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The Implications of Cognitive Science for the Significance of Experimentation in Science Teaching

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Abstract

In this paper we argue for a new role for experiment in science teaching and learning. Our proposition is based on the conception of experiment as an active ingredient of theory construction and not as an mere tool for theory testing. This latter view is based on the classical conception of the mind-world interaction, according to which human action purports to test the validity of a tentative solution to a problem and follows after mental processing. We present the new framework that views the interactions with the environment as active ingredients of the mind's problem solving activity. We also adduce evidence for this new role of experiment from the history of science. Finally, we discuss the repercussions of this view of cognition, as the activity of a mind-environment inseparable whole for the role of experiment in knowledge construction.

Introduction

Experimentation was traditionally deemed to be the main prerequisite for the successful teaching of physical sciences in school, mainly because the experiment was construed as a means of confirmation of theories. As such, it could persuade the student about the adequacy of the theory presented in class and lead her to embrace it. This construal of experiment was based on the thesis that experiment follows theory with a view to testing it empirically (which was the prevalent view in philosophy of science until the 1960's).

This conception about the role of experiment in science, first, and education, later, was subsequently criticized on philosophical, psychological, and educational grounds. The main argument against the standard conception of the experiment was that:

(a) the student has formed a well established body of beliefs, intuitive theories, or phenomenological primitives (diSessa, 1993) about the world before she attends school, which constitutes an alternative, well entrenched, theory to those taught in class (psychological critique);

(b) the knowledge that the student brings to a given learning situation influences the meaning that she constructs in that situation;

(c) experiments are not sufficient to establish the adequacy of theoretical ideas, since by themselves they do not constitute the basic criterion of choice among alternative theories (philosophical critique).

Therefore, experiments should abdicate their decisive role in science education, since even if the student actively participated in their making, they do not suffice to allow her to build the required concepts and to persuade her to abandon her intuitive theories. To demonstrate this point further, one could cite extensive research showing the failure of instruction with regard to classical physics.

In this paper we will briefly present the theoretical framework that led to the dispute about the role of experiment in education. We will argue that this framework is based on an erroneous conception of the role of experiment in problem solving, and *a fortiori* in science. We will claim that this error is based on the classical conception of the mind-world interaction in cognitive science and we will present the new framework emerging in cognitive science that views the interactions with the environment and experimentation not as a follow up of the mind's output purporting to test the validity of a tentative solution to a problem, but as an active ingredient of the mind's problem solving activity, that extend mind beyond its biological boundaries to the world (Clark, 1997). We will also adduce evidence for this new role of experiment from the history of science. Finally, we will discuss the repercussions of this view of cognition as the activity of a mind-environment inseparable whole for the role of experiment in knowledge construction and we will argue for the importance of experiment not as a test of theory only but as an integral part of theory construction.

1. Undermining the Role of the Experiment: An Overview

Logical positivism, the main philosophical paradigm during the first half of the 20th century conceived of experiment as a scientific activity that follows the theoretical, or mental, processing of raw data aiming to provide empirical testing of scientific theories. Hanson (1958), Kuhn (1962), Gregory (1973) , Lakatos (1978) and others criticized this classical conception of science. They outlined the non linear and non cumulative character of the scientific enterprise, a conception that undermined the role of experience and of the experiment in the rationalistic choice among competing theories. In this context, the realization that experience is always interpreted through the lenses of a theoretical framework, led, on one hand, to diminishing the importance of the experiment as a means of theory testing, and on the other hand, to the marking out of the role of theory as the framework within which empirical data are interpreted.

This crisis regarding the role of experiment could not bypass the experiment as an instructional medium. The tendency towards criticizing experiment was strengthened in the early 1970's by the findings of psychologists (Carey, 1985, 1992; Chi, 1992; Karmiloff-Smith, 1992; Medin, 1983; Nersessian and Resnick, 1989; Rosch, 1978; Spelke, 1990) that a child's mind is no tabula rasa upon which the educator is called to imprint the acceptable scientific theories included in the curriculum by proving them experimentally. On the contrary, children have innately acquired, or constructed very early on the basis of some innate constraints, a set of persistent beliefs about the world (intuitive or naive theories).

Seen in this context, the experiment loses its function as the means par excellence of testing and proving theories, since the child has already an intuitive conceptual background from which she can formulate various interpretations of the experimental results that are not compatible with those interpretations that the instructor seemingly wishes the student to acquire. Thus, the mere presentation of, or participation in conducting, experiments does not suffice to prompt the student to accept the intended interpretations.

Leaving aside the issue of whether this set of beliefs constitute a theory, or merely a body of incompatible principles, one notes that even though they contain principles that allow children to make personal sense of their world-experience, they generally deviate from established scientific theories (Carey, 1985; Clement, 1982, 1983; Halloun and Hestenes, 1985; McCloskey, 1983; Nersessian and Resnick 1989; Viennot, 1979). These persistent ideas are epistemological obstacles that instruction must guide students to overcome, if it is to be effective. These obstacles are not merely erroneous pieces of knowledge about the world that the child could easily be persuaded to reject. Since they constitute the schemata on the basis of which she has come to interpret the world, they function as organizing principles. All experiences are made meaningful on the basis of these principles, and as a result, they are the least likely items to be put under experimental inquiry (Quine, 1961).

The criticism of experiment and of its role in science education was reinforced by the well established failure of traditional instruction of, say, Newtonian physics.

This intense criticism of experiment was accompanied by the realization of the need to complement instruction by exposing students in a systematic way to their own intuitive theories and guiding them to compare them explicitly and in detail with current scientific theories. The aim was to make students conscious of the implicit principles that they use to organize and understand the world, to render clear the points at which their intuitive theories are in conflict with the acceptable scientific theories, to make them realize that the latter are more adequate in explaining the world, and finally to lead them to construct the salient concepts of established scientific theories.

Theory becomes, thus, predominant in science education, while experiment loses some of its shine. This criticism of experiment does not imply of course the abandonment of experiments as educational means. It simply points out that experiments by themselves, without the presentation and discussion of the appropriate theoretical background, are no panacea for proper instruction in the natural sciences.

The educational paradigm that emerged in this new framework continued to conceive of the experiment as a follow-up to theory, a discrete step in the scientific enterprise of theory construction, whose role is the empirical testing of theory. Once this empirical testing is put in doubt, experiment automatically loses its appeal. In that regard, this new paradigm does not differ from the one it superseded.

This classical conception of the experiment is based on the belief that all cognizers (and *a fortiori* scientists) when engaged in a problem solving activity function according to the scheme: reception of external input (the data of the problem), mental processing of the internal representations of these data to figure out a solution (problem processing that consists in a search of the problem space) and, finally, output of a tentative solution to the problem that is tested for empirical adequacy and for compatibility with a body of accepted knowledge. This is the well known <input → mental processing → output> scheme of classical cognitivism, which in the case of scientific problem solving becomes the well known positivist scheme <experience → mental formal processing → experiment>.

2. A new Role for Experiment: Its Cognitive Background

The classical view of the interaction between cognizers and their environment, and therefore the classical view of experiment in everyday problem-solving and the scientific enterprise is severely questioned by some new tendencies in cognitive science and by the research findings in the history of science. Some cognitive scientists (Bickhard, 1993, 1998; Clark, 1993, 1997; Clark and Thornton, 1997; Elman, 1991; Hutchins, 1995; Rutkowska, 1993, Varela, et. al., 1993) on the one hand hold a different view for the cognizer-environment, and thus the theory-experiment, interaction, which radically revises the relation between the mind and the world. Research in the history of science (Franklin, 1986; Gooding et. al. 1989; Gooding, 1990; Hacking, 1983; Nersessian, 1984), on the other hand, reveals that the experiment plays a much richer role than merely being a test of empirical adequacy of scientific theories.

According to the new conception of cognition, the mind does not function autonomously from the environment, in the sense that its relation with it does not consist simply in passively receiving input from it, and eventually processing it in its effort to find a solution to a certain problem. Instead, the strategies of mind include actions upon the world as an integral part of its problem-solving activity (Clark 1997), and, one might add, as a part of theory construction. This active intervention of the mind may transform the problem space, affecting the problem-solving process itself.

This can be done in various ways. First, the intervention upon the world may bring into light new data that could transform the problem-space, rendering its search more effective or even possible. Our action, for instance, might reveal some regularities that shed new light upon the existing data allowing perhaps their re-categorization, opening thereby new research avenues. Or, this same action may reveal some structural similarities , that were not lying in the surface structure of the problem-space, which allow the conceptual redeployment from another different field on to the given problem.

Second, the active intervention upon the environment may scaffold it so that the problem-space is structured in such a way that its effective search could be conducted, even allowing for the limited cognitive, perceptual and motor resources of the cognizer (Clark, 1997; Elman, 1991; Raftopoulos, 1997).

All these are ways of reducing, what Clark and Thornton (1997) have called, type-2 difficult problems, (i.e., problems whose statistical regularities do not lie on their surface structures but in their deep structure), to type-1 problems that wear their statistical regularities on their sleeves, and thus can be effectively solved by means of inductive heuristics.

The intervention on the environment, viewed as a part of theory construction, allows one to make sense of what it means to say that the learning process itself induces changes in the structures involved in learning. One way to understand this claim is to say that the neural substrate undergoes changes while it learns, as a result of this learning (Quartz and Sejnowski, 1997). Another way, is to interpret this statement to mean that the learning process changes the representational basis in which the search of the problem space takes place and this change influences this learning.

The active role of the mind and its action upon the environment results in the construction of new representations (either external or internal). This offers an alternative to the classical picture of learning as a search within a defined representational problem space (the problem of selective induction.) The cognizer builds representations as she learns, and thus shapes the hypothesis-space. Since learning depends crucially on the statistical regularities of the problem input and the structural characteristics of the learner, the structure of the training data (and thereby the structure of the problem domain from which these data are drawn) and the processing characteristics of the learner shape the hypothesis space to their constraints and requirements.

Learning, thus, need not be an inductive search through a hypothesis space delineated by fixed representations that restricts search to solutions that can be expressed only by means of the pre-existing representations, in so far as new representations can be built during learning. The result is that processing strategies and representations co-evolve (Clark, 1993; Horgan and Tienson, 1996).

In this sense the result of our action upon the environment does not consist simply in testing a tentative solution to a given problem, and herein lies the fallacy of cognitivism's view of the mind, but in an active intervention upon the environment with a view to discovering new data and building new representations that might help the mind in solving the problem. This action becomes an active ingredient of the problem-solving process, and in the case of the scientific activity, an active ingredient of theory construction.

Schunn and Klahr (1995) offer a computational account of problem solving seen as a search in four problem spaces. These are the *data representation space* (from which representations of the salient data are chosen), the *hypothesis space* (in which hypotheses about causal relations amongst the data are drawn), the *experimental paradigm space* (the classes of experiments relevant to the problem at hand are chosen), and the *experiment space* (in which the values of the parameters within the selected paradigm are chosen). Though we do not have the space here to discuss this model in detail here, one can safely say that the upshot of the model is that the solution of a problem involves a constant flow of information among the four spaces. As a result, the processing within each space depends crucially upon the state of the research in the other spaces. This model shows clearly what it means to say that the learning process itself induces changes in the structures involved in learning, that new kinds of representations are developed which affect the search of the hypothesis space and so forth.

Our world is not merely a place in which we can store information and the testing ground of our theories and tentative solutions, although it certainly functions this way as well. It is also, and perhaps predominantly, the space upon which we act by transforming it and by building external representations so that it becomes an aid to the mind. Understanding the mind presupposes the rejection of the conception of the mind as isolated from the world building internal representations and models and processing them to discover solutions to problems (Rutowska, 1993). This view must be replaced by a mind situated in the world that uses it to facilitate its work and which shows that "the real power of human cognition lies in our ability to construct functional systems that accomplish our goals." (Hutchins 1995, 316).

This movement in cognitive space helps explain, and thus is being strengthened by, findings in the history of science that show that the experiment plays a much richer role in the scientific enterprise than being a mere test of empirical adequacy. The study of the actual processes of theory construction, based either on the notebooks and letters of scientists (Newton or Faraday, for instance) or on the in-situ observation of the workings of a research team renders clear that the experiments transcend the theory in the context of which they are first conceived. They acquire their own autonomy, they become themselves objects of inquiry independently of the theory and they are used not just to test the theory but also to discover new evidence that would facilitate the theoretical enterprise. They accomplish this either by revealing structural similarities with other domains, allowing thus conceptual redeployment, or by bringing forth certain basic regularities that reorganize the existing data, transform the problem space and, thereby, allow the discovery of the hidden structure. They also actively participate in the construction of the (partial) meaning of the theoretical terms of the theory.

Discussion: A New Educational Role for the Experiment

We have seen that, according to cognitivism, the cognizer receives environmental input, builds internal representations and models of the world-situation pertaining to the problem, processes these representations and produces, as output, a tentative solution to the problem. The view of cognition that emerges from our discussion is entirely different. The cognizer is not a passive processor of information from the environment. She acts upon the environment, discovers new data that transforms the problem-space and diminishes the cognitive load of the problem. Hence, the problem space and the opportunities it offers for exploitation become an inseparable part of the problem-solving activity. Thus, the mind transcends its biological boundaries and extends itself to the world. This means, in return, that the well arranged triplet <input-processing-output> cedes its place to an action loop, that is, an interaction in which thought leads to actions which in turn change or simplify the problems confronting thought (Clark 1997). The continuous interaction between mind and environment becomes so intricate and complex that it is difficult to talk of two distinct factors that interact and is better to conceive them as forming an inseparable whole, which gives rise to cognition.

Learning in the physical sciences constitutes the development of a coherent conceptual framework that consists of a network of conceptual models within which mental models are constantly re-negotiated in dynamic interaction with the framework. Conceptual models are robust mental constructs that can be developed through appropriate instructional intervention. In effective learning environments, both mental and conceptual models are processed and manipulated consciously and explicitly by the learner.

In the context of our discussion, learning in science emerges as a process of elaboration of mental models through dynamic interaction between mind and environment. In this interaction, experiment as well as logical argumentation and syllogism both contribute in a dynamic and integral manner to the constructive process.

This view of the experiment has important implications for current classroom interpretations of the constructivist paradigm. Constructivism has attracted a lot of attention in science over recent years partly as the overarching framework underpinning active and collaborative learning. Constructivist classroom strategies invariably seek to facilitate learning outcomes by taking the students through a cycle of stages including formulation of ideas, cognitive conflict, knowledge re-organisation and extension. However, the assumptions that underlie the development and implementation of such constructivist strategies are at odds with the framework that we have presented here.

Before we go on to discuss this, we need to elaborate on two issues. Firstly, the conceptual models whose construction is the objective of effective science learning environments are not necessarily identical with established scientific theory. Learning is the outcome of individual construction of meaning even when that happens in a collaborative environment. Research in science education has repeatedly demonstrated that instructional approaches that rely on a knowledge transmissive model of teaching lead to rote memorization rather than real learning. Examples include rote applications of Ohm's law without fundamental understanding of the current model for electric circuits (McDermott and Shaffer, 1992), calculation of image magnification without basic understanding of geometrical optics (Wosilait et al., 1998) and rote application of the work-energy theorem without the basic realization that work is done by one body on another (O'Brien et al., 1998). It would appear that any effort to transmit knowledge to a group of learners does not usually result in effective construction of meaning.

Second, conceptual models are not in one to one correspondence with the phenomena they seek to model. The learning outcome in science is a series of mental constructs that seek to code and process specific aspects of the behavior of physical phenomena. For the individual learner, both the science discipline and the conceptual models should be aligned with the physical world in the way that this is observed and coded by the learner's mental processes. In other words, both the outcome of research (a socio-cultural construct by a community of researchers) and the outcome of learning (a cognitive construct of the learner) cannot be conceived as a mental reflection of physical reality but only as mental constructs that aid us in systematically pursuing this interaction between mind and matter. For instance, the theory of the Big Bang does not describe the birth of the Universe as we currently know it; rather it seeks to describe the birth of the Universe had an observer been there to observe what happened, for Physics and other sciences are constrained to formulate questions, hypotheses and theories that are epistemologically compatible with the mind-environment interaction that is inherent in their development.

In view of these, the experiment in natural sciences plays a more fundamental and complex role than was traditionally thought. It is not just a means for testing and confirming a theory (as was conceived and implemented by traditional instruction with the laboratory as a supplement to the theoretical lecture-based transmission of the knowledge to be learned), or a means of choosing among conflicting predictions and alternative theories (as is conceived by the modern proponents of the constructivist model in education). In view of the fact that learning is a process of mental construction, and as such the product of the interaction of the mind with the physical world, the experiment provides the means of this interaction and implements it by enabling the construction of meaning.

Inquiry-based approaches to teaching science are closer to this reconceived formulation of the role of experiment in the construction of meaning. In particular, the implementation of inquiry developed by the Physics Education Group at the University of Washington (McDermott, 1996) seeks to familiarize students with the process of using experimental evidence as a medium for recognizing the need of new concepts, constructing operational definitions of useful quantities and using those and the experimental evidence to synthesize models that are, in their turn, continuously open to validation and constant reformulation in the light of new evidence.

To demonstrate the way experimenting can influence the mental representation, it would be useful to present an example from electric circuits. In *Physics by Inquiry*, students initially explore how they might be able to light a bulb with a single wire and a battery. At this stage, post-test data indicate that students have one of several models concerning the underlying cause. Although most often they give the name current flow to their models, they tend to describe flow models that begin at one point and end at another, or alternatively are unidirectional, always running from the battery to the light bulb, or even more commonly involving current consumption along the way. In subsequent experiments they short-circuit a battery with a bare wire and make the observation that both the battery and the wire get warm, and that all points of the wire at some distance from the battery get equally warm simultaneously. All three of these observations contradict different aspects of their initial models. When the issue is raised of what flow model might account for these observations, students have to tackle specific aspects of their initial model one by one until they arrive at a more valid representation of current flow. In the process they have to go back and forth between their observations and their model every time improving on both. The emerging representation is aligned with continuous flow that upon closure of the switch starts instantaneously at all points of the circuit and uniformly cover all parts of the circuit. Once students have developed a model for electric current, they can then use it to make predictions of the relative brightness of light bulbs in fairly complex circuits.

In the context of the interaction between mind and environment, the experiment accomplishes various essential functions. Firstly, the experiment determines which aspects of a hypothesis or working theory are valid or in need of reformulation. The experiment also enables us to identify interacting variables and, via the confirmation of hypotheses, plays a substantial role in the construction of theory. Second, the degree to which the learning outcome is correct is not determined by the extent to which the outcome and hence the student ideas overlap with current scientific thinking. Rather this is determined by the experiments that are accessible to the learner up to the time that instruction takes place. The degree of correctness and of the validity of the learning outcome is determined by the epistemological basis of the experimental process that led to the construction of meaning. Real learning is a result of logical argumentation that feeds on experimental data.

This last point is in stark contrast to current innovative approaches that seek to implement the constructivist paradigm by shifting the student conceptions from the naïve to the established through cognitive conflict and knowledge reconstruction events. The experiment cannot be conceived as an instructional means of shifting student conceptions or as a means of embedding theoretical knowledge. The experiment is a viable tool in the science classroom, a tool that is continuously used in the construction of a coherent conceptual framework and guides subsequent theory development and evaluation by mediating the interaction between mind and matter that extends the boundaries of our cognition beyond the biological confines of the brain.

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