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The role of mental simulation in understanding and in creating scientific concepts.

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Abstract

This article offers an interpretation of scientific concepts' understanding in terms of mental simulation. A series of studies are reviewed, showing that mental simulation is a fundamental form of computation in the brain, underlying many cognitive skills such as mindreading, perception, memory, and language. Current investigations in cognitive neuroscience are then considered, that relate mental simulation with brain regions involved in episodic memory, future thinking and problem solving. The role of mental simulation in scientific thinking is described and a link is made with model-based reasoning in scientists and students. The simulation and linguistic systems are shown to be integrated and mutually reinforcing. The reviewed studies provide a set of ideas that are applied to science education. Finally, instructional design guidelines are proposed to facilitate the mental simulation-based process of concept understanding, together with a list of possible difficulties in concept comprehension and conceptual change.

Keywords: instructional science, mental models, mental simulation, scientific reasoning, model-based learning, model-based reasoning, concept learning, conceptual change, instructional design

1. Introduction

In science education, the learning goal is frequently that of enabling the student to understand the functioning of a given physical, chemical, biological, or socio-economic system. Most of the time, student don't interact directly with the system under study, but with a representation of the system, typically in the form of a teaching model, i.e. a model specially-constructed to aid the understanding of a scientific concept or process. In turn, students develop their own models to face the requests of the teacher. The way in which a model can be expressed by a person through action, speech, written description, and other material depictions has been recently investigated in a new approach in the sciences of learning, called "Model-Based Learning and Teaching" (Gilbert & Boulter, 1998; Gobert & Buckley, 2000). This approach focuses on mental models, i.e., the personal and private internal representation of a system formed by an individual either alone or in a group. Specifically, Buckley (2012a, 2012b) defined Model-Based Learning as the formation and subsequent development of mental models by a student, and Model-Based Teaching as instruction designed to support the development and evolution of students' mental models. In this perspective, the learning process can be viewed as a pathway, which leads from an initial model, based on student's preconceptions and intuitions, to a target model, that one wishes students to possess after instruction, through a succession of intermediate models (Clement, 2000; Seel, 2003).

One of the most significant influences in the development of Model-Based Learning and Teaching has been the recognition of the role of models in the formation of scientific theories and in scientific practice. Accordingly, Clement (1989, 2008) proposed a model-based account of the scientific process of hypothesis formation, based on a cyclical process of hypothesis generation, evaluation, and modification (or rejection), where hypotheses originate from analogies and models. In a similar vein, Nersessian (2008) defined "model-based reasoning" as a kind of reasoning in which inferences are made by means of creating models and manipulating, adapting, and evaluating them—conceiving this form of reasoning as an alternative to the classical logic-based account of scientific reasoning. Moreover, from a “cognitive-historical” perspective, she assumes that model-based reasoning is prevalent in periods of radical conceptual change, during which scientists cannot rely on time-consolidated theories (e.g., she describes how this type of reasoning process was used by Maxwell to derive his field equations for electromagnetic phenomena).

The role of mental models in the comprehension of scientific concepts has also been examined from the perspective of conceptual change research. Vosniadou and Brewer (1992) represented students’ knowledge in terms of mental models, in their studies of children’s concepts of the shape of the earth and of the day/night cycle. Chi (2000) also represented students’ knowledge in these terms, in her research on middle school students’ conceptions of the human circulatory system. These studies revealed that mental model modification is not a process students easily undertake on their own, even when faced with objectively cogent empirical evidence, but it requires a series of teaching interventions aimed at overcoming the resistances to conceptual change.

2. From mental models to mental simulation

The notion of mental model originated in the early ‘80s within two different approaches, respectively in the fields of cognitive psychology and Artificial Intelligence. The first approach focused on mental models viewed as a special kind of mental representation supporting speech comprehension and logical reasoning (Johnson-Laird, 1983). According to Johnson-Laird, mental models are structural analogues of the world: “they are analogies because structural relations between their elements correspond to the perceptible relations between the elements of the corresponding real-world objects” (ibid., p. 147). The approach in the field of Artificial Intelligence conceived mental models as being knowledge structures people use to understand specific knowledge domains (Gentner & Stevens, 1983). These two accounts also have different neuropsychological implications. In the first instance, mental models are considered to be temporary representations in working memory, which are “constructed at the moment” to make inferences or to solve problems, whereas in the second, they are thought to be structures in long-term memory. The two views don’t exclude each other: if mental models are to serve an integrative function between new and existing knowledge, they must combine both kinds of knowledge, based on a process of interplay between information processed in working memory and that stored in long-term memory.

What is the advantage of having a mental model of something? Kahneman and Tversky (1982) first noted that “There appear to be many situations in which questions about events are answered by an operation that resembles the running of a simulation model” (p. 201). Researchers in the field of mental models underscored that “it should be possible for people to ‘run’ their models mentally” (Norman, 1983, p. 12), and that “mental models often permit mental simulation: the sense of being able to run a mental model internally, so that one can observe how it will behave and what the outcome of the process will be” (Gentner, 2002, p. 9684). An analysis of the relation between mental models and simulation was provided by Rumelhart et al. (1986) in the context of Parallel Distributed Processing. In this approach, the cognitive system consists of two types of processing units: an interpretative system, which obtains input from the world and produces action, and a model of the world, which obtains the actions produced by the interpretative system as input and predicts the way the input should consequently change. As the authors stated: “Now, suppose that the world events did not happen. It would be possible to take the output of the mental model and replace the stimulus input from the world with input from our model of the world. In this case, we could expect that we could ‘run a mental simulation’ and imagine the events that would take place in the world when we performed a particular action. This mental model would allow us to perform actions entirely internally and to judge the consequences of our actions, interpret them, and draw conclusions based on them” (ibid., p. 42). However, the concept of mental simulation did not receive much attention in the subsequent years, until new theories and discoveries appeared in the late ‘90s, as described in the next section.

3. Mental simulation in cognitive science

In the Theory of Mind branch of cognitive science, mental simulation has been proposed as one of the mechanisms that possibly underlie people's ordinary capacity to refer to specific mental states (e.g. beliefs and desires), to understand and predict other peoples' thoughts, intentions, and emotions (Gordon, 1995; Goldman, 2006). For instance, to understand how John feels when he goes to school in the morning, we can imagine that we are John walking along the path he takes to school, and simulate the way he feels. From a neuroscientific perspective, Gallese and Goldman (1998) suggested that mirror neurons might represent the substratum of these simulation capacities.

The idea that many different cognitive abilities depend on the basic mechanism of simulation has gained particular attention in theories of "embodied cognition" (Gibbs, 2006a) and "grounded cognition" (Barsalou, 2008). The core idea of these theories is that cognition arises from the interaction of the brain with the body and with the rest of the world. From an embodied cognition perspective, several psycholinguistics studies (see Fischer & Zwaan, 2008, for a review) have examined the role of perceptual and motor simulation in language comprehension. Barsalou (1999) examined the idea of mental simulation as a solution for the grounding of conceptual and abstract mental representations[1]. In his definition: "Simulation is the re-enactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind" (2008, p. 618). In Barsalou's approach, simulation is considered a fundamental form of computation in the brain, underlying many cognitive skills such as perception, memory, language, and problem-solving.

Simulation has also been gaining ground in the area of Cognitive Linguistics, where it has been proposed as a comprehension mechanism for figurative language and conceptual metaphors. According to Gibbs (2006b), when people encounter abstract conceptual metaphors or metaphors concerning physically

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[1] Barsalou calls his approach grounded cognition, as he believes that the term "embodied" places too much emphasis on the role of the body in cognition, and that cognition can be grounded in many ways, including through simulation and situated actions, not only through body states.

impossible actions, they create mental simulations of their bodies performing the actions described in the metaphor. Embodied simulations such as these allow us to understand abstract entities as if they were concrete objects and to mentally act on them thereby.

All of the above mentioned theoretical accounts support the idea that simulations never completely recreate the original experience, but are always partial recreations and can therefore contain biases and errors. Moreover, simulations can be unconscious, as most frequently is the case, or conscious (as in mental imagination).

4. Mental simulation in neuroscience

The topic of mental simulation has recently emerged in the forefront of cognitive neuroscience. Various studies have focused on the possible correlation between mental simulation and activity in the Default Network (DN), a large-scale brain system that plays a key role in internally directed or self-generated thought (for recent reviews, see Buckner et al., 2008; Andrews-Hanna et al., 2014). Evidence has been found that the DN underlies cognitive abilities linked to mental simulation, such as autobiographical memory retrieval, envisioning the future, conceiving the perspectives of others. In particular, researchers hypothesized that the default mode network is involved in "constructing dynamic mental simulations based on personal past experiences such as used during remembering, thinking about the future, and generally when imagining alternative perspectives and scenarios to the present" (Buckner et al., 2008, p. 18).

In the cognitive neuroscience of memory, imagining ourselves in a possible future scenario is considered a kind of mental simulation that has come to be known as "episodic future thinking" or "episodic simulation" (Schacter et al., 2008)[2]. According to this strand of research, memory and imagination consist respectively

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[2] The term "episodic" refers to episodic memory, which is a memory system that receives and stores information about temporally dated episodes or events, and temporal-spatial relations among these events (Tulving, 1972). (Conversely, semantic memory is the organized knowledge a person possesses about the world, not tied to the particular time and place of learning.)

in the simulation of past and future events, and are strongly related with each other. In fact, many studies support the hypotesis that both remembering past experiences and imagining ourselves in a possible future scenario rely on a common network of brain regions, among which a key role is played by the hyppocampal regions (Mullally & Maguire, 2013) and the default network (Andrews-Hanna et al., 2014). Moreover, in the context of a neuroimaging study of problem solving, Gerlach et al. (2011) refer to “goal-directed simulations” as a class of mental simulations that requires higher-level cognitive skills to maintain information, make decisions, and plan action sequences, therefore involving the combined activation of the above mentioned hyppocampal regions and default network areas with regions associated with cognitive control and executive functions, such as the dorsolateral prefrontal cortex (dlPFC) and anterior cingulate cortex (ACC).

5. Mental simulation as reasoning strategy

A strand of cognitive research in which the concept of mental simulation has been also applied is that of “mechanical reasoning”—i.e., the mental representations people form to understand the functioning of simple mechanical systems starting from their description in the form of texts and diagrams. In particular, Hegarty (2004) reviewed the evidence that mental simulation is sometimes used in this kind of reasoning. She also underscored a key difference between visual imagery and mental simulation, by stating that visual imagery is based on the holistic inspection of a mental image of the moving system, and that mental simulation is conversely based on:

- the piecemeal simulation of the events;
- non-visible properties (e.g., force or density);
- the representation of the associated motor actions.

It is important to note Schwartz and Black’s (1996) findings, however, that participants knowing verbal rules to infer a movement rely on these rather than on simulation, so as to solve problems more quickly. The two researchers proposed, in fact, that people use mental simulation in novel situations for which they have no rule available or when their rules are inadequate, and that, vice versa, they rely on the application of verbal rules (e.g., the "parity rule" for determining the motions of linked gears in a mechanical system, which states that "if there are an odd number of gears connected, then the first will go in the same direction as the last").

6. Simulative modeling in science

Recent studies on the ways in which scientific inquiry is practically carried out have yielded evidence that scientists use cognitive processes akin to mental simulation to generate hypotheses (Clement, 2008), create novel concepts (Nersessian, 2008), and to interpret data in complex knowledge domains (Trickett & Trafton, 2007). Clement investigated the activation of analogies and models in the formation of scientific hypotheses, by examining the mental processes of individuals involved in creative problem-solving tasks. Specifically, he conducted a series of experiments based on the protocol analysis method—i.e., by eliciting verbal reports from the participants. The subsequent analysis of the participants' thinking-aloud protocols allowed him to develop the idea that the mental processes involved in the construction of a model are examples of nonformal reasoning. To provide an explanation of the cognitive mechanisms underlying these processes, Clement (2008) closely examined the role of *imagery,* which he defined as "a mental process that involves part of the perceptual/motor systems and produces an experience that resembles the experience of actually perceiving or acting on an object or an event" (ibid., p. 205). A related concept is that of *imagistic simulations,* which consists in processes involving imagining a situation that changes with time to generate predictions of changes or movements.

According to Nersessian (2008), model-based reasoning can occur in three forms: *analogical modeling, visual modeling,* and *simulative modeling,* where the latter is defined as a form of reasoning in which inferences are drawn by employing knowledge embedded in the constraints of a mental model to produce new states of the model.

Another similar line of research is that of Trickett and Trafton (2007), who examined the topic of scientific reasoning in the context of scientific visualization research. They focused on the mental operations scientists perform while examining external scientific visualizations, e.g., weather forecasters examining visualizations of atmospheric data, astronomers analyzing the optical and radio data of a galaxy, physicists evaluating the match between a computational model and empirical data. The two authors then described these mental operations in terms of *conceptual simulations*, which they characterized as sequences of dynamic mental images. They stated that experts most frequently use these simulations when evaluating hypotheses and under situations of informational uncertainty, i.e., when the available data are unclear or anomalous.

Mental simulation can be also compared to scientists' "thought experiments", that consist in visualizing some situation, carrying out one or more mental operations on it, seeing what happens, and drawing a conclusion (Brown & Fehige, 2011). More generally, it can be related to the notion of "scientific imagination", as studied in the history and philosophy of science. Holton (1978) pioneered the study of scientific imagination by investigating its role in the formation of new theories, drawing on case studies from the life of famous scientists. Along the same lines, Miller (1986) analysed the role of mental imagery in scientific thought. In these and similar studies, the emphasis on imagination might be considered a way to balance the widely held belief that science is essentially an empirical-inductive enterprise, as outlined by the standard view of the scientific method and frequently presented to students in science textbooks.

7. Mental simulation and language

If mental simulation is actually based on perceptual and motor processes and is therefore fundamentally analogical, what then is its relation to language, which is conversely based on conventional symbols and rules? The empirical evidence accumulating over the years has demonstrated the close link that exists between the mental simulation and linguistic systems. This link is particularly evident in experiments (reviewed in Barsalou, 2008) showing that *language can activate* *mental simulations*; for example, to represent the meaning of sentences, readers can construct mental models with spatial properties and can simulate the situation described in texts. These experiments have also shown that *simulations can activate language*. For example, people involved in problem-solving tasks frequently activate associated words and syntactic structures to verbalize the solution process, so as to plan their actions and/or to share them with others. Thus, in attempting to understand mental processes it is important to highlight the interaction between the simulation and linguistic systems.

In fact, to account for the richness and complexity of the two systems' interactions, Barsalou (2008b) proposed that symbolic operations result not from simulation alone, but also from language-simulation interactions. He specifically stated that "symbolic capabilities could have increased dramatically once language evolved to control the simulation system in humans. Adding language increased the ability of the simulation system to represent non-present situations (past, future, counterfactual). Adding language increased the ability to reference introspective states, thereby increasing the ability to represent abstract concepts and perform metacognition. Adding language increased the ability to coordinate simulations between agents, yielding more powerful forms of social organization." (ibid. pp. 36-37).

The Language and Situated Simulation (LASS) theory of conceptual processing (Barsalou et al., 2008) proposes a mechanism dedicated to the interaction between simulation and language. The theory proposes that the linguistic system and the simulation system both initially become active, but that word activation peaks before simulation activation. If the linguistic forms generated as inferences thereby suffice to produce accurate performance, there is no need for executive processes to shift attention to the simulation system as an alternative information source. When the linguistic system conversely stops being useful, simulation will begin to dominate conscious, deliberate cognition. In LASS theory, linguistic system and simulation system activation are respectively associated with superficial verbal processing and deep conceptual processing. For everyday decision making processes and planning and problem solving tasks, the theory posits a complex series of interactions among the two systems, during which they are simultaneously activated at many points in time, and do so in varying proportions. The two levels of processing described in LASS theory can be linked to Schwartz and Black's (1996) observations on the use of mental simulation in mechanical reasoning (see Section).

Other theoretical frameworks similar to LASS, which propose that peak activation of the linguistic system is reached before peak activation of the simulation system, are Louwerse and Jeuniaux's (2010) Symbol Interdependency Hypothesis and Lynott and Connell's (2010) Embodied Conceptual Combination (ECCo) model. The findings from all of these studies strongly suggest that the simulation and linguistic systems are tightly integrated and mutually reinforcing. Their relation is therefore complementary and dynamic.

8. From mental simulation to embodied instruction

This section begins with a review of some researches attempting to make a bridge between mental simulation and science education research. A proposal will then be made for integrating mental simulation in an embodied instruction framework aimed at facilitating the comprehension of scientific concepts.

The premise that the cognitive processes students activate to understand novel scientific concepts are similar or equivalent to those involved in the construction of a model by scientists and experts, led to a series of studies conducted by Stephens and Clement (2006, 2009, 2012), on the role of nonformal reasoning and in particular, imagery and mental experiments, in science instruction. Clement (2008) closely examined the link between classroom learning and scientific thinking and found that students achieve deeper understanding of subject matter when using the same nonformal reasoning processes used by scientists and experts in their problem solving activities.

However relevant mental simulation might be for reasoning, solving problems, and learning, it shows clear limits, the most important being that it relies on qualitative rather than quantitative relations. Researchers in the field of Systems

Dynamics have frequently highlighted the limits of mental simulation in reliably reproducing the behavior of system characterized by the mutual interaction of many elements, information feedback, and circular causality. Forrester (1968) described these limits as follows: “The human mind is well adapted to building and using models that relate objects in space. Also, the mind is excellent at manipulating models that associate words and ideas. But the unaided human mind, when confronted with modern social and technological systems, is not adequate for constructing and interpreting dynamic models that represent changes through time in complex systems.” (p. 3-2). Where the situations are more distant from sensorial experience there are fewer guarantees that the simulation process will yield success. This is particularly evident in the case of self-organizing systems, where even very simple rules can determine complex and unforeseeable behaviors. Only computer-based simulation manages to show these behaviors, sometimes counter-intuitive or unexpected also for those who built the simulation model.

Landriscina (2012, 2013) examined the relation between mental simulation and computer-based simulation, with the aim of identifying the similarities and differences between these two types of simulation, how do they interact, and how can they be integrated to enhance learning. He noted that, given the right conditions, simulation models can extend our biological capacity to carry out mental simulations and simulative reasoning. Computer simulation can thus support and enhance mental simulation. In particular, a form of cognitive partnering can be set up between student and simulation, where the mental and the computational models modify each other in real time, a circular interaction thanks to which the computer can become a proper “tool for thinking”.

The comprehension of scientific concepts can be examined at different levels of analysis. Traditionally, it has mostly been identified with the ability to recognize the instances of a concept, and to differentiate it from other similar concepts. From a teaching perspective, this view corresponds to the technique of giving students a concept’s name, definition, and (positive and negative) examples. An additional level of complexity is that of representing relations among concepts, as in the concept map method. Although concept maps might be an effective way for students to represent and organize knowledge, they do not allow, by themselves, the meaning of a given concept to be grounded in sensorimotor experience. For instance, students will unlikely learn the concept of magnetism exclusively by knowing its relations with other concepts and without having first-hand experience of, or having imagined the effect, of a magnetic field. Thus, a third level of concept understanding is required, i.e., that of mental simulation, which is based on sensorimotor experience and structured by language.

In this perspective, understanding a concept entails the ability to:

1. construct an adequate mental model of the concept and run the corresponding mental simulations;
2. linguistically express the content of mental simulation;
3. compare the outcomes of mental simulation with empirical evidence.

To facilitate the mental simulation-based process of concept understanding, the following instructional design guidelines are proposed:

1. identify the experiential and verbal input that can be associated with the concept's comprehension.
2. imagine the possible mental simulations underlying this input.
3. devise and design instructional activities that can facilitate mental simulation of the concept.

Landriscina (2013, pp. 199-202) provided a use example of these guidelines for teaching the concept of *temperature field*—a thermal physics concept which is required to understand the phenomenon of point-to-point temperature variation in a body.

According to the Model-Based Learning and Teaching framework (see Section 1), learning occurs by comparing the expected results of mental simulation with the observed consequences. In the case of gaps between expectations and observations, the outcomes are used to update or revise the mental model. From this perspective, mental simulation can facilitate students' learning paths, and is particularly effective when learning goals require the restructuring of students' mental models, as in the instance of conceptual change. However, one should not underestimate the difficulties students might encounter in the process of building, simulating and updating (or changing) their own mental models of the system under study.

In particular, any difficulties in concept comprehension and conceptual change frequently pertain to:

- lack of domain-specific knowledge (essential for constructing and simulating an adequate mental model);
- difficulty in grounding the new knowledge in an embodied sensorimotor experience;
- difficulty in comparing the outcomes of mental simulation with contrary empirical evidence;
- high extraneous cognitive load (which exceeds the available working memory capacity)[3].

The latter point take on special relevance in that mental simulation is a cognitive process which is typically characterized by a high number of interacting elements requiring simultaneous processing in working memory. This frequently occurs when students must mentally integrate multiple and dynamically changing representations of information, while carrying out complex tasks, such as testing hypotheses or exploring alternative courses of action. Therefore, students will not automatically allocate the resources they have available in working memory to constructing and simulating the mental models required for learning. A relation

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[3] Cognitive load is defined as the total quantity of activity imposed on in working memory at a given moment. Intuitively, cognitive load corresponds to learner-perceived mental effort and therefore, to the subjective difficulty of a learning task.

can be made with Kahneman's two modes of thought, namely *System 1*, that operates automatically and quickly—with litte or no effort—and *System 2*, that allocates attention to the effortful mental activities that demand it—including complex computations like those occurring in mental simulation (Kahneman, 2013).

As a general guideline, one should consider that students are more likely to use mental simulation:

1. in novel situations for which they have no rule available or when their rules are inadequate;
2. when the learning task requires that a specific analogy or metaphor be used for inferences.

These situations are cognitively analogous to those scientists face in periods of radical conceptual change and/or when the available data are unclear or anomalous (see Section 6).

Conclusion

By looking more carefully at the many ways the notion of mental simulation is used in scientific literature, one may note that this cognitive ability is not that different from the human faculty commonly termed "imagination". Actually, one has the impression that terms such as "mental imagery", "imagistic simulations" and "mental simulation" have been devised as more scientifically respectable versions of the term imagination. This may be due to the fact that the etymology of the word imagination (lat. "imaginationem") shows that it could also mean *hallucination*, or *fantasy*, and therefore has a negative connotation. This negative connotation can hark back to Plato's scepticism towards the senses, and his conception of the “μίμησις” (*mimesis*, Greek term for *imitation*) as the imperfect copy or fictitious replica of reality. On the contrary, according to Aristotle imitation is a means to know nature through representations which can be valid and acceptable. In fact, Aristotle introduced the cognitive faculty of “φαηντασία” (*phantasia)* as the necessary intermediary between the senses (particularly vision) and the intellect. Also Plotinus speaks of phantasia as a faculty which is essential for the attainment of intellectual, even divine, knowledge—an idea shared by the Neoplatonists. The faculty of imagination has been also highly valued in the the classical period of Arabic philosophy, and in the Renaissance philosophy of Marsilio Ficino and Giordano Bruno. At the turn of the seventeenth century, imagination was a crucial concept for the understanding of marvellous phenomena, divination and magic in general. However, with the affirmation of the quantitative paradigm in natural philosophy the role of imagination has been relegated to the realm of subjective phenomena, such as dreams and the arts.

As a conclusion of this article, the idea is proposed that mental simulation has many correspondences with the notion of imagination as intended in ancient philosophy and in the Renaissance. Along these lines, *scientific imagination* can be defined as *the disciplined and informed use of mental simulation for envisioning a system’s behaviors and drawing testable inferences.*

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