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Conceptual change and anomalous data: A case study in the domain of natural sciences

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Cognitive conflict has been proposed as a strategy to promote conceptual change. The history and philosophy of science have shown the importance of anomalous data to change scientific theories and to the progress of science. Often, scientists use anomalous data to develop new interpretations that lead to new conceptualizations and finally, to a deep conceptual change. To be aware of contradiction seems to be a first step in the process of conceptual change. A study to explore novice students responses to anomalous data has been carried out. Sixty nine ninth graders, fifty seven eleventh graders and sixty three twelfth graders participated in the study. A paper and pencil task about the origin of life on the Earth was designed. Subjects were divided into two conditions. In condition "A" only anomalous data were presented to the subjects. In condition "A+B", both anomalous and confirmatory data were presented.

Results indicated that younger students were less aware of contradiction than older students when both anomalous and confirmatory data were presented. However, no differences have been found among them when just anomalous data were presented (condition A). Twelfth graders were aware of contradiction in both conditions. Some students' epistemological beliefs influenced their response to anomalous data. Although no conceptual change (weak or strong restructuring) was achieved, as it could be predicted by the low domain-specific knowledge of the subjects and the complexity of the topic, presenting anomalous data facilitated the achievement of the first steps of the conceptual change process.

Introduction

"Quantum mechanics is, undoubtely, impressive. But a voice inside me tells me that it is not still the truthful and definitive. The theory says a lot, but in fact, it does not come close to the Old's secret [that is, to understand how God created the world]. Anyway, I have the conviction that he does not play dice".

(Extracted from a letter from Einstein to Max Born in December, 1926. Quoted by Weisberg, 1986, p. 109)

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This well-known sentence of Einstein may be a good example of how difficult is to achieve conceptual change that often involves the acceptance of "anomalous" and new data that contradicts our beliefs. In this case, as Weisberg says, Einstein was the author of one "conceptual revolution" (Thagard, 1992), named the relativity theory, but was not able to accept the quantum theory because of his metaphysical view of the universe. He considered the universe was directed by determistic laws. Although he had open the way for the works that led to the quantum theory, he never accepted it. One more interesting example is shown in a recent article in Scientific American (Bernstein, 1996). According to Bernstein, in 1939 Einstein published an article were he used his gravity equations to show that the black holes could not exist. Nevertheless, his theory of the relativity and of the gravity was employed in the same year, by Oppenheimer and Snyder to show exactly the opposite: that is, the existence of the black holes. In this case, the same tool, guided by the scientists' beliefs, led to contradictory hypothesis. However, the discrepant positions among the physics stimulated the research and nowadays, the black holes cannot be explained without the quantum mechanics, a theory that the scientists have not been able to integrate with the general relativity theory yet because of their incompatibility (Thagard, 1992). This example is just one among many others that can be found along the history of science that seem to indicate that, at least in some cases, conflicting, anomalous or contradictory[1] data have played an important role to lead to conceptual changes and to scientific progress.

These examples illustrate some of the questions that will be addressed in this paper. For example, what is the role of anomalous data in the process of conceptual change? When are anomalous data integrated or accepted in the subject's theory? What factors may facilitate subjects' metaconceptual awareness of anomalous data and which factors may hinder subjects' recognition of contradiction? Is contradiction and subsequently cognitive conflict a good strategy to promote conceptual change?

These problems have been dealt with from different disciplines that faced these questions with different interests and purposes. We will review briefly some contributions from philosophy and history of science, cognitive psychology and science teaching and learning.

Anomalous data and science progress

Philosophers of science often illuminate the problem of understanding conceptual change and the role of anomalous data in this process. Popper (1968, 1969) considers that observation is guided by the subject's theory and presuppose it. Theories are bold speculation, creatively constructed, but knowledge is non-provable and non-confirmable. A theory can be disproved (falsified) by testing it against counter-evidence using deductive logic. Science progress is achieved thanks to trial and error, to conjectures and refutations. Every hypothesis or theory has to be falsifiable. A hypothesis is falsifiable if it is possible to find observational data that in case of being truth, would falsify the hypothesis. In other words, a hypothesis can be falsified if anomalous or conflicting data can be found. As much as a theory can state withstanding falsification, as good as it will be. It does not exist a "truth theory". Every theory can be substitute for a new one, that can bear more falsification tests than the previous one. That is, the theory change takes place when anomalous data appear to false the old hypothesis or theory. Thus, conceptual change would be "mini revolutions" and the sucession of scientific theories is genuine progress.

Lakatos considered that a theory is not rejected by its falsification, but only in the comparison with rival theories using research fruitfulness as the criterion (Nussbaum, 1989). The central core of the theory is protected from falsification by a protective belt containing auxiliary hypotheses, initial conditions, etc. (Chalmers, 1982). When conflicting data are found, they can be ignored or they can be included in the protective belt of the theory. These conflicting data would help to refine the refutable protective belt and therefore the research programme. But these empiric counterevidence are only anomalies. Anomalous data cannot lead to reject a theory, but it is a new theory able to predict new data and also all what the old one was able to explain. The central core of this alternative theory will introduce important changes in relation to the central core of the old theory.

Kuhn (1970) stated that it is normal to find some "anomalies" inside the normal paradigm. The presence of anomalous data is not enough to start a crisis of the paradigm. Paradigms always will find difficulties. There are many factors involved in the normal paradigm shift. For example, the number of anomalies or cases of anomalous data found, the resistance of the anomalous data to be explained using the normal paradigm, how much time takes to explain those conflicting data, etc. Conceptual change (paradigm shift) is like a Gestalt shift. A revolutionary shift that occurs only in moments of crisis. According to Kuhn, there is no purely logic argument that leads the scientists to change to a different paradigm. The reason for that change would depend on factors such as the conection of the new paradigm to a social urgent necessity, the easier way of explaining some data or resolving a certain problem, etc.

According to the explanation of science progress and scientific theory change, the role of anomalous data is different. Following Popper's ideas, anomalous data, as data that falsified a hypothesis, are crucial in the process of scientific theory change and science progress. However, following Lakatos or Kuhn's ideas, anomalous data are not enough to produce a scientific theory change. They can produce some partial changes, affecting the protective belt (Lakatos) or be just one factor to take into account by a scientist to change the normal paradigm (Kuhn). Anomalous data are only fully integrated when a theory change is produced.

Responses to anomalous data and degrees of conceptual change

Describing the processes of equilibration, Piaget (1975) distinguishes adapted and unadapted reactions to anomalous data. Unadapted ones are produced when subjects do not realize the conflict between the new information and the old one. Adapted responses are classified in three types. Subjects ignore or do not take into account the conflicting data in "alpha" behaviours. "Beta" behaviours are characterized by producing partial modifications in the subject's theory. New data are considered a variation and are integrated in the subjects' theory including these data in an explicative schema that before was not used to explain them (generalization), or excluding those data from a schema previously employed, explaining them by a different schema or even building an "ad hoc" principle (differentiation). These partial modifications never affect the central core of the subject's theory. Generalization and differentiation are used to solve data-theory conflicts. Nevertheless, "gamma behaviours" involve the modification of the central core of the theory. Conceptual modifications need to be made in this type of behaviour, suppressing the conflict. This "gamma behaviours" would imply a strong restructuring (Carey, 1985) of the subject's theory.

Recently Chinn and Brewer (1993) have proposed seven types of response to anomalous data: ignoring, rejecting, excluding, hold them in abeyance, reinterpreting, peripheral changes and theory change. Anomalous data are not accepted when the individual ignores or rejects them. In contrast, they are accepted in the other type of responses. Anomalous data are explained by the individual when some changes in the individual's theory are produced (peripheral or theory change). When conflicting data are ignored, rejected or hold in abeyance, the individual is not able to explain them. At last, no theory change is achieved in any of these responses except when peripheral or theory change are made. Chinn and Brewer (1993) have taken these reactions from relevant observations dispersed widely in the literatures on the history of science, philosophy of science, science education, cognitive science, cognitive psychology, developmental psychology, and social psychology. They consider the fundamental ways in which scientists react to anomalous data appear to be identical to the ways in which nonscientist adults and science students react to such data.

Thagard (1992) has analyzed some conceptual revolutions in science and he has proposed a theory of conceptual change for them. He considers a variety of different discovery methods being instrumental for the different revolutions. For some of them (i.e., Lavoisier chemical revolution or Darwin's theory) data-driven discovery of empirical generalizations played a large role. In contrast, in other cases, i.e., Copernicus' theory or the Einstein's relativity theory, discovery came from incoherencies in existing views. Thagard states that in most revolutions there is a large explanation-driven component, in which concepts and hypotheses are generated to explain puzzling facts or as we have termed, anomalous data. Therefore, some relevant examples from the history of science seem to indicate that anomalous data play an important role in the process of conceptual change.

Although he refers to the relations between the old and the new theories, he distinguishes four kind of relations between sucessive theories, ordered by decreasing amounts of cumulativeness that can be related to the responses to anomalous data proposed by Chinn and Brewer (1993) and the alpha, beta and gamma behaviours described by Piaget (1975) (see Table 1). This four kinds of relations are: incorporation, sublation, supplantation, and disregard. If a new theory T2 completely absorbs the previous theory T1, then T2 incorporates T1. Therefore, T2 is just an extension of T1. If T2 partially incorporates T1 while rejecting aspects of T1, then T2 sublates T1. If T2 involves the near-total rejection of T1, then T2 supplants T1. Finally, if the adoption of T2 comes about simply by ignoring T1, then T2 disregards T1.

In the first steps of the process of conceptual change, the awareness of the anomalous data promotes different types of responses that can be ordered in a continuum from the least acceptance of the data to the most acceptance of them. The more the anomalous data are integrated and accepted a deeper conceptual change is achieved and the least amount of cumulativeness. The degrees or kinds of conceptual change have been described widely by different authors (i.e., Carey, 1985, 1991; Thagard, 1992; Chi, 1992; Dykstra, 1992; Hewson & Hewson, 1992; Dagher, 1994; Vosniadou, 1994), therefore, we will just summarize some of the proposals to regard them to the responses to anomalous data (see Table 1).

Table 1

Reactions to anomalous data and degree of conceptual change

Responses to Anomalous Data			Degree of Conceptual Change	Relation Between the Old and the New Theory
	Piaget (1975)	Chinn & Brewer (1993)		Thagard (1992)
Unadapted responses	Unawareness of contradiction	Ignore *	No conceptual change at all	T1
Adapted responses (awareness of contradiction)	Alpha	Ignore Reject Exclude Abeyance	No conceptual change but awareness of contradiction	T1
	Beta	Reinterpret data maintaining T1	Weak restructuring	Incorporating (T2 is just an extension of T1) Sublating (T1 & T2)
		Peripheral changes to T1		Sublating (T1 & T2) Supplanting (T1 & T2)
	Gamma	Accept the data and change of theory	Strong restructuring	Disregarding (T2)

Note. * Subjects can ignore the anomalous data being unawareness of the contradiction they involve, or being awareness of it, but putting the data aside.

Factors that influence the recognition and the response to the anomalous data

Chinn and Brewer (1993) discussed that there are four main factors that influence how people response to anomalous data: characteristics of prior knowledge, characteristics of the new theory, characteristics of the anomalous data and processing strategies.They postulated there are four characteristics of prior beliefs that are specially important in influencing the response to anomalous data: the entrenchment of the prior theory, the ontological beliefs, that is, the fundamental beliefs about the fundamental categories and properties of the world; the epistemological beliefs subjects' have about science and the background knowledge. The more entrenched a belief is, the harder it should be to change it, and the less background knowledge subjects' have, the more difficult it should be for them to evaluate the anomalous data.

The availability of a plausible alternative theory and the quality of the alternative theory are the characteristics of the new theory that influence people response to anomalous data, according to Chinn and Brewer. The credibility and the ambiguity of the data influence also subjects' response. A deep processing strategy seems to be an affecting factor in the response to the anomalous data. Processing evidence deeply includes to pay a careful attention to contradictory evidence. Therefore, this strategy facilitates the awareness of the conflicting data and also the attempting to look for an alternative theory. This processing strategy can be encouraged choosing a task where people feel personally involved or making the subjects to look for arguments to justify other people their ideas.

Dunbar (1995) studied the use of inconsistent evidence by scientists working in their own experiments. He described two uses of inconsistent evidence. First, inconsistent evidence was used to change specific features of a hypothesis, maintaining basically the same overall hypothesis. Subjects employed the generalization-specialization heuristics (beta behaviours, in Piagetian terms). Second, when subjects needed to invent a new hypothesis, concept or frame to explain anomalous data they rarely made it individually but working in group. Individual scientists out of a group context usually attributed the anomalous data to error of some sort. These results point out one more factor that can influence the response to anomalous data: social support and social context. Particularly, Dunbar says that when: a) surprising findings occurs, b) the researcher believes that these findings are not due to error, and c) other members of the group challenge the researcher's interpretation of the findings, then significant conceptual change occurred. Question answering was a potent mechanism of inducing conceptual change. Thus, members of a group can induce to adopt new goals and perspectives that seem to facilitate the reorganization of knowledge.

One more factor influencing the response to anomalous data is the domain-specific knowledge, or in other words, the level of expertise. Dunbar (1995) reported that the way in which inconsistent evidence was treated also varied as a function of experience. Less experienced scientists were more willing to maintain a hypothesis than more experienced scientists. More experienced scientists showed much less confirmation bias than less experienced researchers, but nevertheless, they often displayed falsification bias, that is, they discarded good data that actually confirmed their hypothesis. This bias appeared to be the result of much experience with being proved wrong.

Dreyfus, Jungwirth, and Eliovitch (1990) reported that novices (in their case, their sample were 16 years-old students) often lack of ability to reach a stage of meaningful conflict. They consider this may be related to the difficulties in formal reasoning with abstract concepts (Lawson, 1985) and also to the poor understanding of conceptual data which they are expected to have mastered (Stewart, 1985). These results may explain at least in some extent, the failures to promote conceptual change applying a cognitive conflict instructional strategy (i.e., Baillo & Carretero, 1995; Dreyfus et al., 1990; Champagne, Gunstone, & Klopfer, 1985).

Cognitive conflict as an instructional strategy for science learning

In their well-known paper of 1982, Posner, Strike, Hewson, & Gertzog, pointed out that one of the conditions to achieve accomodation (in Piagetian terms, a radical form of conceptual change that involves the replacement or reorganization of the students' concepts) is the dissatisfaction with existing conceptions. Before of more radical changes an individual must have collected anomalies or anomalous data. According to this, anomalies would provide a sort of cognitive conflict that would prepare the student for accomodation or for radical conceptual change.

Nevertheless, when contradictory data have been presented as an strategy to learn science concepts, results have not been really successful. For example, Pulos, Benedictis, Linn, Sullivan, and Clement (1982); Burbules and Linn (1988) and Chaiklin (1985) reported very little conceptual change after employing this strategy to study weight and density concepts. Students hold onto some ideas and readily change others. For example, they may change their ideas about water to defend their ideas about volume. Eylon and Linn (1988) concluded that contradiction is not clearly sufficient to achieve radical conceptual change. Nevertheless, for these authors, contradiction draws attention to a problem and increases the likelihood for students to consider an alternative view.

In contrast, Dreyfus et al. (1990) reported some positive effects of conflict when both the conflict and the solution were meaningful to the student. Levin, Siegler, Druyan, and Gardosh (1990) also found some positive results using an experientially based contradiction.

Therefore, cognitive conflict seems not to be enough to promote conceptual change, at least in a radical sense. Many of the factors described in the previous section may explain some of the failures in promoting conceptual change. However, this strategy seems to promote reflection and in some cases, at least students develop a certain degree of contradiction awareness.

Empirical study

Research questions and aims of the study

The research questions and the aims of this research report can be summarized as follows:

a) What ideas students' have about how life started on the Earth? Are they influenced by values and religious beliefs?

A high number of studies have explored students' ideas about different scientific topics. However, often the problems and tasks posed to the students were well-defined problems where there were a correct solution from the scientific point of view. In our study we have employed a question that still has not been solved by scientists. Several hypotheses are being discussed among scientists having a different degree of support in the scientific community, but there is no agreement to accept any of them. On the other hand, it is a rather complex question that requires to get data from chemistry, physics, astronomy, geology, etc., thus, it is an interdisciplinary problem rather complex to be understood for secondary school students, but nevertheless it is a topic included in their science curriculum in Spain. Therefore, one of our aims was to explore students' preferences on some possible explanations about how life started on the Earth.

b) What are novice students' responses to anomalous data?

Taken into account the theoretical framework described in the introduction, it seems pretty clear that the first step to solve a cognitive conflict and to achieve conceptual change may be to be aware of the contradiction between the anomalous data and their own ideas. As our sample did not have a high previous knowledge about the content of the task, we have focused on the awareness-unawareness of the contradiction. Were students' in spite of their lack of knowledge able to realize the anomalous data? Are there significant differences on the ability to realize conflicting data between the subjects that have received more instruction on the topic and those who have received less? Are there developmental differences?

c) When scientists or researchers are working, or when we solve a problem in our daily life not only anomalous data are found. Often, confirmatory data are also found. Are students' more or less awareness of anomalous data when they are presented confirmatory and contradictory data, than when they are presented only anomalous data? Do novice students' show a higher confirmatory trend when they are presented confirmatory and contradictory data, than when they are presented only anomalous data?

d) Even when students' do not have a high previous knowledge on the topic, may presenting anomalous data be an useful instructional strategy to promote, at least the first steps of the conceptual change process? Is it equally useful for every educational level?

Sample and procedure

Sample. Three groups of students have participated in our study:

Group 1: Sixty nine ninth grade students (14-15 years-old) who received instruction about the origin of life during the same course they participated in the study.

Group 2: Fifty seven eleventh grade students (16-17 years old) who did not receive instruction about the topic since two years ago.

Group 3: Sixty three twelfth grade students (17-18 years old) who received instruction about the topic during the same course they participated in the study.

Procedure. A paper and pencil task was designed

First part. A text presenting six hypotheses about the origin of life and a table summarizing the main important points of the hypotheses were presented (see appendix). Hypothesis 1 explained that life originated on a solid medium that was common on the Earth at that time, namely, clay crystals. These crystals would have been made up of self-replicating units (i.e., units capable of copying and duplicating themselves) that were sufficiently complex to be able to mutate and evolve in a similar way to living material. Therefore, life appeared in a solid medium. Hypothesis 2 represented the spontaneous generation theory: living beings were able to appear spontaneously, by chance. No specific medium is required. Hypothesis 3 proposed that life began as a metabolic process, i.e., a cyclical chemical reaction driven by some energy source (such as heat from the Earth's interior) that took place on a solid surface protected from the sun's rays, extremely harmful given the absence of ozone in the atmosphere. Pyrites, a solid medium is required for this cyclical reaction. Hypothesis 4 suggested that a superior being (God) as being responsible of the origen of life. Hypothesis 5 was a brief summary of Oparin's hypothesis. According to it, a chemical reaction was the origen of life. But in contrast to hypothesis 3, it took place in a liquid medium. Moreover, some atmosphere conditions (a reductor atmosphere, that means there was no oxygen) were required and also an energy source providing heat. At last, hypothesis 6 pointed out that the first organic compound could come from the outer space. Comets and meteorites were responsible for bringing these compounds to Earth so that life could develop from them.

As the topic of the task was rather difficult, specially for the younger subjects, a summary table was designed to help students to understand and to compare the hypotheses presented, although it was taken into account that in general, their knowledge was low to fully understand all the hypotheses. Subjects were asked to choose the one/s they considered the most adequate according to their beliefs and to explain their choice. They were allowed to construct their own hypothesis, mixing some of the ones presented or introducing new ones if they wanted to do so.

Second part. In this part, each group of subjects were divided into two conditions.

Condition A (Only anomalous data were presented)

A fictitious situation was presented in a short text where it was told that two research groups, one leaded by Dr. Hamilton and the other leaded by Dr. Smith, maintained opposite hypotheses. It was told that Dr. Hamilton maintained the fifth of the hypotheses presented (Oparin's hypothesis about the origen of life, that was the one students studied). Then, three statements made by Dr. Smith that clearly refused hypothesis 5 (Dr. Hamilton's) were presented (see appendix). The statements referred to three key points in Oparin's hypothesis: the primeval atmosphere conditions, the liquid as the medium required for the appearance of organic compounds and the energy source.

Then, they were asked if they thought Dr. Hamilton could maintain or not his hypothesis and why. Finally, they were asked again to choose which hypothesis they considered the most adequate of the six presented in the first part, although they were not constrained to choose one of the six hypotheses presented: they could construct their own hypothesis, mixing some of the ones presented or introducing new ones if they wanted to do so. They could also answer that none of the hypotheses were adequate. They could check the text with the hypotheses and the summary table as much as they wanted.

Condition A+B (Confirmatory plus anomalous data were presented)

The same fictitious situation was presented, but in this case, three counterarguments of Dr. Hamilton defending his hypothesis (Oparin's hypothesis) from Dr. Smith's arguments were also introduced (see appendix). Therefore, in this condition *not only anomalous data but also confirmatory data* were presented.

Finally, they were also asked again to choose which hypothesis they considered the most adequate of the six presented in the first part, although they were not constrained to choose one of the six hypotheses presented: they could construct their own hypothesis, mixing some of the ones presented or introducing new ones if they wanted to do so. They could also answer that none of the hypotheses were adequated. They could check the text with the hypotheses and the summary table as much as they wanted.

Results

Hypotheses selected by the students in the pretest (first part of the task described). The chi-square analysis carried out showed that there were no significant differences among the three groups regarding to the hypotheses they selected. The hypothesis the students chose the most was the hypothesis 5 (Oparin's hypothesis) – 128 out of 189, 67,7% –. This was the one they studied. Forty subjects (21,2%) selected mixed hypotheses. The mixed hypotheses the students suggested the most (percentage higher than a 5%) were a combination of hypothesis 5 and another one. For example, thirteen of the forty subjects who chose a mixed hypothesis said that a superior being (God) created the conditions described by the hypothesis 5 (that is, a combination of hypotheses 4&5). Eleven out of the forty subjects said that a cyclic chemical reaction produced the conditions described in the hypothesis 5 (combination of hypotheses 3&5). Seven out of the forty subjects said that something from the outer space came to the Earth and then everything happened as it was described in the Oparin's hypothesis (combination of hypotheses 5&6). At last, 4 out of the forty subjects said that the conditions described by the hypothesis 5 appeared by random (combination of hypotheses 2&5). Hypothesis 1 (a solid crystal as the starting point) and hypothesis 2 (random) seemed not to be very credible for the students.

Hypotheses selected by the students in the postest (after they completed the second part of the task described). A chi-square analysis carried out showed that there were no significant differences among the three groups, once they were presented the conflicting data (condition A) or the conflicting and the confirmatory data (condition A+B). Hypothesis 5 (Oparin's one) was again the most selected (113 subjects out of 189, 59,8%), although the percentage decreased in comparison to the pretest (pretest: 128 subjects out of 189, 67,7%). Hypothesis 3 (cyclic chemical reaction), 4 (a superior being) and 7 (none of them) increased slightly (hypothesis 3 pretest: 1,6%; hypothesis 3 postest: 9,5%; hypothesis 4 pretest: 4,2%; hypothesis 4 postest: 7,9%; hypothesis 7 pretest: 0,5%; hypothesis 7 postest: 3,2%) and the mixed answers decreased (mixed answers pretest: 21,2%, 40 subjects out of 189; mixed answers postest: 14,3%, 27 subjects out of 189). The mixed hypotheses most selected were again a combination of hypothesis 5 and another one: hypotheses

4&5 combination was chosen by 7 out of 27; hypotheses 3&5 combination was chosen by 6 out of 27; hypotheses 5&6 combination was selected by 5 out of 27 and hypotheses 2&5 combination was given by 3 out of 27.

Were the students aware of the contradiction? The answers given to the question "Taking into account Dr. Smith's results, do you think Dr. Hamilton could maintain his hypothesis? Why? Justify your answer" were classified into two categories: category one and category two. Category one included those students who realized the contradiction, and category two those who did not realize the contradiction. Category one included those who answered "no" and justified their answer explaining clearly that the scientists' hypotheses were contradictory. Subjects who answered "yes", but justified their answer showing some epistemological beliefs that allowed them to support their answer were also included in category one. For instance, a ninth grader subject belonging to the "A" condition, said: "Yes, Dr. Hamilton could maintain his hypothesis if, in spite of Dr. Smith's statements, he continues believing on his hypothesis". For him, anomalous data are not enough for a scientist to change a hypothesis: if you continue believing on your own hypothesis, you must maintain it. In these cases, subjects clearly realized the contradiction, but answered "yes" because of their epistemological ideas about how science and scientists work.

Category two included: a) those who answered "yes" and gave an explanation where it was clear they did not realize the contradiction between the scientists' statements and b) those who did not give any explanation or this was meaningless. Table 2 shows the results.

Table 2

Students who were aware and were not aware of the contradiction between Dr. Hamilton and Dr. Smith's hypotheses (frequencies and percentage they represented from the total number of subjects in each group)

	Awareness of contradiction	
Grade	Aware of contradiction (Category 1)	Not aware of contradiction (Category 2)
9th grade n=69	49 (71%)	20 (29%)
11th grade n=57	45 (78,9%)	12 (21,1%)
12th grade n=63	61 (96,8%)	2 (3,2%)
Total n=189	155 (82%)	34 (18%)

The chi-square analysis performed pointed out that there were significant differences among the three groups regarding the awareness of the contradiction (χ^2=15.38990, p=0.00046). Almost all of the twelve graders realized that Dr. Smith and Dr. Hamilton's maintained opposite hypotheses. The number of students who were not aware of the contradiction decreased strongly from ninth graders to twelfth graders.

Table 3

Students who were and were not aware of the contradiction in the A+B and A conditions (frequencies and percentage they represented from the total number of subjects in each group)

		Awareness of contradiction	
Grade	Condition	Aware of contradiction (Category 1)	Not aware of contradiction (Category 2)
9th grade n=35	A+B	18 (51,4%)	17 (48,6%)
11th grade n=28	A+B	19 (67,9%)	9 (32,1%)
12th grade n=31	A+B	29 (93,5%)	2 (6,5%)
Total n=94	A+B	66 (70,2%)	28 (29,8%)
9th grade n=34	A	31 (91,2%)	3 (8,8%)
11th grade n=29	A	26 (89,7%)	3 (10,3%)
12th grade n=32	A	32 (100%)	0 (0%)
Total n=95	A	89 (93,7%)	6 (6,3%)

In the A condition (anomalous data only) there were no significant differences among the three groups regarding students who were aware of the contradiction. 93,7% of the subjects in the A condition (89 subjects) realized that the Dr. Smith and Dr. Hamilton's hypotheses were contradictory. However, in the A+B condition (anomalous plus confirmatory data) there were very significant differences among the three groups (χ^2=14, 05061; p=0.00089). A 70,2% of the A+B subjects (66 subjects) realized the contradiction, and a 44% of them (29 subjects) were students of the group 3. Group 3 students realized the contradiction both in the A and A+B conditions. However, the younger the students were, the more difficulties they had to realize the contradiction in the A+B condition. Nevertheless, they were able to detect it when only anomalous data were presented (A condition).

Change between the pretest and the postest. To study the change in the selection of the hypothesis chosen before (pretest) and after the task (postest), an ANOVA with two between subjects factor (educational level and task condition) and one within subjects factor (change between pretest and postest) was performed, including only the subjects that realized the contradiction[2]. The results showed a very significant effect of the task condition ($F_{1,149}$=7,17; p=.0082): subjects that realized the contradiction in the A condition (conflicting data) changed significantly more their choice than subjects that realized the contradiction in the A+B condition (conflicting and confirmatory data). However, there was no significant effect of the educational level and no interaction effect.

From a qualitative point of view, most of the subjects (21 out of 27,77%) that changed their choice in the A condition (only anomalous data were presented) justified their change because of Dr. Smith's statements (that is, the anomalous data) making explicit references to them to support their new choice. For example, the subject 51 who chose the hypothesis 5 in the pretest, selected the hypothesis 3 in the postest and explained: "Hypothesis 3 is the most correct according to Dr. Smith. Life had to appear in a solid medium instead of a liquid one". However, in the A+B condition (anomalous plus confirmatory data) only 6 out of the 14 subjects (43%) who changed their choice justified their postest answer in this way. Four of these six subjects were twelfth graders, one was a eleventh grader and one ninth grader. The remainder eight subjects did not explain their new choice or repeated the content of the hypothesis selected instead of justifying their answer.

In sum, most of the subjects who changed their answer noticed the contradiction and many of them realized they should take into account the anomalous data, but they were not able to integrate these data in a coherent and complete explanation to justify their change.To some extent, probably this was due to their lack of knowledge about the topic. Those who justified their new choice making explicit references to the anomalous data presented (mainly in the A condition) only were able to name them but not include them in their explanation.

Discussion

Student's ideas about how life appeared on the earth

The hypothesis students chose the most was the Oparin's hypothesis, that is the one they studied. The mixed answers were a combination of hypothesis 5 and another. As students' did not have a high domain-specific knowledge about the topic, they selected what they read on their textbooks. That it is not very surprising, but it shows some positive effects of instruction: at least students' were able to recognize what they studied and hypotheses such as the spontaneous creation (hypothesis 2) were discarded. Nevertheless, it is quite clear they did not have a deep understanding of most of the hypotheses.

Hypothesis 1 (a solid and inert matter such as clay crystals as the starting point of life on Earth) seems to be a very counterintuitive idea for our students: almost nobody selected it. Darwin's ideas students knew helped them to reject hypothesis 2 (spontaneous creation), although maybe if we would have examined more deeply their understanding, more students would have maintained this idea. The same may have happened with hypothesis 4 (a superior being). However, it is interesting to point out that some students' suggested that the idea of a creator was not incompatible with a scientific hypothesis such as hypothesis 5. They distinguished religious and scientific explanations as different levels of explanation of the same event, not incompatible but even sometimes complementary.

In the postest, there were no significant differences among the three groups regarding the hypotheses they selected. Hypothesis 5 and mixed answers slightly decreased (7,9% and 7,4% respectively), and hypotheses 3 (chemical reaction on a solid medium-pyrites) and 4 (superior being) slightly increased (7,9% and 4,2% respectively).

Response to anomalous data

Employing Piagetian terms (Piaget, 1975, see Table 1) the answers given by our subjects could be classified into unadapted and alpha behaviours. A certain percentage of the subjects did not realize the contradiction (n=34, 18% of the total sample), that is, they gave unadapted responses. There were significant differences between ninth graders and twelfth graders. The younger the students were, the lesser they were aware of contradiction (see Table 2). However, when only anomalous data (condition A) were presented, all the students were able to realize the contradiction. In contrast, twelfth graders were aware of contradiction in both conditions. Therefore, it might be some developmental differences. It seems to be easier for the oldest students to realize contradiction rather than for the younger students. Nevertheless, presenting only anomalous data facilitates younger students awareness of contradiction. Thus, this strategy seem to be more appropiated than presenting anomalous and confirmatory data for younger students to give adapted responses to anomalous data. Why were ninth and eleventh graders less aware of contradiction and just a few of them changed their choice in the postest when confirmatory and anomalous data were presented? Although this is only an starting study and further research is needed, some suggestions may be indicated. Firstly, more information is presented in the A+B condition, therefore, the task became more complex. Students had to read a longer text and to pay attention to three more statements. Secondly, students may recognize confirmatory data as being part of the hypothesis they chose, and this may strengthen their ignoring, rejecting or excluding of the anomalous data.

Our students showed only unadapted and alpha behaviours, therefore, properly no conceptual change was achieved (see Table 1). This is not strange considering the low domain-specific knowledge level of our subjects, in fact we did not expect any conceptual change (understanding by conceptual change a strong restructuring) from any of our students. However, to present anomalous data has revealed as an useful strategy to promote contradiction awareness even for young students with a low domain-specific knowledge level.

Only a small group of students chose a different hypothesis in the postest (about a 25% in each group), but they changed their choice significantly more in the A condition (only anomalous data) than in the A+B condition (anomalous plus confirmatory data). This change does not represent a conceptual change, they were not able to reinterpret or integrate the new data and they were far from accepting them. As our students did not have a strong and clear prior theory because of their lack of knowledge and understanding of the topic, they were able to realize the contradictory data supporting different hypotheses, but they really did not have "a theory" to be changed. They realized there were data against Dr. Hamilton's hypothesis, therefore, they considered their choice should be different, but without really being able to integrate the conflicting data and to build a new explanation.

On the other hand, if they did not have strong entrenched beliefs about the topic because of their low level of knowledge and understanding, probably, they did not feel too engaged as to be motivated to reflect about the topic and to change. As Dreyfus et al. (1990) have pointed out, the conflict should be meaningful for the students to be successful.

Taking into account the justifications students gave to the question: "could Dr. Hamilton maintain their hypothesis taking into account Dr. Smith's results?", it is interesting to point out that they showed some epistemological beliefs about science that sometimes were used to defend their choice and to reject or to exclude the anomalous data. For example, a twelfth grader belonging to the A condition said:

> *"I think Dr. Hamilton should do the same than Dr. Smith, that is to say, try to find out if the conditions he thinks that were necessary for the appearence of life beings, have really happened, and then, if they are the best to explain the origin of life on Earth. I think, that until he, by himself, does not discover what Dr. Smith has said, he should maintain his hypothesis".*

For this student to maintain opposite hypotheses – as it is the case of Dr. Hamilton and Dr. Smith- does not mean that any of them had to be changed. According to her ideas, the scientist has to discover the "truth" by himself. If not, he/she should maintain his/her hypothesis. This student realized the contradiction, but due to her ideas about how science works, anomalous data seem not to have had any effect in her own thinking and she ignored them.

One more example. Some students, mainly ninth and eleventh graders, were looking for "the correct" hypothesis. For example, an eleventh grader of the A+B condition said:

> *"I don't know who is right. It is clear that one is saying the truth and the other is lying. I think each one should maintain their hypothesis until somebody discover which of the two hypothesis is really true. In my opinion, this is not going to happen. I disagree with this hypothesis – number 5 –, because I think God is the creator of life".*

These kind of ideas seem to be influencing students' reactions to anomalous data and they may be blocking at least to some extent, the efficacy of presenting anomalous data as an instructional strategy to promote the process of conceptual change. Maybe some previous work to modify these "epistemological misconceptions" would be required to get more successful results. Nevertheless, this strategy may be useful to detect some of these epistemological ideas students' have about how science and scientists work.

Presenting anomalous data as an instructional strategy to promote the process of conceptual change

Some of our results seem to be dissapointing in order to suggest the presentation of anomalous data as an efficient instructional strategy to promote conceptual change. It is true that conceptual change is an effortful time consuming process that, obviously, cannot be achieved by only introducing some anomalous data. At most, our subjects were able to realize the contradictory data and to be conscious of them. No conceptual change (weak or strong restructuring) was achieved, but nevertheless, the strategies followed both in the A and the A+B conditions had some positive effects. For example, they facilitated students' awareness of the coexistence of different positions to explain some scientific phenomena. Therefore, these strategies may be useful to introduce to the students open science problems such as the origin of life, and to teach them that scientific knowledge is not something closed and static where there is always a true and correct answer, but that science is dynamic and changes with new discoveries and new explanations. On the other hand, the presentation of anomalous data facilitated students awareness of contradiction between the two hypotheses presented. Although our students did not make neither a weak nor a strong restructuring, most of them – in spite of their low level of knowledge – realized the contradiction and this could be a good starting point to promote their reflection about the problem presented and about their own thinking about it. This reflection and awareness of their own ideas and of alternative explanations may be a first step to achieve a deeper degree of conceptual change. Critical and argumentative skills to argue in favour of a hypothesis and against the other/s presented may be also developed by mean of these strategies.

In sum, to make students aware of contradictory positions and anomalous data may be a starting point to: a) realize their own ideas about a topic, b) to promote reflection and to motivate students to get more domain-specific knowledge about the topic, c) to bring out some of their epistemological ideas about science and teach them how scientists work.

Futher research is needed to explore in depth the efficacy of this strategy, and the response to anomalous data of higher domain-specific knowledge level students.

Notes

1 We will employ the three terms as equivalent throught the text.

2 Most of the students that did not realize the contradiction did not change their answer (29 out of 34, 85,29%). Just 5 students – 4 of them in group 1 and 1 in group 2 – did not realize the contradiction and changed their answer. Reviewing carefully their answer, they seem to have changed just by random.

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Appendix

a) First part

Summary Table of Hypotheses Presented

	What was the origin of life? (Specifically of organic compounds)	Medium required for the appearance of organic compounds
Hypothesis 1	Clay crystals	Solid
Hypothesis 2	Chance	No specific medium required. Medium may be a solid, a liquid or a gas
Hypothesis 3	Chemical reaction driven by an energy source	Solid (pyrites), situated on the ocean floor, protected from the sun's rays
Hypothesis 4	A superior being who created the organic compounds and the conditions necessary for them to be synthesized	No specific medium required Medium may be solid, liquid or gas
Hypothesis 5	A chemical reaction for which was necessary an atmosphere with special conditions (a reductor formed from a solar cloud, an energy source providing heat and a liquid medium)	Liquid
Hypothesis 6	Outer space. Organic compounds, or even very primitive living beings arrived on Earth by means of meteorites and comets	Uncertain. Depends on location and characteristics of point in outer space from which they came

b) Second part

Page A: Dr. Smith's statements (presented to all the subjects)

Sheet A (Dr. Smith's Statements)

1. *The conditions of the primeval atmosphere (i.e., at the point where life began on Earth) could not have been those described in Hypothesis 5.*

According to this hypothesis, this atmosphere would have been characterized by possessing methane, ammonia, hydrogen and water (reductor atmosphere, i.e, an atmosphere that tend to win electrons), and was formed from the solar cloud. Geologists from my team and other laboratories have demonstrated that the primeval atmosphere did not result from the solar cloud, but that it came from the interior of the Earth (volcanic emissions). In this case, the primeval atmosphere would have been composed of nitrogen, carbon dioxide, water vapour and a small quantity of free hydrogen (neutral atmosphere). If ammonia and methane had been present, they would have been destroyed by the chemical reactions set off by light from the sun.

We have carried out experiments to see whether, in the absence of methane and from the components of a neutral atmosphere, it is possible to synthesize organic compounds; the results show that it is not possible. Thus, if there was no reductor atmosphere, rich in methane, the synthesis of organic compounds would have been impossible, at least in the way described in Hypothesis 5.

2. *The synthesis of organic compounds could not occur in a liquid medium.*

The presence of free hydrogen favoured the synthesis of organic compounds. Water does not generally contain free hydrogen, as it tends to combine with oxygen to form water molecules. As we stated in Point 1, the primeval atmosphere that came from the Earth's interior contained some free hydrogen. This indicates that it was more probable that the synthesis of organic compounds occurred in a solid, rather than a liquid medium.

3. *Solar radiation would have destroyed the organic compounds synthesized, as described in Hypothesis 5.*

In the absence of oxygen (Hypothesis 5 maintains the existence of a reductor atmosphere, i.e., without oxygen), there would be no ozone (a gas, composed of three oxygen molecules, that protects the Earth from the sun's ultraviolet rays). Consequently, the organic compounds would have been unable to survive, given temperatures in excess of 100ºC.

Page B: Dr. Hamilton's statements. (Presented just to the subjects assigned to A+B condition).

Sheet B (Dr. Hamilton's Statements)

1. *The primeval atmosphere was reductor (rich in methane, among other gases), originated from a solar cloud and was protected from the harmful effects of solar radiation by the clouds.*

The results obtained by my team, in collaboration with a Japanese laboratory, show that the breaking of water molecules by the action of solar particles and cosmic rays (such conditions were to be found on Earth at the point when life began) stimulates the synthesis of free hydrogen, and thus of methane and ammonia. Thus, the primeval atmosphere was reductor, and there is ample proof that in these conditions it is not merely possible, but indeed probable, that the synthesis of organic compounds will occur.

Moreover, some astrophysicists have found interstellar dust clouds resulting from the solar cloud, and in conditions similar to those which must have produced the Earth's atmosphere, composed fundamentally of methane, ammonia and hydrogen. This data indicates that the primeval atmosphere originated mainly from the solar cloud and was reductor (that is, made up of methane, ammonia and hydrogen, among other gases).

The clouds would have protected the methane and the ammonia from the effects of solar radiation, so that there would continue to be free hydrogen in the atmosphere, which would favour the synthesis of organic compounds.

2. *The synthesis of the first organic compound occurred in a liquid medium.*

Whilst it is true that some organic compounds may be formed in a solid medium, the experiments carried out in my own and other laboratories have demonstrated that the synthesis of those organic compounds that were the precursors of nucleic acids and proteins requires a pH (measure of the concentration of [H]+ that indicates whether a substance is acid, alkaline or neutral) that only a liquid medium could possess in the conditions prevailing on the primeval Earth.

3. Organic compounds could survive perfectly, despite the absence of ozone.

In the experiments carried out we have found that those organic compounds that were the precursors of nucleic acids and proteins can withstand temperatures of over 100° C.

Le conflit cognitif a été proposé comme une stratégie pour favoriser le changement. L'histoire et la philosophie des sciences ont montré que les données non conformes à la théorie sont source de progrès scientifique et qu'elles jouent un rôle important dans l'évolution et le changement des théories. Les scientifiques s'appuient souvent sur des donnés non conformes pour développer de nouvelles interprétations qui conduisent à de nouvelles conceptualisations et finalement, à un profond changement conceptuel. La prise de conscience de contradictions semble bien constituer une première étape dans le processus de changement conceptuel. Nous avons donc mis en place une recherche visant l'exploration des réponses d'élèves débutants à des donnés non conformes. L'étude a été conduite avec 69 élèves de neuvième année, 57 élèves de 11ème année et 63 élèves de 12ème année auquels on a proposé une tâche papier-crayon à propos de l'origine de la vie sur la terre. Les sujets ont été répartis dans deux conditions: dans la condition dite "A" les données présentées aux sujets étaient toutes non conformes; dans la condition dite "A+B" les sujets étaient disposaient à la fois de données non conformes et confirmées.

Les résultats montrent que les élèves jeunes sont moins conscients des contradictions que les élèves âgés quand les données non conformes et confirmées ("A+B") sont présentées simultanément. Mais aucune différence n'a été constatée entre les plus jeunes et les plus âgés dans dans la condition ne comportant que les données non conformes ("A"). Les élèves les plus âgés (12ème année) se sont montrés conscients des contradictions dans les deux conditions. Des croyances épistémologique influencent les étudiants dans leurs réponses aux données anormales. Bien qu'aucune changement de conception (qu'il s'agisse de faible ou forte restructuration) ne soit en place, comme on pouvait le prédire du fait des faibles connaissances spécifique des sujets et de la complexité du domaine, la présentation de données non conformes a facilité la réalisation de premiers pas dans le processus de changement de conceptualisation.

Key Words: Anomalous data, Biology misconceptions, Cognitive conflict, Conceptual change, Contradiction, Origin of life, Science teaching.

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