebra), the programmers use high level languages in order to generate and test new programmes in a simpler way. Mental models and images would correspond to these high level languages, whereas propositional representations would correspond to the machine languages.

Another important characteristic of mental models, as defined by Johnson-Laird, is recursiveness, which characterizes mental models as dynamic representations. A mental model is never complete, but it continues to be enlarged and improved as new information is incorporated into it. This is what occurs in discourse comprehension. As we proceed with a conversation, new elements are incorporated to the original idea, modifying it. This recursive process depends on the subject's knowledge, on his/her dexterity and on the reason why the model is being constructed. This distinction is important when we want to explain, for example, why it is not important to know Maxwell equations to fix a television set.

Summing up, the fundamental difference between the two sources of the research program on mental models is the type of internal representation that supports them. Those derived from what could be called the `instructional' source assume that mental models are sets of propositional representations, that is, series of propositions and of causal rules of manipulation that must be made explicit. The theoretical source emphasizes the analogical character[3] of the models. This is what gives Johnson-Laird's approach a differential character. Not having to determine rules, the models of Johnson-Laird represent properties implicitly. The analogy between mental models and the system, which they represent, allows for certain properties of the system and certain relations between them to be able to be read or to be inferred directly, without the need of postulating that people have either production rules or a built-in logic in their heads to provide those rules.

As it was pointed out before, many papers related to mental models in physics have appeared lately; such as, for example, the work of Mayer (1992) and of Gutierrez and Ogborn (1992), which can be included within the research framework of de Kleer and Brown. On the other hand, the work of Vosniadou and Brewer (1994), Nersessian (1992, 1996), Halloun (1996) and Greca and Moreira (1996, 1997a, 1997b) use the theoretical basis of Johnson-Laird (for a review of these works, see Moreira 1997).

Conceptual models

Nersessian (1992) considers mental models as intermediate levels of analysis between the phenomenon and the resulting final mathematical model. This mathematical model is a conceptual model. Generally, a conceptual model is an external representation[4] created by researchers, teachers, engineers, etc., that facilitates the comprehension or the teaching of systems or states of affairs in the world. According to Norman (1983, *apud* Moreira 1997), conceptual models are precise and complete representations that are coherent with scientifically accepted knowledge. That is, whereas mental models are internal, personal, idiosyncratic, incomplete, unstable and essentially functional, conceptual models are external representations that are shared by a given community, and have their coherence with the scientific knowledge of that community. These external representations can materialize as mathematical formulations, analogies, or as material artifacts. An artifact that indicates the functioning of a water pump, an analogy between Rutherford's atom and the solar system, or the mathematical formulations of the shell model for nuclear physics are examples of conceptual models. Conceptual models are simplified representations of real objects, phenomena, or situations.

When we teach, it is common to assume that students have acquired or constructed mental models that are copies of the conceptual models that have been presented to them. This confusion also happens with the research that uses analogies as instructional aids. In Gentner and Gentner (1983), for example, they start from the hypothesis that if subjects are instructed on the use of analogies to explain electric current (water flux or multitudes of people), they will build mental models that are consistent with these conceptual models, and they will respond coherently with them in certain problematic situations. However, this does not happen. Duit and Glynn (1996) also suppose that meaningful learning would result from the evolution of mental models students bring with them to the classroom towards the conceptual models with which they are instructed, as they seem to identify, at this final stage, conceptual and mental models. Norman (1983, p. 12) emphasizes that `ideally there should be a simple and direct relation between a conceptual model and a mental model. However, this does not seem to be the case'. It seems important to state here that the students do not necessarily see those conceptual models as such. Firstly, because they do not have the necessary knowledge of the field to interpret them as conceptual models. It is as if we see Picasso's Guernica for the first time, without knowing what the Spanish Civil war was. One is able to see eyes, paws, heads, knives, but the painting will be meaningless. Secondly, because students often do not understand that a conceptual model is a simplified and idealized representation of phenomena or situations, without being told the actual phenomenon or situation.

Based on what we have said so far, one could think that, when people intend to understand a conceptual model, they extract from it those elements they consider relevant, then they relate it - if this is possible - to what they already know, generating, or not, mental models that are not necessarily similar to the conceptual models presented to them. An illustrative example of this is described by Vosniadou and Brewer (1994) relating to hybrid mental models of the shape of the Earth: some interviewees thought that the Earth was hollow, with an inner flat surface, though they had received instruction about it. This instance of no coincidence between mental models and conceptual models does not occur only with those who are not experts. In research carried out with active physicists (Greca and Moreira 1996), it was found that they use distinct mental models when they are engaged in understanding phenomena linked to an electromagnetic field, thinking about it as a geometric deformation, as a `gas with little arrows', or they think about it as starting from its generating elements (charge and magnetic dipoles). For them, these models were an heuristically valid way to understand such phenomena, although further on they would use a conceptual model scientifically shared (Maxwell equations) to formalize and present their findings. In these cases, the analysis benefited from the analogical character of mental models. As Nersessian (1992) points out, when scientists communicate their findings, they present them by means of the logic of their mathematical formulae and the conceptual models they have created, without even mentioning the mental models which had served them as intermediate analysis levels to the comprehension of the physical phenomenon in question.

Unfortunately, this confusion, which presupposes an isomorphism between the finished model and what people have or construct inside their heads, can be perceived in textbooks,[5] where scientific models and theories appear as finished structures, logically organized, without considering that this does not imply that the types of representations used by scientists to think about the theory are primarily in this format, nor that in order to reason in a problematic novel situation they would use the same logic rules. It would seem that, in fact, one thinks that the students learn conceptual models in the same way that the mathematicians of the Lagado Academy, visited by Gulliver, proclaimed: if the students properly digested a thin wafer, in which theorems and their demonstrations had been inscribed with some kind of neural ink, this ink would ascend to their brains, and the adequate propositions would get fixed together inside their heads.

Modelling

In spite of their most daring efforts, the mathematicians of the Academy of Lagado did not succeed in having the students learn what they wanted. Something similar happens in science education. Regardless of the effort that teachers invest on their task, quite often they do not manage to have their students construct mental models that are coherent with the conceptual models and the shared theories presented in the class, and that will enable the students to understand physical phenomena according to these theories. Nevertheless, the students limit themselves to learning by heart long lists of formulae and definitions, which they do not understand, because the phenomena described there are not being interpreted according to the mental models the students should be constructing.

How should one handle it if he/she wants the students to construct these internal representations consistent with knowledge that is scientifically accepted? The magic word seems to be modelling. Modelling is the scientists' main activity, and of physicists in particular, for the generation and application of scientific theories; therefore, as stated by Halloun (Moreira 1997), learning physics implies learning to play `the modelling game'. However, it might seem that this game is learned implicitly, and sometimes at high cost, only by those students on the track to become physicists, and by physicists themselves.

The modelling process has been understood as the learning of a series of steps to identify only those salient elements of a system, and to evaluate, according to distinct rules, the chosen model (Halloun 1996); as the `learning of a new language' that would allow for another perception of the description of the phenomena (Sutton 1996), or as the integrated reasoning process which

> uses an analogical and visual modelling, as well as thought experiments in the creation and transformation of the informal representations of a problem (Nersessian 1995, p. 204).

Independently of differences of analysis and of the pedagogical consequences that these three approaches could imply, their authors agree that this modelling process is a semantic one, so that the produced models are `interpretations that should satisfy the restrictions derived from the text, equations, diagrams, and other salient information source in the external medium and in the mental representations of those who solve the problems' (Nersessian 1995, p. 209). They also agree when they emphasize that the learning process of modelling should be explicit, that is, the students should be explicitly taught the procedures through which they can construct mental models that, in turn, will enable them to understand the taught conceptual models, which must agree with the restrictions presented earlier.

Besides these developments, there has been a series of research studies that propose the learning of modelling starting with computational programs specifically designed (Devi *et al*. 1996, Raghavan and Glaser 1995), although the findings of these studies do not seem to have been clearly stated yet.

Implications for teaching and research

We should now examine the resulting panorama according to what has been discussed so far: students, in order to understand their surrounding world and its phenomena, construct internal representations - mental models - that will allow them to learn, explain, and/or predict it. These models are personal, incomplete and qualitative. That is, these models of physical phenomena - models that are neither consistent with those scientifically accepted, nor have to be consistent among themselves, and whose only necessary condition is to be useful (functional) in permitting students to handle them in their daily life - constitute the prior knowledge that the students bring to the classroom. It is there, in the classroom, that conceptual models are introduced to them.[6] When the students receive this information, they have different possibilities. The first one might be the attempt to interpret it in accordance with the knowledge they already have, thus generating hybrid models. The second possibility would be to memorize it in unconnected lists - through internal propositional representations - to pass the assessments. A third one, and perhaps the most far-fetched, would be to construct mental models in consistency with the information the students get. Nevertheless, the modelling process through which it would be possible to facilitate the construction of these mental models, and, thus, the comprehension of the conceptual models presented, has not been explicitly emphasized. Most certainly, the type of activities and assessments that characterize physics classes - lists of problems - and the type of textbook presentations - lists of formulae and definitions - do not contribute to this process.

Thus, the task, within this theoretical framework, is not an easy one for either teachers or researchers. For teachers, this is rather difficult since the modelling process is highly complex and, moreover, our knowledge about it is still quite poor. We, so far, know neither how to identify what kinds of mental models the students have in a given domain, nor what specific mental models they construct. For researchers, the main difficulty here seems to be a methodological one: how to seize these incomplete, unstable, and personal representations? (For a more detailed discussion on the subject, see Moreira 1997). However, many interesting lines of discussion seem to emerge from this conceptual framework.

1. Mental models would allow us to understand why the so-called misconceptions resist change so much. They would not be isolated conceptions, since these models would help people to explain groups of phenomena, visualized as similar ones. However they would not constitute a theory either, such as it was claimed by those who maintained that the students were modern Aristotelians, since they are neither explicit nor consistent[7]. Besides, these models are personal, that is, although they are constrained by the cognitive system capabilities, by perception biases, especially in the case of classical mechanics, it is doubtful that we could establish a closed `catalogue' of these initial models and of their possible changes.
2. If these initial models are utilitarian, their modification - understood here as a total replacement of one conception for another - will not be a simple task. If this is true, conceptual change should be understood, as indicates Vosniadou (1994), mainly as enrichment processes of previous models, and only in extreme cases will there be a complete review of these models. It

might also happen that people would establish `spatial-temporal' areas discriminated for the application of difficult models.

3. Because mental models are personal constructions, it may seem that the most adequate path for meaningful learning in science would be more closely related to the teaching of construction processes for these representations - modelling -, processes that would become more common than the teaching of conceptual models themselves, which would imply idiosyncratic results.
4. Although, as it was indicated before, novices do not have the necessary knowledge of the domain to interpret as conceptual models those presented to them, or to impose upon the modelling process the necessary constraints, they do have the basic tools to generate mental models which is exactly what they have been doing to interpret their world: to make analogies; to create mental simulations; to make idealizations and general abstractions. Learning science would not require any kind of magic virtue besides explicitly learning how to use these mechanisms they already have.
5. Mental models also open up an interesting path for research on the heuristic of images and mental simulations in the process of creation and comprehension of a scientific theory, at least in Johnson-Laird's version (1983). The pedagogical potential of analogical representations (mental models and images), which often appear in the history of the great achievements in physics, such as the images of field lines in Faraday, or the thought experiments in Einstein, has not yet been studied in depth.[8]
6. These developments about internal representations may allow for a reconsideration of the research on analogies to study why sometimes they do not work.

Summing it up, it is possible that this type of theoretical framework, because of its foundations, as well as its issues, could help subsidize, to a large extent, research on ideas and reasoning in science in the years to come, as well as on science teaching.

Notes

1. Paper presented at the X Reunioń de Enseñanza de la Física (REF X), in Mar del Plata, Argentina, October 27 to 31, 1997. Originally published in Spanish in *Caderno Catarinense de Ensino de Física*, Florianópolis, Brazil, 15: 107-120, 1998.
2. Judging from the results, this does not seem to be what happens in science education
3. In 1990, Johnson-Laird introduced the idea that mental models can include a few propositional representations to represent some properties or relations, thus, becoming analogic-symbolic representations. Barquero (op. cit.) states that this would change the models into bilingual representations, translators between analogical representations of a higher order (images) and the representations typically more symbolic (propositional representations).
4. This does not mean that mental models do not use external representations. For example, sometimes to think better, we draw. By the way, drawings might be used as raw data for the research on mental models.
5. At least at college level.
6. It should be so. Sometimes, however, what the students get, in the classroom, are just lists of definitions and formulae.

7. This conception about the Students' previous ideas, which derive from mental models, is similar to the one claimed by the approach of implicit theories of Pozo *et al*. (1992).
8. Psychological theories which are used in the research on science education did not deal with the mental imaging theme.

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