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COMMENTARY

Conceptual Change, Crucial Experiments and Auxiliary Hypotheses. A Theoretical Contribution

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Abstract Theories about conceptual change have been generally related to historical and philosophical analysis of science. Yet, there is still much debate on how ideas coming from the history of science and their implications can be applied in this field. Our study intends to investigate the complex structure of conceptual change, by making use of some particularly representative features of the History and Philosophy of science, while considering the structure of so-called crucial experiments and the specific role of implicit hypotheses. Due to their historical importance and logical reasoning aspects, examining these issues may contribute to understand how conceptual change may take place.

Keywords Conceptual change · Epistemology · Philosophy of science · History of science · Crucial experiments

Introduction

The study of conceptual change is one of the core topics in cognitive research (Limón and Mason 2002; Nersessian 2008; Schnotz et al. 1999; Sinatra and Pintrich 2003; Vosniadou 2008). The Philosophy of Science—particularly Kuhn's work (1970)—has exerted great influence on the development of these studies. In fact, one of the first models of conceptual change (Posner et al. 1982) was based on this author's contribution, and thenceforth researchers have given this influence a preferential attention, both from theoretical (Arabatzis and Kindi 2008) and applied

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perspectives. This kind of attention to this classic author started some decades ago and it is still alive and influential (Vosniadou et al. 2007). In this sense, this paper shall make a contribution in the context of this renovated interest on the relation and mutual contribution of classical analysis of Philosophy and History of Science and the theories of conceptual change, based on the work of Kuhn, Laudan, Lakatos and related authors. An essential problem in the study of change in theories throughout history is how scientists substitute a particular theory for another. In this sense, it is fundamental to establish how individuals carry out this process, regarding the theories at their disposal. Some influential analyses of these processes have pinpointed the difficulties subjects face in changing their theories, even when they encounter strong anomalous data. To this respect, Laudan (1977) has showed how scientists can simultaneously operate with two theories, and that anomalies can be explained within the context of one theory but not within the other. This author, upholds that scientific inquiry seeks to solve problems, regardless of the truth or falsity of theories, and efficacy in the solution of problems is the only important thing. Thus, the problem of anomalies now days continues being an essential issue on the use of scientific theories. For example, one of us has studied the problem of how some anomalies in Einstein's General Relativity Theory may be treated in alternative theories (Levinas and Umerez 2000). Chinn and Brewer (1993; see also Pozo and Carretero 1994) have classified seven types of responses to anomalous data, amongst which only the most advanced, entailing a change of theory, may produce change. But, how can one arrive to adopt this type of response and to effect change toward a new theory? It has been argued that cognitive conflict is not enough to generate the change, because on the one hand, it can be solved simply producing a defensive answer, and on the other hand, cognitive conflict in itself does not provide the subject with new elements of the new theory. It simply shows that the old theory does not work (Limón 2001; Limón and Carretero 1999). Anyway, starting with Kuhn, it has been acknowledged that a new theory is not imposed upon the previous one because it is more satisfactory—which implies that empirical data cannot decide by themselves between the two theories—, but rather, because based on very complex mechanisms, consensus is attained around the consideration that the new theory offers adequate answers when its hypotheses are confronted. In this way, the two theories, the new and the old, are often revealed as mutually competing and thus excluding, for they refer to concepts that have been modified, often quite drastically. In this respect, it is very important to consider the role played by crucial experiments, since these allow for comparing two rival theories.

Now, such experiments imply accepting a new theory for their interpretation; yet this theory is paradoxically based on the interpretation of the results of that kind of experiments. Consequently, according to Lakatos (1971), crucial experiments were never considered really crucial when they were conducted for the first time; their acknowledgment as crucial came later, when they were explained in the light of a new, already accepted theory.

The crucial experiment's legitimacy depends on the understanding of data and the theoretical context where the experience is interpreted (Cassini and Levinas 2005). In Cassini and Levinas (2009) we show how, for example, Einstein produced a drastic change in the concept of ether. Firstly, in the context of the Special Relativity theory he considered ether superfluous, unnecessary and even nonexistent. But, on the contrary, in the context of the General Relativity theory, he claimed its existence if some changes in the meaning of the concept were accepted. Interestingly enough this is something that has not been widely considered (see for example Einstein and Infeld 1938, 159–160).

Consequently, the interpretation of these experiments depends on the use of principles and hypotheses. In this respect, it is very important to keep in mind that not all hypotheses used in a new theory appear explicitly. In many cases, the identification of auxiliary hypotheses is necessary if one intends to determine the advantages and disadvantages of two competitive theories. Thus, in order to better understand how both conceptual change and acceptance of new theories are produced, we think it is essential to recur to the role played by auxiliary hypotheses, which often remain implicit.

Our specific objectives in this paper are: i) to study the role of auxiliary hypotheses and to analyze how some of them are usually implicit and how they influence the process of conceptual change; ii) to make a specific contribution based on two significant examples provided by the History of Science in order to show how scientists use certain experiments in order to agree about both the acceptance and the rejection of a theory, and iii) to analyze how these processes have important implications for conceptual change theories, providing a more precise characterization of the process of deciding between competing theories.

Therefore, we will be focusing on a type of analysis, which is rather specific and particularly related to just one step of the scientific activity. This is to say, on the particular uses of experiments, which includes its relation to theory generation processes. We think it is important to clarify that we consider our contribution as complementary of some recent advances in this area, which have been more related to the general and social contexts of theories generation and scientific practices. To this respect, it is important to consider the contributions, based on epistemological and History of Science analysis which maintain that scientific activity is not only a matter of correct logical conclusions derived from particular experiments, but also it is based on contextually valid reasoning processes (Hacking 1988; Zammito 2004). On the other hand, even though an important number of present investigations on scientific understanding are more focused on one or several integrated episodes of inquiry, rather than focusing on discrete 'processes' (Lehrer et al. 2008), our contribution could nevertheless being useful as a mean to better understand those discrete processes. Being the experiments, and its relation to theory generation, probably the most important part of the scientific activity, we think it is relevant and fruitful to try to get a better understanding of how theory and data interact (Duschl 2008).

Crucial Experiments and Conceptual Change

When should we call an experiment "crucial"? Tracing back the History of Science, it becomes evident that the design of crucial experiments has aimed to either confirm or invalidate a certain fundamental hypothesis, a set of hypotheses or a complete theory. Popper (1972) argued that this kind of experiments should be used to decide between competing theories that make contradictory predictions on an experiment's outcome. Yet epistemological and historical analysis has proved that no logical scheme verifies a hypothesis or a set of hypotheses satisfactorily, since scientists can only corroborate hypotheses. On the other hand, as regards the rebuttal, it is incorrect to sustain that observational results that are contrary to what a hypothesis predicts, suffice to reject the hypothesis (Brown 1977). To this respect, the so called *Context of Justification* is not enough to decide about the truth value of a hypothesis. In fact, a fundamental hypothesis is always accepted or rejected through very complex processes that include external elements into the explanatory outlines (Kuhn 1970) which strongly depend on the so called *Discovery Context*.

Earlier on, in 1906, Duhem (1982) wrote that an experiment in physics can never condemn an isolated hypothesis, but only a whole theoretical group. As a matter of fact, for Duhem, crucial experiments are actually impossible in physics because "unlike the reduction employed by geometers, experimental contradiction does not have the power to transform a physical hypothesis into an indisputable truth; in order to confer this power on it, it would be necessary to completely enumerate the various hypotheses that may cover a determinate group of phenomena, but the physicist is never sure he has exhausted all the imaginable assumptions" (Duhem 1982, p. 190). Accordingly, Quine (1961) asserts that crucial experiments do not solve the differences between rival theories, because hypotheses are not examined in isolation, rather as part of theories which have numerous auxiliary hypotheses associated to them. In spite of all these epistemological obstacles, the main point is that many experiments in the History of Science have operated as if they had been crucial, in such a way that based on their results, scientists have rejected theories or have adhered to other new ones.

We need to clarify two points: a) the concept of auxiliary hypothesis, like any fundamental concept, has been altered over time. Anyway, here, we use the concept of auxiliary hypothesis in a general sense, according to the so called Duhem-Quine thesis that claims that a scientific theory can not be tested in isolation because a test of a theory always depends on other theories and hypotheses. Secondly, auxiliary hypothesis may be considered, in some cases, ad-hoc hypothesis (i.e. a kind of auxiliary hypothesis that is accepted without any experimental confirmation, for the only purpose of making coherent theory and avoid refutation by observation and experimentation). This depends on the theory that is being defending or attacking and on the degree of independence between the hypotheses considered fundamental and those considered auxiliary. When anomalies appear, some auxiliary hypotheses are usually used as ad-hoc hypotheses. In this paper, we will referring to auxiliary hypothesis which are often implicit and which not necessarily are used as ad-hoc.

The strength of the examples we have selected is due to their containing of *two* well-established hypotheses that appear to be isolated from one another—a fundamental and an auxiliary hypothesis in each example—, which allows us to clearly establish how they can exchange their roles, according to the theory to be stated. This is fundamental in understanding the nature of conceptual change in those processes leading to a change in theory, based on the interpretation of certain experiments.

Therefore, due to their characteristics, crucial experiments reveal two fundamental issues that should be considered in our analysis:

1. Different understandings of the same results for an experiment may conduce to contradictory and even opposite conclusions. Numerous crucial experiments

have been interpreted as either supporting or rejecting the *same* fundamental hypothesis throughout the History of Science. The meaning of some significant and the relation among them can vary drastically. Thus, conceptual change may stem from a new *crucial interpretation* of an experiment.

2. Certain assumptions are generally hidden. Auxiliary hypotheses supporting a fundamental hypothesis can often be implicit or lack corroboration, or both. Identifying auxiliary hypotheses and their supporting role for the fundamental hypothesis under examination is essential in order to establish how old interpretations change and produce novel ones. The two following examples are very representative cases of these issues.

The Shape of the Earth: A Crucial Experiment

Historically, the most powerful argument supporting the roundness of the Earth was recreated by Copernicus in his book *On the Revolutions of the Celestial Spheres*: "It is also deduced [the spherical shape of the Earth] because waters sailed by navigators have that [spherical] shape: because, those who are aboard do not see the land, but can view it from the mast: on land, those who stay ashore see it as if it were descending little by little, while the ship is sailing away, until it slowly hides, as if it were setting". (Copernicus, 1543, 1, II). Copernicus puts forward the arguments used by Ptolemy in II BC, the greatest Geocentric Astronomer in History Fig. 1.

Although Copernicus does not mention it, to support the argument, light needs to move following straight lines. This is the "crucial" auxiliary hypothesis. It is implicit and supports the fundamental hypothesis of the Earth's roundness. Otherwise—following Copi's suggestion (Copi 1953)—Copernicus' statements would be compatible with the hypothesis of a flat Earth:

The Fig. 2 illustrates why, if luminous rays are curved, when the ship is far from the observer the hull seems to disappear but the mast remains visible. At this point, it is interesting to indicate that actually density and air temperature produce refraction thus changing the trajectory of light, which does not propagate in straight lines. Another point to be taken into account is that an implicit perception theory is occurring: in Copernicus' day, when Optics was part of Physics and Anatomy, most optics researchers were extromissionists who believed that vision went from the eye to the object that favored a rectilinear conception of light. This was the case of Leon Battista Alberti, who wrote the first treaty of modern perspective in 1435, as well as much later-of Galileo. This is relevant in being able to notice the importance of preconceptions.

In our example, the issue of how light travels over the surface of the Earth is essential in order to explain how we perceive and conceive the shape of different objects, particularly and fundamentally how we are able to describe the shape of the

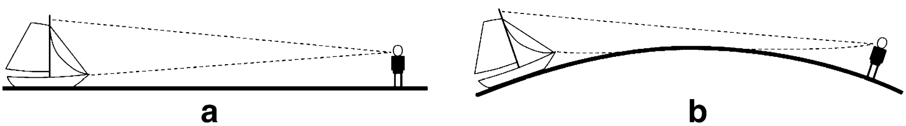


Fig. 1 "Paths are rectilinear"—in (**a**) and (**b**)—plays the role of an auxiliary hypothesis

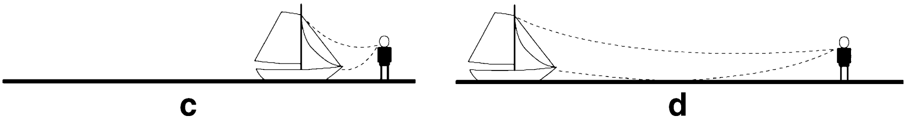


Fig. 2 If paths were curve—in (**c**) and (**d**)—, the observational data would be compatible with the hypothesis of a flat Earth

Earth itself. Thus, in the context of this experiment, the surface of the Earth is understood as the *surface* of a *huge body*—no longer as a plane as seen by any observer situated in the surface of the Earth—, i.e. the Earth is no longer conceived as being a plane, it "becomes" a spherical body. This produced a conceptual change in relation to the concept "Earth".

While the Earth's flatness should be related to certain passivity with regard to what is almost directly observed, the hypothesis of sphericity depends strongly on a reasoning process. Furthermore, we could see how the hypothesis of the Earth's roundness might be incorporated as a datum, in such a way that the experience itself could be presented providing an argument in favor of the hypothesis of the rectilinear trajectory of light. In this sense, there would be an "exchange" of roles between both hypotheses, from the fundamental to the auxiliary one, and vice versa.

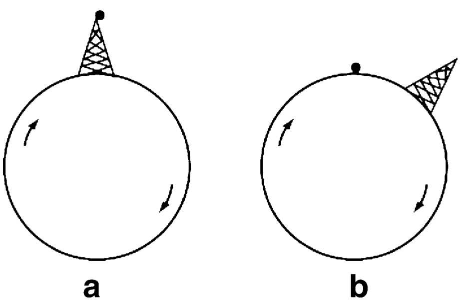
The Earth's Movement: A Crucial Experiment

A dynamic problem in the Copernican system was related to unattached bodies on the Earth's surface rotating from West to East (maximum speed at the Equator). If the Earth rotates, why don't the bodies dropped from a certain height fall toward the West Fig. 3?

Ptolemy, presented this experience as crucial in order to reject terrestrial motion.

This problem has been historically assimilated to that of a stone falling from a moving ship's mast. Galileo—the main defender of the Copernican system—argues in his *Dialogues* that it is not necessary to perform the experiment in order to demonstrate that the stone will fall *to the base of the mast*: it is enough to reason appropriately (Galilei, 1632, Second Day). At this point, it is important to introduce a Galilean argument that relates this problem to the trajectory of luminous rays (as stated above): "Salviati: '...suppose you are aboard, staring at a point of the mast. Do you think, because the ship is sailing fast, you will have to move your eyes onto that point of the mast following its movement?". Simplicio's answer is: No. Then,

Fig. 3 This Figure shows what should happen, according to Ancient Physics, if the Earth were moving from situation **a** to **b**



Salviati says: "'... this happens because the movement the ship provides to the mast, is the same movement provided to you and your eyes; so, you do not have to move them to watch the highest point of the mast (...) And vision rays go from the eye to the mast just as if a cord were tied to both ends of the ship'" (Galilei, 1632, Second Day). Thus, we find extromissionist ideas in Galileo. For Galileo the stone must fall to the mast's base, just as with a stone that is let fall from a tower on a moving Earth.

Galileo's contribution was to introduce—through convincing arguments—the concept of inertia: in the "horizontal" direction, every stone follows a uniform movement. This is the same "horizontal" movement followed by the tower, according to the almost constant rotating movement of the Earth. From the tower, the "horizontal" movement cannot be observed, because both the tower and the stone follow the *same* movement as the surface of the Earth. However, in the "vertical" direction, bodies are accelerated because of their weight. The result in space is two overlapping movements: a parabola. Yet when the situation is observed on Earth, only a vertical fall is observed Fig. 4.

The auxiliary hypothesis, historically introduced to sustain the basic hypothesis of the Earth's movement and to save the tower experience from geocentric attacks, is thus based on the principle of inertia. However, due to its definition, inertia is unobservable because it would require an absolutely isolated body and the absence of any reference system to measure its movement without interference. Moreover, deep controversy still exists on the true origin of inertia—Newtonians and Machians discuss whether inertia should be related to space or to the distribution of stellar matter (Hartman and Nissim-Sabat 2003).

For the case of the Earth's movement, an exchange of the fundamental and the main auxiliary hypotheses has been taking place historically. Precisely, the Earth's rotation in itself (acceptance of one of Copernicus' hypotheses) might be taken as a fact in order to refute Aristotle's former non-inertial dynamics. In this sense, the tower experiment acts as a refutable crucial experiment, but with respect to... Aristotle's dynamics! Regarding the demonstration of the inertial hypothesis, the hypothesis of the Earth's movement plays an auxiliary role. In this sense, the experiment may be taken as crucial for the demonstration of both the Earth's movement and the existence of inertia.

It is worth remembering that Copernicus thought the sphere was the natural shape of compound bodies, and for compound bodies like the Earth, only circular movements were natural. The fundamental properties of Earth's particles were: to meet in a spherical way around a moving center, to turn around with regard to the Earth's north–south axis, and to orbit around the Sun at a certain distance. Thus, a stone falling free off a tower possesses a natural circular movement—which is the

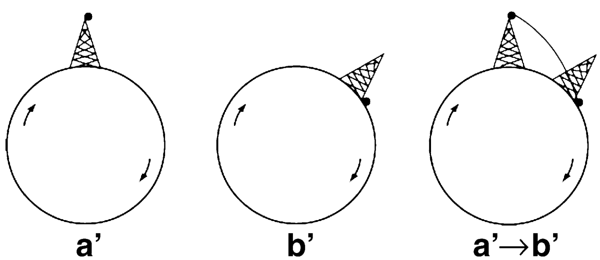


Fig. 4 Inertial Physics: A stone describing a parabola in space for the case of Earth's rotation

"horizontal" one-compatible to the Earth's rotation, and a rectilinear movement toward the center of the Earth, one that reunites it with the rest of the terrestrial matter. This comes from the fact that the body was previously displaced from its natural position, when it was part of a sphere together with the rest of the terrestrial bodies. So, Copernicus' "inertia" is linked to the natural circular and uniform movements, which are the universal kind of movements—not only for supra—lunar bodies as in Aristotle's case; which implies a covert inertia. This means the naturality of the universal circular movement plays an analogous role to inertia. But there exists simultaneously a mutual determination between the bodies' natural sphericity and their also natural, spherical movements. Thus, from a historical point of view, it can be said that when Copernicus defended his fundamental hypothesis on the Earth's movement, based on the tower experiment, he implied the existence of some kind of (hidden) "inertial" movement that was implicit. Let us see how both experiments combined turn out to be decisive in order to establish a heliocentric theory like Copernicus'. Precisely, his ideas about dynamics, referring to how bodies tend to form compound bodies with a spherical shape (such as in the case of the Earth), and to how the natural movement of spherical bodies is circular, lead to the following conclusions: 1) The Earth's surface is round (interpretation of experiment I), invalidating the idea that it is flat and favoring the notion that the Earth may be considered as a body with a spherical shape. 2) Insofar as the Earth is a spherical body, then it is entirely conceivable and acceptable that it moves with circular movements (interpretation of experiment II), invalidating the idea that it is a plate or a disc, in equilibrium and standing still in the center of the universe.

Discussion

We think our previous analysis, based on the discussion of specific examples from the History of Science, has two types of implications. One is related to cognitive theories on the conceptual change process, and the other, to possible educational applications. Concerning the first one, we would like to emphasize on the essential role of auxiliary hypotheses, particularly when they appear to be implicit. In this sense, we think it would be very important, in future cognitive research, to analyze the subjects' auxiliary hypotheses related to the theory or concepts they are supposed to change. The analysis of these hypotheses could contribute to a fuller understanding of the process of change, being this subjects either scientists or students of different ages. According to our analysis of the two presented cases from the History of Science, we think reasoning is a necessary but not sufficient condition for conceptual change. By reference to the title of a paper published some years ago (Brewer and Samarapungavan 1991), it would be possible to wonder about concepts, before and after changing their meaning, as "differences in reasoning or differences in knowledge?". In our opinion, and according to the present state of the art (Vosniadou 2008), the answer to this question is still unclear. We think what is now clear is that insofar as defending a theory or replacing it for another requires the use and some knowledge of auxiliary hypotheses involved, which favor the activation of reasoning. So, in our opinion, it is clear that crucial experiments have historically favored conceptual change processes, when the assumptions they involved—both principles and fundamental auxiliary hypotheses—were taken explicitly into account.

In relation to educational implications, it is well known that in science teaching, crucial experiments may favor *genuine* conceptual changes if they are adequately presented and discussed, that is, with an adequate help of the teacher, making it possible for students to make explicit the involved assumptions and taking into account the historical changes on the use and interpretation of scientific experiments. Most educational attempts to apply conceptual change theories to science education (Duit et al. 2008; Duschl and Grandy 2008) have developed instructional strategies based on a sequence that takes into account students' previous ideas about scientific phenomena. Those strategies promote a number of activities for students to be able to change their ideas, either through facing contradictory evidence or through analogies and alternative theories. In the first case, it is assumed that students might achieve conceptual change through logical reasoning geared to invalidate their previous idea. The new conception will appear as a result of the previous conception's invalidation. As a matter of fact, very often in formal education, and also in science museums and other informal educational environments, crucial experiments are presented to students as definitive valid proofs in order to validate or invalidate competing theories. In this way, students do not have the opportunity to really reconstruct the historical process of theory generation. Thus, they do not take into account possible auxiliary hypothesis that may be implicit, and their conceptual change process runs the risk of being similar to an unconscious conversion process. This is to say, it could be the case that they change their theory without really having fully understood the two competing theories and the difference between them. We think that instructional strategies could be very much improved if they take into account not only students' prior ideas, but also the related auxiliary hypotheses. In this sense, it is important to insist on the positive role crucial experiments might have in the teaching and learning of science. Anyway, it is important to consider that a more detailed view of the educational implications of this work should be developed in a more extended way, and also in relation to recent developments in this field (e.g. Duschl and Grandy 2008).

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