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Designing learning environments to promote conceptual change in science

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Abstract

It is argued that research on the acquisition of science concepts has rich implications for the teaching of science and can lead to the development of useful principles for the design of learning environments. An experimental project that attempted to use these research-based principles to construct a learning environment for teaching mechanics to fifth- and sixth-grade students is described. The students were encouraged to take active control of their learning, express and support their ideas, make predictions and hypotheses and test them by conducting experiments. They worked in small groups and presented their work to the classroom for debate. Metaconceptual awareness was promoted by encouraging students to make their ideas overt, to test them and compare them with those of other students and to give scientific explanations. Emphasis was also placed on giving the students the opportunity to use models, representational symbols, and measurements. Results showed significant differences between the experimental and control groups in pre-test–post-test comparisons, confirming our hypothesis that the experimental learning environment would result in cognitive gains for the participating students. Further interview analyses and analyses of the classroom discourse helped to clarify some of the variables contributing to the observed conceptual change.

Keywords: Learning environments; Conceptual change; Science education; Scientific reasoning

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1. Introduction

The advancement of cognitive science research in the 1970s and 1980s and the realization that this research had revolutionary implications for education have had an important role in the emergence and rapid development of instructional psychology in the 1990s (see Bruer, 1993; Glaser, 1994; Vosniadou, 1996). Instructional psychology is the study of the relationships between learning and teaching and of the nature and design of environments that can facilitate learning. A great deal of instructional research in recent years has tried to understand how complex instructional interventions change the learning environment in real classrooms and whether they result in more successful and efficient teaching. An important task for instructional psychology in the coming years will be to elaborate and validate a coherent framework of principles for the design of powerful learning environments (De Corte, 1995).

There is general agreement on some of the design principles for the construction of learning environments which have emerged from basic and applied cognitive science research (see, for example, Bereiter & Scardamalia, 1989; Brown, 1995; Cognition and Technology Group at Vanderbilt, 1993; Collins, Brown, & Newman, 1989; Glaser, Ferguson, & Vosniadou, 1996). For example, most researchers agree that *learning environments should support active learning and guide the students towards the acquisition of self-regulated processes*. Learning is an effortful and mindful process and students should be encouraged to construct their own knowledge and skills through active processing, rather than being passive listeners. This can be done by asking students to participate in projects, to solve complex problems, to design and execute experiments, to think about their ideas, to listen to the ideas of others, and in general to assume control of their learning.

Researchers also seem to agree that in the design of learning environments we must also take into consideration *the relevance and meaningfulness of educational tasks*. Learning is not an activity that occurs only in the head but is also an activity that happens in a social and cultural context. When learning is situated in real-world contexts, what is learned is better remembered, and problem-solving skills become linked to situations similar to those likely to be used, thus facilitating transfer. It is therefore important to present students with culturally meaningful and purposeful tasks that make deliberate use of the physical and social context. Since *learning is not an individual but a social affair*, schools should encourage children to work with other children and learn from them in ways that *take into consideration their individual differences*. Each child is a unique individual and schools should respect this individuality. Teachers are encouraged to understand the strengths and weaknesses of each child and to take them into consideration when they design instructional activities.

Principles such as the above are necessary to take into consideration when designing learning environments but are not sufficient by themselves. They need to be supplemented by principles emerging from research on the acquisition of subject-matter knowledge. The need to take into consideration the acquisition of subject-matter knowledge seems to be well understood in some subject-matter areas, such as instruction in the area of reading. Instructional programmes in reading are based on the results of reading research, which have shown how reading development takes place. However, the need to develop research-based curricula and instruction does not seem to be well understood in the area of science teaching. In order to design effective environments for teaching science, we need to know how children learn science, and not only science in general but also how specific science concepts are acquired. What are the specific difficulties students encounter when they learn the concept of photosynthesis? Why is the explanation of the seasons so difficult to understand? Why students fail to differentiate between heat and temperature or between energy and force?

Until now, the teaching of science has not been based on systematic research-based knowledge on the acquisition of science concepts. The work presented in this paper is an attempt to design a learning environment to teach science to elementary-school children based on the results of previous research. The purpose of this paper is twofold: first we want to show how the results of research on the development of the concept of force can be used in the design and evaluation of a learning environment to foster conceptual change in mechanics for fifth- and sixth-grade children. Second, we want to show how the study of this learning environment and, more specifically, the analysis of classroom discussions can provide further information about the teacher–student variables that can influence the process of conceptual change.

2. The conceptual change approach: definitional issues

Before proceeding, we would like to clarify the use of the term *conceptual change*. This term is used to distinguish the current approach from the usual empiricist approaches followed by most science teachers. According to the usual empiricist approach, science learning is mostly a matter of enrichment and improving existing conceptual structures. These structures are built on the basis of experience that are initially concrete and limited. Science learning proceeds along a continuum in which students' ideas become gradually more general, more abstract, and more widely applicable as the result of increased experiences. What this implies for instruction is that learning environments should provide children with more experiences and more opportunities to understand the process of doing science.

The *conceptual change* theoretical framework described here to explain the learning of science differs in important ways from the above-mentioned empiricist approach. It focuses on knowledge acquisition in specific domains and describes learning as a process that requires the significant reorganization of existing knowledge structures and not just their enrichment (see Vosniadou & Brewer, 1987).

More specifically, the argument is made that during the process of evolution the human mind has developed specialized mechanisms to pick up information from the physical world that make it possible to construct, during the first years of life, a *framework theory of physics*.[1] The development of this framework theory encapsulates humans' intuitive knowledge of the physical world and makes it possible for them to function in it. While this early competence forms the necessary foundation for further learning to occur, it may also hinder the acquisition of scientific knowledge. This happens because scientific explanations of physical phenomena often violate fundamental principles of intuitive physics, which are confirmed by our everyday experience. For this reason learning science requires the radical reorganization of existing conceptual structures and not just their enrichment, and the creation of new, qualitatively different representations. After all, the historical developments of the physical sciences, in particular, have been characterized by revolutionary theory changes, which have restructured our representations of the physical world.

Some researchers have criticized the conceptual change approach on the grounds that earlier beliefs do not disappear when the currently accepted scientific explanations are understood. This disappearance of earlier representations is not, however, a necessary requirement of the conceptual change approach. The conceptual change approach forces the creation of new, qualitatively different representations. The old representations may continue or may disappear. This is a question for empirical research to determine.

3. Research on the development of science knowledge: basic findings

One of the most important findings of cognitive science research during recent years is the realization that expert scientists organize and represent knowledge in memory in ways different from those used by novices. Expert physicists seem to represent problems in physics in terms of the currently accepted scientific concepts and laws, while novices include surface features of the problem situation in their reasoning (Chi, Glaser, & Farr, 1988). For example, Chi et al. (1988) found that novices formed a representation of the concept of an inclined plane which contained surface features such as angle of incline, length, height, etc. On the contrary, expert physicists organized their representations of the incline plane primarily around Newton's laws and the conservation of energy law.

More recently, developmental studies have provided more information about the way knowledge is acquired and the mechanisms by which novices become experts. These studies have shown that the knowledge acquisition process starts early in infancy and is based on interpretations of everyday experience (see Baillargeon, 1990; Spelke, 1991). For example, Spelke (1991) has described five constraints about the behaviour of physical objects which infants appear to appreciate from early on, such as continuity, solidity, no action at a distance, gravity and inertia. Vosniadou (1994a) has argued that such knowledge forms an initial framework theory of phys-

[1] This framework theory is assumed to be quite different from scientific theories. We are basically talking about a causal explanatory framework for organizing physical phenomena which not only does not have the status of a scientific theory but is not even available to conscious awareness and hypothesis testing.

ics, which forms the foundation upon which further knowledge about the physical world is organized.

Investigations of elementary and high-school students' knowledge of the physical world have revealed further information about children's initial explanations of physical phenomena and have shown how these explanations change as the children are exposed to the teaching of science. For example, research in the area of mechanics has shown that young children construct an initial concept of force according to which force is a property of objects that feel heavy. This *internal force* model attempts to capture the potential these objects have to react to other objects with which they come in contact. Later, they differentiate animate from inanimate objects with respect to force and think of force as an *acquired* property of inanimate objects that move. The *acquired force* model becomes central in explaining the motion of inanimate objects. In the ontology of the young child, the natural state of inanimate objects is that of rest, while the motion of inanimate objects is a phenomenon that needs to be explained, usually in terms of a causal agent. This causal agent is the force of another object (Ioannides & Vosniadou, 1991).

This initial concept of force is obviously very different from the currently accepted scientific concept. In Newtonian physics, force is not an internal property of objects but a process which is used to explain changes in the kinetic state of physical objects. In the framework of the accepted view, motion is a natural state that does not need to be explained. What needs to be explained is changes in kinetic state.

The process of understanding the meaning implicit in the scientific concept of force is usually a slow and gradual affair, likely to give rise to misconceptions. Research in science education has documented many misconceptions in mechanics, most of them related to students' interpretations of force as an acquired property of objects that move. For example, in a study conducted by Clement (1982), first-year engineering students taking a physics course were presented with a drawing depicting a coin that was thrown upwards vertically (see Fig. 1). Clement asked the students to draw vectors to represent the forces that were exerted on the coin. Only 12% of

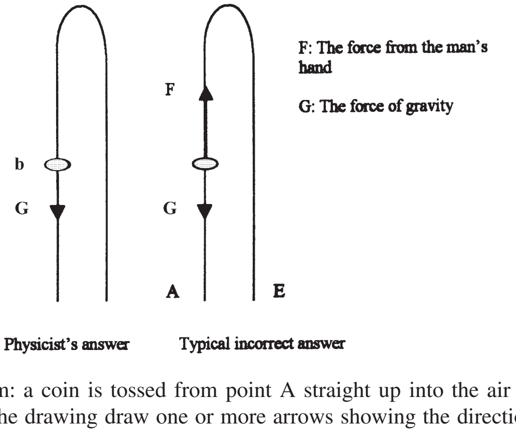

Fig. 1. The toss problem: a coin is tossed from point A straight up into the air and caught at point E. On the dot to the left of the drawing draw one or more arrows showing the direction of each force acting on the coin, when it is at point b. (Draw longer arrows for larger forces.)

the students gave correct responses, while 90% of those who gave a scientifically wrong answer drew two vectors, one representing the force of gravity (towards to the ground) and another in the opposite direction. This latter force was supposed to represent—according to the subjects' explanations—the "force I am giving it" or "the force of the throw", etc.[2] Clement reported that at the end of a course in mechanics the scientifically correct responses to the same task given by two other groups of engineering students were respectively 28% and 30% only.

In another study, conducted in New Zealand, Osborne and Freyber (1985) presented students (ages 7 to 19) with a drawing of a golf ball moving in the air, away from the golf player who had hit it. The researchers asked the subjects the question: "Is there a force on the golf ball?" More than half of the subjects believed that there was a force within the ball acting in the direction of its motion. Some common explanations were: "The force from when he hit it is still in it", or "It is the force from the golf stick which slowly dies out". These responses show that the subjects consider that there should be a force within the moving object which explains its motion. The cause of this force is usually attributed to the original mover.

Students' ideas about the relation between force and objects in rest have also been studied (e.g. Ministrel, 1982; Clement, 1986; Osborne & Freyber, 1985). Many students believe that if an object is not moving, there is no force exerted on it. In the study mentioned before by Osborne and Freyber (1985), students were presented with a drawing depicting a man pushing a car. The students were informed that the car was broken and the man was trying to move it but unsuccessfully. They were then asked: "Is there a force on the car?" Some subjects gave negative responses to the question. Common explanations were such as the following: "There is no force on the car, because he is not forcing the car—the car won't move, it would be too heavy."

In summary, there is much empirical evidence that supports the argument that both children and adults hold alternative ideas about force and give explanations about motion and rest that are incompatible with the Newtonian theory of mechanics. It appears that the perceived relation between force and motion is rather strong and does not go away even after years of instruction. Misconceptions, of course, do not occur only in the case of force. They have been found in practically every subject-matter area of the physical sciences. Most adults in our society who are not expert scientists do not understand even some of the most commonly used concepts in the physical sciences, such as the concepts of energy, pressure, heat, temperature, etc. (see Wiser & Carey, 1983; Tiberghien, 1994). The question these findings pose is: Why is it so difficult to understand concepts in science and how can we construct learning environments to foster science learning?

[2] The scientific explanation is that there is only one force exerted on the coin, the force of gravity. According to the law of inertia, the coin is moving because it tends to retain its initial velocity.

3.1. The reinterpretation of deeply entrenched presuppositions and beliefs

A series of developmental studies undertaken in several subject-matter areas in the physical sciences (see Vosniadou, 1994a) reveal that children's interpretations of scientific information are often constrained by a few deeply entrenched presuppositions that are part of their framework theory of how the physical world operates. For example, studies of children's representations of the earth (Vosniadou & Brewer, 1992) have shown that elementary school children have a great deal of difficulty creating an exact representation of the spherical shape of the earth and the regions of the earth where people live. Many children believe that the earth is shaped like a flat *rectangle* or a *disc* that is supported by ground and covered by the sky and solar objects above its "top". Other children think of the earth as *a hollow sphere*, with people living on flat ground deep inside it, or as *a flattened sphere* with people living on its flat "top" and "bottom". Finally, some children form the interesting model of a *dual earth*, according to which there are two earths: a flat one on which people live, and a spherical one which is a planet up in the sky. These representations of the earth are not rare. In fact, only 23 of the 60 children (20 first-graders, 20 third-graders and 20 fifth-grades) that participated in the Vosniadou and Brewer (1992) study had formed the accepted model of the spherical earth. This finding has been confirmed by a series of cross-cultural studies that investigated the concept of the earth in children from India, Greece, and Samoa (see Vosniadou, 1994b, for a discussion of the cross-cultural findings).

In previous work, children's difficulty in understanding the spherical model of the earth has been explained on the grounds that this model violates certain fundamental presuppositions about the physical world, such as the presupposition that space is organized in terms of the directions of "up" and "down" with respect to a flat ground, and that unsupported objects fall in a "downward" direction—what we call the up/down gravity presupposition (see Vosniadou & Brewer, 1992; Vosniadou, 1994a).

It appears that children start with an initial concept of the earth as a physical object which has all the characteristics of physical objects in general (i.e. it is solid, stable, stationary, and needing support), in the larger context of a physical world in which space is organized in terms of the direction of up and down and in which unsupported objects fall "down". When they are exposed to the information that the earth is a sphere, they find it difficult to understand because it violates certain of the above-mentioned presuppositions about physical objects. Many of their "misconceptions" regarding the spherical shape of the earth are in fact synthetic models, attempts to reconcile the accepted view with these entrenched presuppositions without giving them up, or by changing them partially.

Synthetic models have not been obtained only in the case of the earth concept. They are common in mechanics (Ioannides & Vosniadou, 1993), in geology (Ioannidou & Vosniadou, 1997), and in biology (Kyrkos & Vosniadou, 1997). In a study of conceptual change in the domain of the neo-Darwinian theory of evolution, Archodidou and Jacobson (1997) found that students' initial models were embedded in an explanatory framework constrained by at least four basic presuppositions about the nature of biological phenomena: (a) psychological essentialism, (b) causal determinism, (c) animals are sentient beings who choose their actions, and (d) nature is an all-encompassing and well-functioning system where each part fits in its proper place and has a specific function to fulfil. They were then able to identify a number of synthetic models that represented attempts to synthesize the scientifically accepted neo-Darwinian model with these four presuppositions.

In the case of force, an important presupposition that seems to constrain the understanding of the Newtonian concept of force as discussed earlier is the presupposition that force is a property of objects (either an *internal* or an *acquired* property of the objects that move). This presupposition stands in the way of understanding force as the action of an object on another and creates many misunderstandings about force and energy.

The construction of synthetic models (or misconceptions) shows that knowledge acquisition is a gradual process during which existing knowledge structures are revised slowly. Vosniadou and Brewer (1992) have assumed that the knowledge base consists of a number of interrelated observations, beliefs, and presuppositions that form a relatively coherent explanatory framework. Despite their assumed interrelatedness, the various beliefs and presuppositions have different degrees of entrenchment and some are more difficult to change than others. Vosniadou and Brewer (1992, 1994) distinguish between beliefs which are based on relatively superficial observations and those which are easy to change (such as, for example, the belief that the sun and/or the moon are shaped like a disc rather than a sphere), compared with "entrenched presuppositions" which are deeper theoretical constructs, more difficult to change (such as, for example, the presupposition that space is organized in terms of the directions of up and down). This distinction is crucial in order to explain the empirical findings that show that in the process of knowledge acquisition some aspects of children's knowledge about the physical world are more difficult to change than others.

3.2. Metaconceptual awareness

It is important to take into consideration the fact that students are often not aware of the presuppositions and beliefs that constrain their learning. Students are not, for example, aware that they consider force as a property of objects. Even when they become aware of such presuppositions they do not always understand their theoretical nature. They take them to be facts about the way the physical world operates rather than propositions in a hypothetical explanatory framework subject to verification and falsification. Finally, as diSessa (1993) has pointed out, the explanatory frameworks students use usually lack the systematicity and coherence of the theory of physics used by experts. In other words, conceptual change involves not only change in specific beliefs and presuppositions but also the development of metaconceptual awareness and the construction of explanatory frameworks with greater systematicity, coherence, and explanatory power.

3.3. The importance of mental representations

In addition to deeply entrenched presuppositions, the specific mental representations children use when they try to understand new information seem to exert their own, unique influence on the knowledge acquisition process. We have used the construct of the "mental model" to describe individuals' representations of the physical world. This construct has been used differently by different researchers (e.g. Johnson-Laird, 1983; Gentner & Stevens, 1983). It is used here to refer to an analog and generative representation which can be manipulated mentally to provide causal explanations of phenomena (see Fig. 2). It is assumed that most mental models are created on the spot to deal with the demands of specific situations.

The mental models individuals generate during cognitive functioning can constrain the knowledge acquisition process in ways similar to presuppositions as described earlier. For example, students' explanations of the day/night cycle are often constrained by their mental models of the earth (Vosniadou & Brewer, 1994). Thus, students with a rectangle, disc or dual earth model explain the day/night cycle by saying that the sun goes down behind the mountains (see Fig. 2, sketch 1) or other similar explanations based on everyday experience. These students do not provide

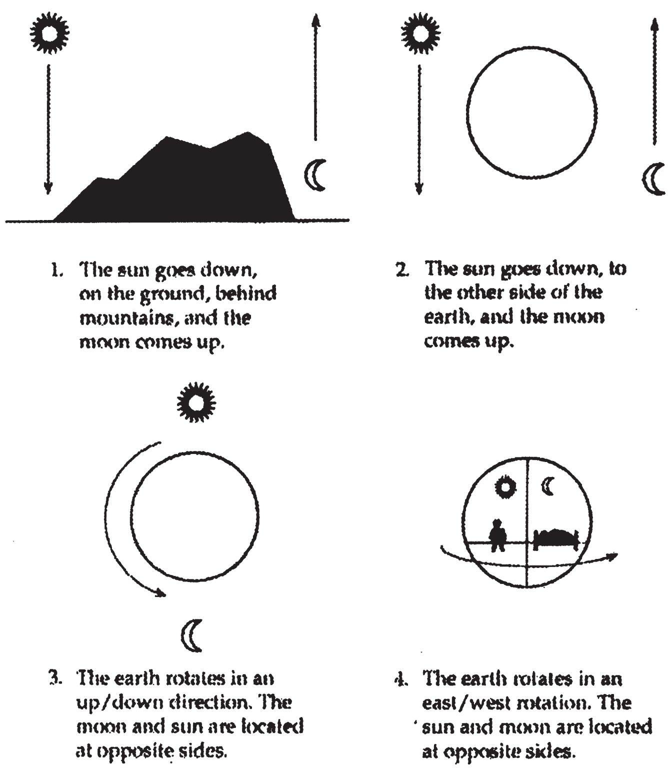

Fig. 2. How students' mental models of the earth influence their explanations of the day–night cycle.

explanations of the day/night cycle in terms of the axis rotation of the earth (see Fig. 2, sketches 3 and 4), or even explanations according to which the sun "goes down to the other side of the earth" (see Fig. 2, sketch 2). These latter explanations are obviously inconsistent with the mental model of a flat, stationary earth rooted on the ground. It is only when the model of a spherical earth, suspended in space, is formed that explanations of the day/night cycle in terms of the rotation of the earth become available to students. This brings us to the last point of the present discussion which has to do with the sequence of acquisition of the concepts that comprise a given subject-matter area.

3.4. Sequence of acquisition of the concepts that comprise a given subject-matter area

The concepts that comprise a subject-matter area have a relational structure that influences their order of acquisition. For example, it is not possible to understand the spherical shape of the earth and where people live in the earth without achieving a very elementary knowledge about gravity. Children believe that unsupported objects fall downwards. This presupposition stands in the way of understanding how people can live on a spherical earth. What is needed for students to understand the spherical shape of the earth is to revise the up/down gravity concept and to understand that gravity acts by pulling objects towards the centre of the earth. Similarly, it is not possible to understand the scientific explanation of the day/night cycle in terms of the rotation of the earth; they must first understand that earth is a sphere, and so on.

In other subject-matter areas similar sequences in the order of acquisition of concepts have been observed. For example, studies by Ismini Ioannidou and Vosniadou (1999) have shown that an understanding of the spherical shape of the earth and of gravity are prerequisites for understanding the spherical arrangement of layers inside the earth and the placement of lava in the centre of the spherical earth. In mechanics, children must understand that force is not an internal property of objects and start to form a distinction between force and energy.

3.5. Summary

Cognitive science and science education research have produced important findings about the nature and process of conceptual change. One is the finding that by the time they enter elementary school, children have already constructed initial conceptual structures about the physical world which are in many ways different from the scientific concepts to which they will be exposed through instruction. These initial conceptual structures form the basis upon which further information is incorporated. The process of conceptual change appears to be a gradual and complex affair during which information that comes in through observation and/or instruction is incorporated into the existing knowledge base and can produce different outcomes. It can add new knowledge, it can create new explanations, synthetic models, it can restructure the knowledge base, and so on.

The characterization of the process of conceptual change that emerges from these studies is different from the view of science learning presented by Posner, Strike, Hewson, and Gertzog (1982) in fundamental ways. The Posner et al. (1982) theory focuses on the incompatibility between two distinct and equally well-organized explanatory systems, one of which will need to be abandoned in favour of the other. The results of the above-mentioned cognitive/developmental studies, on the other hand, suggest that conceptual change is a slow revision of an initial conceptual system through the gradual incorporation of elements of the currently accepted scientific explanations. During this process students need to be helped to *become aware of their existing beliefs and presuppositions*, to understand their theoretical nature and possibility of falsification. They also need to slowly change their existing conceptual structures in ways more consistent with the currently scientifically accepted views. Eventually they need to be helped to create larger theoretical constructions that have greater explanatory adequacy and also achieve the flexibility needed to take into consideration other points of view.

4. Designing a learning environment

The domain-specific restructuring interpretation of the process of learning science which was outlined above has specific recommendations to make for the design of learning environments for science instruction both at the level of curricula and at the level of instructional methods and interventions. These recommendations will be discussed below.

4.1. Breadth of coverage of the curriculum

The finding that the understanding of science concepts and explanations is a difficult and time-consuming affair probably gives rise to misconceptions, and calls for a reconsideration of current decisions regarding the breadth of coverage of the curriculum in science education. It may be more profitable to design curricula that focus on the deep exploration and understanding of a few, key concepts in one subject-matter area rather than curricula that cover a great deal of material in a superficial way. For example, the science curriculum for the fifth grade in Greece includes short units on mechanics, thermodynamics, energy, particulate nature of matter, the processes of life, etc. This approach does not give students enough time to achieve a qualitative understanding of the concepts being taught. On the contrary, it encourages the casual memorization of facts, and it is very likely to lead to logical incoherence and misconceptions. It also makes teachers very anxious about covering all the material with the result that not enough attention is paid to what students actually understand.

4.2. Order of acquisition of the concepts involved

This relational structure in which the concepts of a domain are acquired needs to be taken into consideration. For example, research has shown that in the subject-matter area of mechanics, students have developed an alternative concept of force as a property of an object that moves. This force has been transferred to the object from the agent that sets the object in motion and gradually dissipates (as the moving object stops). This initial concept of force shares many similarities with the scientific concept of energy. Therefore, it is not surprising that students conflate the two concepts. In order to facilitate the differentiation between force and energy it is important to provide instruction that makes the differences clear, something that does not happen in existing curricula.

4.3. Taking into consideration students' prior knowledge

The realization that students do not come to school as empty vessels but have representations, beliefs and presuppositions about the way the physical world operates that are difficult to change has important implications for the design of science instruction. Teachers need to be informed about how students see the physical world and learn to take their points of view into consideration when they design instruction. Instructional interventions need to be designed to make students aware of their implicit representations, as well as of the beliefs and presuppositions that constrain them. It is important to provide meaningful experiences that lead students to understand the limitations of their explanations and to motivate to change them. Finally, it is necessary to provide the necessary cultural support for the reorganization of existing knowledge, necessary for learning science.

4.4. Facilitating metaconceptual awareness

Although students are relatively good interpreters of their everyday experiences, they do not seem to be aware of the explanatory frameworks they have constructed and of the presuppositions that constrain them. Even when they start to achieve this metaconceptual awareness they do not understand that their explanations are hypotheses that can be subjected to experimentation and falsification. Therefore, their explanations remain implicit and tacit. Lack of metaconceptual awareness of this sort prevents students from questioning their prior knowledge and facilitates the assimilation of new information into existing conceptual structures. This type of assimilatory activity seems to form the basis for the creation of synthetic models and misconceptions and lies at the root of the surface inconsistency so commonly observed in students' reasoning.

To help students increase their metaconceptual awareness, it is necessary to create learning environments that make it possible for them to express their representations and beliefs. This can be done in environments that facilitate group discussion and the verbal expression of ideas. It is also important to create learning environments that make it possible for students to express their internal representations of phenomena, to compare them with those of others. Such activities may be time-consuming, but they are important for ensuring that students become aware of what they know and what they need to learn.

4.5. Addressing students' entrenched presuppositions

It is very often the case in science instruction that counterintuitive information is introduced as a fact. For example, in astronomy, students are often simply told that "the earth rotates around its axis", "the sun is much bigger than the earth", or "the sun is a star", without an explanation of how it is possible for the earth to move when we do not feel any movement, how it is possible for the sun to be bigger than the earth when it appears to be much smaller, and how it is possible for the sun to be a star when stars appear in the sky only in the night, have a different shape than the sun, are smaller, and so on.

It is important in instruction to distinguish new information that is consistent with prior knowledge from new information that runs contrary to prior knowledge. When the new information is consistent with prior knowledge, it can be incorporated easily into existing conceptual structures. This type of information is most likely to be understood even if it is presented as a fact without any further explication. However, when the new information runs contrary to existing conceptual structures, simply presenting the new information as a fact may not be adequate. In this situation students seem to have two courses of action available to them. One is simply to add the new fact to their existing conceptual structures. If they do this the new representation will probably be inconsistent with the old. The other is to distort the new fact to make it consistent with the existing structure. In this case the result will most probably be a synthetic model. In order for the counterintuitive information to be understood, students must *restructure* the conceptual structures they already hold to make them consistent with the new information. This is difficult and hard work and the students need to be motivated enough to undertake it.

4.6. Motivation for conceptual change

Students often do not see the reason to change their beliefs and presuppositions because they provide good explanations of their everyday experiences, function adequately in the everyday world, and are tied to years of confirmation. In order to persuade students to invest the substantial effort required to become science literate and to re-examine their initial explanations of physical phenomena, we need to provide them with an environment that will motivate such changes and relate them to the social and cultural environment outside the narrow context of the school. Students need meaningful experiences, for example in the form of systematic observations or the results of hands-on experiments, that will prove to them that the explanations they have constructed are in need of revision. If we want these experiences to be useful in the process of conceptual change we need to select them carefully so that they are theoretically relevant. What we mean by theoretically relevant is that they address the underlying presuppositions and beliefs that constrain students' representations and influence the way they interpret scientific information and show them that these presuppositions are not adequate to explain the known empirical facts.

4.7. Cognitive conflict

Some researchers have focused their attention on students' misconceptions, and have argued that it is important to make students confront these misconceptions and replace them with scientific concepts by producing cognitive conflict. Although we believe that cognitive conflict can be useful in an overall programme of science instruction, we also think that it should be used carefully. First, it is often the case that the focus of cognitive conflict is to confront a specific misconception. However, focusing on students' misconceptions alone may not always provide a solution to the problem of conceptual change. If misconceptions are formed because of students' inadequate attempts to change their entrenched presuppositions, then what is needed for misconceptions to be abandoned is for students to change the entrenched presuppositions that give rise to misconceptions. As an illustration, let us take once more the example of the concept of the earth. Telling a child who believes that people live on flat ground inside the earth that the earth is not hollow will not immediately solve the child's problem with the notion of a spherical earth. Children believe that the earth is a hollow sphere because they do not understand how people can live at the "bottom" of the sphere without falling off, and because they cannot reconcile their perception of a flat earth with the idea that the earth is round. What children need in order to get rid of this misconception is a lesson on gravity, and a lesson on how round things can sometimes appear to be flat. Otherwise one misconception will be replaced with another, or children will remain confused.

Similarly, with the impetus misconception in mechanics. This misconception is based on the presupposition that the movement of inanimate objects must be explained in terms of an outside agent. Unless students understand that what needs to be explained is not the movement of inanimate objects but changes in motion, the impetus misconception will not disappear. Finally, as discussed earlier, conceptual change is a difficult process that involves the reorganization of not just one misconception or one belief but an interrelated system of beliefs and presuppositions that takes a long time to be accomplished. Thus, conceptual change cannot but be a gradual affair, which requires the use of many different instructional interventions of which cognitive conflict is only one.

4.8. Providing models and external representations

If students think in terms of models, then instruction that is model-based, rather than only linguistically and/or mathematically based, may have a better chance of producing conceptual change. One of the problems of traditional instruction is that it moves students very quickly from memorizing and applying formal quantitative laws into problem-solving situations without teaching students the qualitative models that the scientists themselves use to support their reasoning (see, for example, Nersessian, 1992, 1995). Models and external representations can be used to clarify aspects of a scientific explanation that are not apparent when the explanation is given in a linguistic or mathematical way. The visual qualities of a model are useful in making an explanation better understood and more easily memorized (e.g. Mayer, 1993).

5. Understanding the environmental variables that promote conceptual change in the classroom

Cognitive/developmental research usually focuses on descriptions of the cognitive performance of subjects at different ages and at different levels of expertise rather than on the mechanisms that explain how cognitive performance and cognitive change happen. Cognitive psychologists are interested primarily in understanding the cognitive, mental processes that are assumed to go on inside the head during intellectual activity. This research does not provide information about the external, environmental variables that can be manipulated to facilitate cognitive performance and conceptual change. Knowledge of these variables is also needed, however, to guide instructional research and practice.

The results of the instructional experiments and interventions of the past years have shown clearly that concepts are embedded in rich situational contexts, in the tools and artefacts of the culture, and in the nature of the symbolic systems used during cognitive performance. Conceptual change can, and most often is, initiated, facilitated, and consolidated by social and cultural processes. As conceptual change research moves ahead towards a description not only of the performance of subjects at different ages and level of expertise but also of the mechanisms that can bring about these changes, the role of the situational context and of culture become much more important. Research on how to promote conceptual change should certainly try to understand and describe these processes in greater detail.

Moving in the direction of taking into consideration situational and cultural variables does not necessarily mean the abandonment of the level of mental representations and its replacement with discourse analysis as suggested by some radical situationists (e.g. Säljö, 1999). A theory of conceptual change needs to provide a description of the internal representations and processes that go on during cognitive activity but should also try to relate these internal representations to external, situational variables that influence them.

In an effort to understand some of these variables we undertook an analysis of the dialogue that happens in the classroom as a means of obtaining further information about how the classrooms' communicative interaction influences learning and conceptual change. Methods have been developed that try to take into account the dynamic interactions in the dialogue between a teacher and a group of students (the class) to understand better how knowledge construction occurs. This approach is consistent with the argument that future developments in cognitive science need to develop methodologies that make it possible to relate individual, internal cognitive variables to external, situational and cultural factors (such as aspects of the context, the task, the communicative interaction, the tools and artefacts of the culture). We believe that such an approach can provide us with a more complete and balanced understanding of the processes of conceptual change (Vosniadou, 1996). From the analysis of the teacher–students' instructional dialogues and interactions, we also attempt to determine the kinds of teacher strategies that could be causally related to representational change. Such results could also offer better means to teachers to analyse and become aware of their own practices.

The analysis of classroom discourse is important from an educational point of view because it focuses on the communicative process and tries to relate it to conceptual change in the classroom. So far, research on educational practices has focused on the objectives, the content, the tasks, and the modes of pedagogical interventions. The activity of students and their responses to the questions of the teacher were analysed either to point out their conceptual difficulties and misconceptions or to determine the success of instructional interventions. However, learning does not result from passive responding to external stimuli but from the interactions of the learner in a physical and social context. The quality and the variety of these interactions permit the learner to reorganize and restructure what already exists in the knowledge base. Knowledge acquisition and conceptual change take place through a process of formulation, reformulation, and reinterpretation of knowledge, where the learner is constantly evaluating their relevance, contrasting different points of view, and testing their validity. The learner is an active constructor of his/her knowledge, and the process of knowledge acquisition is greatly facilitated by interactions with peers and particular with a teacher acting at the zone of proximal development (Vygotsky, 1978).

5.1. The present study

The present study involved the design and implementation of a learning environment to teach mechanics to fifth-grade students (10–11 years of age). It was part of a larger project whose purpose was to develop and test learning environments to promote the learning of science in elementary school. The larger project included units in astronomy, thermodynamics, and the particulate nature of matter, in addition to mechanics. The mechanics course lasted for a period of 8 weeks (8 lesson units, 90 minutes each). It was designed by our experimental team and was taught by one of the experimenters in the presence of the classroom teacher who also participated in the instruction. Further information about the unit on mechanics will be provided in the Section 6.

5.1.1. Evaluation

The cognitive effects of the learning environment were evaluated on the basis of the results of a pre-test–post-test comparison for both the experimental and the control groups. In order to have a better understanding of how students changed their ideas during the period of instruction, in-depth interviews were conducted with a small number of students when the period of instruction was finished. All instructional units were videotaped and detailed analyses of the videotapes took place in order to better understand the teacher–student interactions, the classroom environment, the exchanges among students, and so on. Finally, the classroom discourse was recorded, transcribed and analysed to be used as another source of information about the dynamics of conceptual change. In the following text, examples will be given from the pre-test–post-test comparisons, the in-depth interviews and the analysis of the classroom discourse.

6. Method

6.1. Participants

Students of two different classes participated in this study. They attended the same school in the centre of Athens. The students of the one class comprised the experimental group and those of the other class the control group. The control group received the regular instruction in mechanics, as specified in the National Curriculum (3 weeks of instruction, 9 lesson units of 45 minutes each), by the regular teacher. All class activities of the experimental groups were videotaped, while some lessons of the control classes were also videotaped.

6.2. The design of the curriculum and of the instructional interventions

In designing the learning environment we tried to take into consideration the general principles derived from cognitive science research discussed in the Introduction. Therefore, much attention was placed on promoting the *constructive aspects of learning*, *facilitating collaboration* and *providing opportunities for meaningful activities*.

In order to achieve the above, the students of the experimental class were divided into five groups of five students each. Each group worked together to do various activities. Usually the class work began with a question given to the students. They were asked to give an individual answer in their notebook before discussing it with the other members of the group. After the group discussion the students were asked to agree on a group response and prepare a class presentation for general discussion. Class discussions were common and, in addition to the group representative, all the other children could participate. Students asked questions to the group representative, or made comments to clarify or challenge the answer proposed by his/her group. The aim of these discussions was to arrive at an answer to the initial question accepted by all. However, there were often unresolved disagreements among the groups and an experiment was proposed that would provide an objective answer to the problem being investigated. The experiments were conducted in the class, using everyday materials and were always related to questions and issues the students had already discussed. The above-mentioned activities ensured an energetic, constructive role for each student while at the same time demanding collaboration at the level of the small group and participation in the class discussion.

In the previous section it was argued that it is important to take into consideration the results of specific research on the acquisition of subject-matter information when designing a learning environment for science learning. In this project, the results of research on the acquisition of the concept of force were taken into consideration in designing the mechanics learning environment in the ways that will be outlined below.

6.2.1. Taking into consideration students' prior knowledge

Students' prior knowledge and their particular difficulties in understanding the different concepts and explanations of phenomena guided the selection both of the content and of the instructional interventions. We have argued that students operate on the basis of a naive theory of physics constructed on the basis of their everyday experience and acting as a constraint in the acquisition of scientific knowledge. In the case of phenomena of mechanics, such as rest and motion, our research (Ioannides & Vosniadou, submitted for publication; Vosniadou, Kayser, Champesme, Ioannides, & Dimitrakopoulou, 1999) and that of others (Clement, 1982; McCloskey, 1983) have shown that elementary school children believe that force is an acquired property of inanimate objects that explain their movement. According to this acquired force model, also known as the impetus misconception in the literature, force is the agent that causes an inanimate object to move. The object stops when this "acquired force" dissipates in the environment. These characteristics of force frequently make students conflate *force* with *energy*, and make it difficult for them to understand the scientific explanation of motion.

The experimental curriculum was designed to help students to develop distinct and well-differentiated concepts of force and energy: force as the interaction between two objects that has a magnitude and a direction that can be represented by a vector; energy as the potential of physical objects to exert forces on other objects, that also has a magnitude and that in contrast to force can be transferred from one object to another and transformed from one form to another (e.g. potential energy can be transformed to kinetic energy). We tried to embed these concepts in meaningful activities around everyday phenomena, such as man's ability to produce work (e.g. to lift/push/pull a box), the physical fatigue experienced after a long muscular effort, the deformation of objects on which a force is exerted, etc. The design of the learning environment was based not only on the results of prior research on student's ideas about force and motion but also on the analysis of the responses given by the students of the experimental group to the questions of a pre-test. In addition, during the period of instruction the experimental teacher encouraged the students to make their ideas overt and was always ready to make the necessary adaptations in the instruction in order to address children's specific ideas and help them to develop the scientifically accepted model.

6.2.2. The use of measurements, external representations and models

The students worked in small groups and were involved in hands-on experiments during which *measurements of the magnitude of various forces* were taken. They also used symbolic *representations of force and energy* and *models* to represent the cause of frictional force, as described below.

6.2.2.1. Measurement of forces. During the second lesson unit, students were shown how to use a dynamometer to measure forces. They were also encouraged to construct their own dynamometers (using simple materials) to acquire a better understanding of the function of the dynamometer. The purpose of these activities was to provide students with an instrument with which they could measure and compare forces. We believed that the measurement of forces would help children towards an understanding of the scientific concept of force, as the measurable interaction between two objects, instead of thinking of force as a property of physical objects.

6.2.2.2. External representations of force and energy. Emphasis was also placed on providing different representational symbols for expressing force and energy. We reasoned that the use of external representations would help children form a mental model of force consistent with the scientific interpretation. To this effect, students were provided with vectors as symbols for the representation of forces. Vectors were introduced not only in graphical representations, as they are commonly used by scientists, but also as three-dimensional objects made of cardboard so that they could be used in the classroom to represent forces exerted on real, three-dimensional objects. Fig. 3 shows how these representations of vectors were used in the classroom to represent the force of gravity and the reaction from a table exerted on a brick placed on top of the table.

For the same reasons there was also need for a representational symbol of energy. Given the lack of a representational symbol for energy, small yellow stickers were used to represent energy units. The stickers were attached to a piece of cardboard to represent objects' energy deposits. The students were shown how to transfer stickers from the energy deposit of the first object to the energy deposit of another object in order to represent energy transfer. They were also shown how to use the vectors described above to represent forces exerted by one object (e.g. a man kicking a ball) onto another object (e.g. the ball). We believed that the simultaneous use of two different representation symbols, one for energy and another for force, would maximize the probability of differentiating the two concepts.

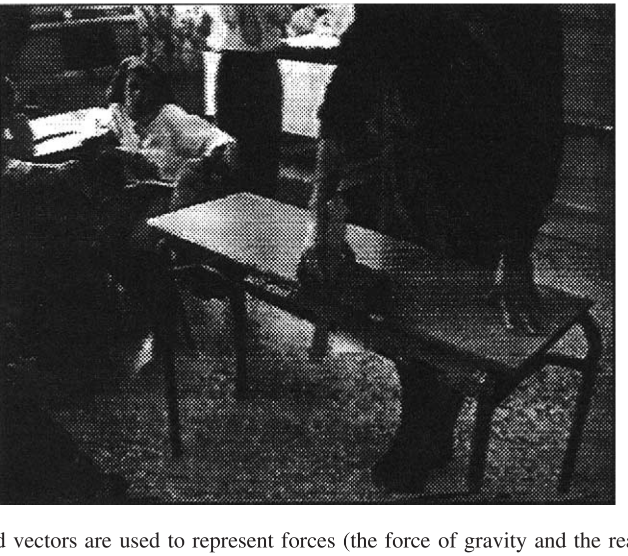

Fig. 3. Cardboard vectors are used to represent forces (the force of gravity and the reaction force from the table) exerted on a brick placed on the top of a table.

6.2.2.3. A model to explain friction. In order to help children construct the scientific representation of the concept of frictional force, the "friction model" was introduced in lesson unit 6. This model was introduced after the children had already experienced how the hardness of different surfaces affects the motion of the objects that slide on them. At this point the teacher asked the students to explain the fact that even the polished smooth surface of the top of a table hinders the motion of the objects moving on it. He then presented to them slides with photographs of glass surfaces magnified by an electronic microscope as proof that even the smoothest surface has anomalies that cause the appearance of frictional forces. After a short discussion at the class level about how these anomalies of the surfaces can hinder the motion of objects, the teacher presented the "friction model" to the students. The model was made of cardboard and represented a magnification of the anomalies of the surface of the moving object and of the supporting object, as shown in Fig. 4.

The students were asked to use the model to explain how the roughness of the surfaces (longer "teeth" of the two pieces of cardboard) and the weight of the object (more points of contact between the teeth of the two pieces of cardboard) affect the frictional force (see Fig. 4B).

The students were asked to represent the frictional force as well as the other forces exerted on the sliding object (force of gravity, reaction force from the ground, and the force of push/pull from the man), using cardboard vectors and the "friction model". The role of the lubricants was also represented. For this purpose two pieces of cardboard (coloured yellow) representing the lubricant were placed among the two surfaces and filled the gaps between the teeth. The students had the opportunity

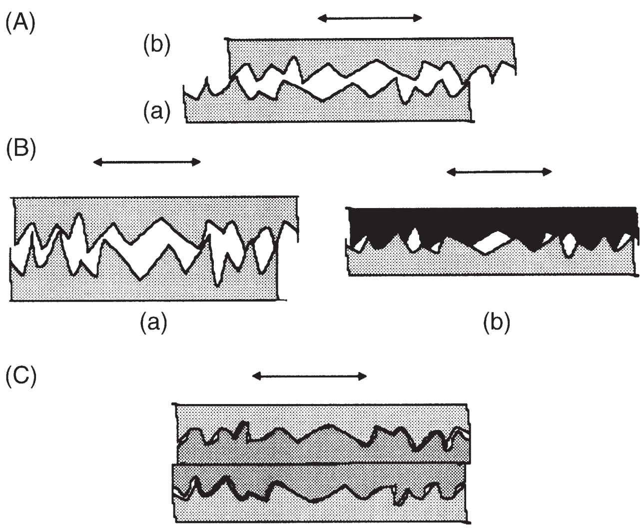

Fig. 4. The "friction model": (A) representing a magnification of the surface of an object (b) sliding on a supporting surface (a); (B) used to explain how (a) the increased roughness of the surfaces and (b) the increased weight of the object affect its motion; and (C) used to explain how lubricants affect the motion of an object.

to experience how the piece of cardboard on the top could now slide easily over the other and relate this to the actual motion of a brick on the top of the table covered with lubricant (see Fig. 4C).

6.2.3. Using cognitive conflict to deal with entrenched beliefs

Cognitive conflict was used in certain occasions to make children realize that their explanatory framework could not explain some empirical results. In one case (lesson unit 3) the students' model that unless an object is moving there is no force on it was challenged. In this model (*acquired force*), force is considered as an acquired property of the moving object. Children were given the opportunity to measure (using the dynamometer to which they were introduced in lesson unit 2) the force exerted on objects that were being pushed or pulled but did not move. For example, the students were asked to pull a heavy table in the classroom, which they could not move. The dynamometer was used to prove that a force was being exerted on the table even though it did not move.

In another case (lesson unit 6), we challenged students' belief that in order to make an object slide on the ground a force must be exerted on the object that is greater than its weight. In this model, weight is considered as a property of the object and not as an interaction between the earth and the object. Children were asked to test their predictions using different objects and dynamometers to compare the weight of the objects and the magnitude of the force that makes the objects slide on different surfaces. Children were surprised to see that the forces exerted were always smaller than the weight of the objects. This created a strong motivation for them seek the scientific answer. Through carefully selected activities children realized that motion of the object is affected by the hardness of the surface on which the objects slides and thus could approach the concept of frictional force.

6.2.4. Sensitivity to the order of the concepts to be taught

A great deal of attention was paid to the sequence in which the concepts were introduced in order to avoid the formation of new misconceptions and to overcome existing ones. In designing every instructional intervention, we tried to think of all the possible synthetic models that could be construed by children on the basis of their prior knowledge. This analysis provided the basic criteria for designing the order of the concepts and the phenomena being taught. For example, before students were engaged in the study of reaction force (e.g. the force exerted by the table on an object that is standing on the top of it), their belief that force is exerted only on moving objects was addressed.

Sensitivity to the order of the concepts being taught was also the main reason for providing students with the tools to measure and represent forces at the beginning of the instruction sequence. The vectors used were very useful symbols that helped students to externalize their ideas about force and communicate them to the other students and the teacher. The dynamometer was also an invaluable tool for the students to measure and compare forces exerted on objects and to test the validity of their ideas. It was believed that both the measurement of forces and the use of vectors would help children to move from their intuitive model of force as a property of objects and to construct a mental representation of force as a quantity that springs out of the objects at the moment they interact with each other.

6.2.5. Dealing with linguistic problems

Class discussions were used to make students aware of the differences between the everyday language meanings of certain key words such as “force” and “energy” and their scientific meaning or explanation. For example, in the seventh lesson students were asked to say whether a small child would exert the same force as that of a full-grown man to lift the same heavy object. The students believed either that the small child would need to exert more force because he must try harder or that the small child would need less force because he has less force. Only one student gave the scientifically correct response that the man and the child would exert equal forces to lift the object because there is only one and the same object. The class discussion did not produce agreement and the students proposed to conduct an experiment to test their predictions. A dynamometer was used to measure the forces exerted by the teacher and by a student on a heavy brick while they were trying to lift it from the ground. The students were astonished to see that the teacher and the student exerted equal forces.

During the class discussion that followed, the teacher tried to make the students understand that the different predictions arose from the different meanings given to the word force. In other words, the “more force due to more effort” response implies that force is interpreted as the “effort exerted by someone”, while the “less force because the child has less force” response implies that force is interpreted as a property of the man. The “equal force” response implies that force is interpreted as an action on an object and its size is related to the effect produced. A distinction was then made between the two everyday meanings of the word force (*effort* and *property of humans*) and the scientific meaning (the action of one object on another). The discussion made clear to the students that the scientific meaning of force was the one they were taught in school and was used to explain physical phenomena in the currently accepted scientific way.

7. Results

This section starts with a discussion of the results of the pre-test and post-test comparisons. It continues with a discussion of the in-depth interviews and concludes with some results from the classroom dialogue analysis.

7.1. Pre-test and post-test comparisons

The pre- and post-tests were identical and were given to the students of both the experimental and the control class a week before the beginning of the instructional period and a week after it ended. The tests consisted of four sets of questions containing 14 questions. The results of two sets of questions will be reported here: (a) two questions regarding force in relation to stationary objects and (b) two questions regarding force and energy in relation to humans. Of the remaining two sets of questions, the first concerned force and energy in relation to moving objects and the second consisted of questions asking the definitions of concepts. The responses were scored on the basis of a scoring key containing a set of categories for each question. The scoring key was designed to capture the range of specific responses obtained.

The results obtained from these four questions are similar to those obtained from all the questions. A McNemar test showed that in 13 questions there was a significant increase from the pre-test to the post-test in the number of experimental group students who gave scientifically accepted responses, while there was no significant change in the control group in any question. A chi-square test showed that in the post-test in nine questions the experimental group students performed significantly better than the control group students, while in the pre-test either there was no difference between the two groups or the students of the control group performed better. In the remaining four questions, the experimental group performed significantly better in both the pre- and the post-test.

7.1.1. Force in relation to stationary objects or objects being pushed by a man

Table 1 presents the frequencies and percentages of the scientifically accepted responses given by the children of the experimental and the control groups in the pre-test and post-test to the three questions concerning stationary objects and objects being pushed by a man.

We will start with Question 1 of Table 1, where two stones of different size/weight are presented standing on the ground. Here, most of the responses in the pre-test for both the experimental and the control groups are either that there are no forces exerted because the objects do not move (force is related to movement: *acquired force*) or that there is a force being exerted on the objects because they are heavy or only on the big stone because it is heavy (force related to weight: *internal force*). These two responses are indicative of the models of internal force (force as an internal property of objects related to their weight/size) and acquired force (force related to the presence of movement) characteristic of the initial understanding of force prior to instruction. Some children use a third model (the push/pull model) and say that there is no force exerted on the stones because the man is not pushing/pulling them. These three models have been discussed in our previous research (Ioannides & Vosniadou, submitted for publication; Vosniadou, Kayser et al., in press) as well as in the general literature (Clement 1982, 1986; McCloskey, 1983).

These responses remain almost the same in the control post-test but change in the experimental group. The experimental group mentions gravity much more in the post-test than in the pre-test (from 12% to 50%) than the control does (11.8% to 0%). The increase in gravity responses is accompanied by a decrease in the internal, acquired force and push/pull responses for the experimental group.

In Question 2 of Table 1, the students of both the experimental and the control groups focus on the action of the man pushing the stone and say that a force is exerted because the man tries to move the object (*push/pull*). There are also some *internal* and *acquired* force responses which, however, disappear in the post-test for

Table 1
Response categories to the questions regarding force in relation to stationary objects and objects being pushed by a man

	Q1  These two stones are just standing there. Is there a force exerted on them?				Q2  The second stone moves, the first does not. Is there a force exerted on the stones?			
	Experimental (*n*=24)		Control (*n*=17)		Experimental (*n*=24)		Control (*n*=17)	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
1. *Energy consumed*. The man exerts a force on the object because he consumes energy (applies only to Q2)	0	0	0	0	0	3 (6.3%)	0	0
2. *Push/pull*. Q1: No force is exerted on the objects because the man does not try to move them. Q2: A force is exerted on the object because the man tries to move it	4 (16.7%)	1 (4.2%)	3 (17.6%)	1 (5.9%)	14 (58.3%)	20 (83.4%)	9 (52.9%)	7 (41.2%)
3. *Acquired force*. Q1: There is no force exerted on any stone because they are not moving. Q2: There is a force exerted only on the second stone because it moves	11 (45.8%)	4 (16.7%)	5 (29.4%)	4 (23.5%)	4 (16.7%)	0	2 (11.8%)	2 (11.8%)
4. *Internal force*. There is a force exerted on the big/heavy objects or there is more force on the heavy objects than on the light ones	6 (25%)	4 (16.7%)	2 (11.8%)	7 (41.2%)	2 (8.3%)	0	3 (17.6%)	6 (35.3%)
5. *Gravity*. The force of gravity is exerted on all the objects	3 (12.5%)	12 (50%)	2 (11.8%)	0	0	0	0	0
No explanation—Other	0	3 (12.5%)	5 (29.4%)	5 (29.4%)	4 (16.6%)	1 (4.2%)	3 (17.6%)	2 (11.8%)
Total	24	24	17	17	24	24	17	17

the experimental group but not for the control. In the experimental group (and also in the control), we also observe an increase in the number of push/pull responses (which is consistent with the scientific model). Finally, in the post-test some children mentioned the consumption of energy as the justification for the man exerting a force on the stone. This is also a response consistent with the scientifically accepted model that shows the influence of instruction.

In order to evaluate the results using statistical tests, we characterized as "correct" all responses that were consistent with the scientifically accepted model (that is, the gravity, push/pull, and energy consumption categories) and as "incorrect" all other responses. As can seen in Table 1, the frequencies of the correct responses of the students of the experimental group increased in the post-test in the case of both Questions 1 and 2, while in Question 3 there is the same number of correct responses in both tests. On the contrary, in the control group there is no such increase. A chi-square test showed no statistically significant differences between the experimental and the control groups in the pre-test, but there are significant differences between the two groups in the post-test (Question 1: $\chi^2(1)$ 0.21, p=0.65, $\chi^2(1)$ 8.95, p=0.00; Question 2: $\chi^2(1)$ 0.17, p=0.68, $\chi^2(1)$ 12.25, p=0.00).

The McNemar test was also used to compare pre- and post-test responses separately for the experimental and the control groups. The McNemar test showed that the increase in the number of correct responses from pre- to post-test was statistically significant for both Questions 1 and 2 for the experimental group but not for the control (Experimental: Question 1 p=0.01, Question 2 p=0.02; Control: Question 1 p=0.63, Question 2 p=0.29).

7.1.2. Force and energy in relation to humans

A second group of three questions was aimed at testing students' ability to differentiate between force and energy as applied to humans. These results are shown in Table 2.

The first question in Table 2 concerns a situation where two men are stretching the same spring, but one stretches it more than the other. The children are asked to explain why. In this question we distinguished between the categories *energy consumed* and *force consumed*. In the first category, children provide explanations related to energy consumption. This is a response consistent with the accepted model. As shown in Table 2, this response appears only in the experimental group post-test. In the second category of responses, force consumed, we see that children think of force as an internal property of humans which can be consumed. This response is the predominant one in the pre-test for the experimental group as would be expected, since it is not consistent with the scientifically accepted model to which they have been exposed during instruction. This is not the case for the control group, in which the *force consumed* explanation continues to be the predominant one in the post-test as well as in the pre-test. The third category of responses is *force exerted*, in which the children simply say that the second man exerted more force. This is consistent with the scientifically accepted model and increases slightly in the post-test for the experimental group.

In order to test the statistical significance of the differences between the two groups

Table 2
Response categories to the questions regarding force and energy in relation to humans

	Q3  The second man stretches the spring more than the first. Explain why				Q4  The man is very tired. He cannot exert enough force to lift the boxes. Explain what happened to him			
	Experimental (*n*=24)		Control (*n*=17)		Experimental (*n*=24)		Control (*n*=17)	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
1. *Energy consumed*. Q3: The second man has/consumed more energy. Q4: The man is tired because he consumed a lot/all of his energy	0	8 (33.3%)	0	0	9 (37.5%)	20 (83.4%)	2 (11.8%)	1 (5.9%)
2. *Force consumed*. Q3: The first man has/consumed more force. Q4: The man is tired because he consumed a lot/all of his force	16 (66.7%)	9 (37.5%)	6 (35.3%)	10 (58.8%)	6 (25%)	1 (4.2%)	9 (52.9%)	9 (52.9%)
3. *Force exerted*. Q3: The first man exerted more force. Q4: The man could not exert any force at all	3 (12.5%)	5 (20.8%)	8 (47.1%)	3 (17.6%)	1 (4.2%)	0	0	0
4. Tautology, e.g. the man is tired	0	0	0	0	7 (29.2%)	3 (12.5%)	6 (35.3%)	6 (35.3%)
Other	5 (20.8%)	3 (12.5%)	3 (17.6%)	4 (23.5%)	1 (4.2%)	0	0	1 (5.9%)
Total	24	24	17	17	24	24	17	17

we again characterized children's responses which were consistent with the scientific model (response categories 1 and 2) as "correct" and the responses which were inconsistent with the scientific model (the remaining response categories) as "incorrect". The McNemar test showed that the change from the pre-test to the post-test is statistically significant in the experimental group (p=0.00) but not in the control group (p=0.22). The chi-square test showed that there is significant difference between the experimental and the control groups in both the pre-test ($\chi^2(1)$ 6.05, p=0.01) and the post-test ($\chi^2(1)$ 3.85, p=0.04). As shown in Table 2, in the pre-test the control group performed much better than the experimental group, while in the post-test the relation has been reversed. This change in the performance of the two groups makes the influence of the teaching appear even more significant.

In Question 4 of Table 2 the children were asked to explain why a man that has been loading boxes in a track for a few hours is so tired that he can no more lift any boxes. Children's responses were again placed in four response categories. In the *energy consumed* category students claimed that the man is tired because he has consumed all or a lot of his energy. This response is consistent with the scientific model and the number of children who responded in this way increased in the experimental group post-test (from 35.7% to 83.4%), but not in the control. The second response category (force consumed) is inconsistent with the scientific model. According to this response force is a property of humans and can be consumed and even exhausted. There is a decrease in the frequency of the force consumed responses from the pre-test to the post-test in the experimental group, while there is no change in the frequency of these responses in the control group. One student of the experimental group responded that the man cannot exert any force on the boxes and was placed in the *force exerted* category. Finally, in the last category of responses children did not give an explanation but they simply state that the man is tired. There is a decrease in the frequency of such responses in the experimental group after instruction (from 29.2% to 12.5%), while there is no change observed in the control group post-test.

As in the previous questions responses that were consistent with the scientific model were characterized as "correct" (response categories 1 and 3), while the remaining categories (categories 2 and 4) were characterized as "incorrect". The McNemar test showed that the change from the pre-test to the post-test is statistically significant in the experimental group (p=0.00) but not in the control group (p=1.00). The chi-square test showed that there is significant difference between the experimental and the control groups in both the pre-test ($\chi^2(1)$ 4.30, p=0.04) and the post-test ($\chi^2(1)$ 23.89, p=0.00). Table 2 shows that the experimental group performed better than the control in the post-test as well as in the pre-test. However, the difference between the two groups in the percentages of the correct responses has been enlarged in the post-test.

7.2. Interviews

In addition to the pre- and post-tests, interviews were also used to clarify some of the questions regarding children's understanding that could not be answered by the analysis of their responses in the written tests. The interview, which was really a discussion with the interviewer who was also the teacher, was a situation where the students were prompted to express their opinions, were helped by the teacher through hints to re-evaluate their answers, and to provide more information. Thus, the interviews tested the students more at the zone of proximal development (Vygotsky, 1978) than the post-tests did. In this paper we will provide some examples from the interview data to show the kinds of additional information obtained from those data regarding students' understanding.

The analysis of students' responses to the questions of the pre- and post-tests left unanswered the question whether the students had developed an explanatory framework which included the simultaneous presence of more than one force, such as, for example, gravity, friction and reaction forces. As can be seen in Table 1, in their responses to Question 1 only 50% of the students of the experimental group referred to the force of gravity. In Question 2 there was no reference to gravity and 83.4% of the students said that the force from the man is exerted on the stones. However, the results from the interviews show that three out of five students mentioned all forces (eight in total) exerted in a situation where the stone was pushed by a bulldozer (shown in Fig. 5). The example that follows shows how the interviewer helped the students to report all forces exerted.

Interviewer: (Presents to the student the drawing shown in Fig. 5) The bulldozer pushes the rock. The rock moves. Is there a force or forces exerted on the rock and on the bulldozer?
Student: The action force and the reaction force.
Interviewer: Can you represent them?
Student: (Draws vectors to represent the force from the bulldozer on the rock, and the reaction of the rock on the bulldozer, as shown in Fig. 5. He also draws the vectors representing the force of gravity and of the reaction from the ground exerted on the bulldozer and on the rock).
Interviewer: Is that all?
Student: No, we also have the frictional force (he represents the frictional force exerted on the rock).
Interviewer: What about the bulldozer?
Student: (The student represents the frictional force exerted on the bulldozer). All forces are shown in Fig. 5.

It seems that the students of the experimental class were capable of representing

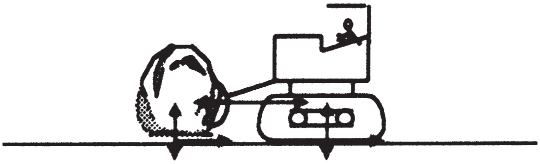

Fig. 5. Drawing used in the interviews depicting a bulldozer that pushes a rock.

more forces and their relations with each other. However, they needed to be prompted by an expert in order to recall these forces and to use them to explain a situation.

The interviews also allowed us to further test students' understanding and to reveal synthetic models and misconceptions that were not apparent in the post-test. A common synthetic model revealed in the interviews was the following. The students recognized that the bulldozer exerts a force on the rock ("action" force) and that the rock exerts a force on the bulldozer ("reaction" force). However, four out of five still believed that the force of reaction does not equal the force of action but that their relative size depends on whether the bulldozer succeeds in moving the rock. They believed that if the rock moves then the reaction force is smaller than the action force and this relation is reversed when the rock does not move.

The formation of this synthetic model can be better understood if we relate it to some of the ideas that the students expressed before instruction regarding the relationship between the force exerted and the weight of the object. During instruction the students were asked to estimate the magnitude of the force that a man should exert on a box to make it slide on the ground. All the students were convinced that this force exerted from the man should be equal to or greater than the weight of the box. Students think of weight as a property of the object related to their potential to react on actions that tend to set them in motion (Ioannides & Vosniadou, submitted for publication). After instruction, the students believed that in order for the rock to be set in motion, the action force should overcome the reaction force. It seems that students assimilate the action and reaction concepts in their existing explanatory framework, thus forming the idea that the so-called reaction force is the force that reacts to any force that tends to set an object in motion (action force). Therefore, they think that the magnitude of this force should be related to the object's weight (how heavy the object is). The example that follows illustrates the change in the way a student explains how a rock is moved by a bulldozer during the course of the instructional period.

> Interviewer: The force that the bulldozer exerts on the rock is equal to or different from the force that the rock exerts on the bulldozer?
> Student: The action is greater than the reaction, because this is how the rock moves.
> (The same student in a class discussion a few weeks earlier gave the reply: The force (from the man) must be greater than the weight of the object.)
> Teacher: Why?
> Student: Because if it was equal to the weight it would be counterbalanced by the weight. If it was smaller than the weight of the box, the box would not move at all, but if it is greater than the weight, the box will move.

7.3. Analysis of classroom discourse

As mentioned in the Introduction, one of the main purposes of the analysis of the classroom discourse was to help us identify the scientific elements of the dynamic interaction between teachers and students that may be related to conceptual change. In this paper we will compare a piece of classroom discourse coming from the experimental group (95 utterances) and another from the control group (103 utterances). The two dialogue pieces are a little unequal in terms of the number of utterances but this had to be done in order to have coherent pieces of dialogue and not interrupt them at an arbitrary point. They represent approximately 15 minutes of classroom time and were reproduced through careful analysis of videotapes. The themes treated by the teachers in the two dialogues are presented in Table 3A and B.

By presenting the thematic content of the experimental and control class exchanges, we attempt to capture the general strategy adopted by the two teachers in the planning and execution of their lesson. The themes could be considered as phases of dialogue evolution. The dialogue exchanges are related to each theme by the citation of the corresponding numbers in the second column of Table 3. The table also presents the kind of situational support used by the teacher during the treatment of each theme. Sometimes the teachers use a real experience as an experimental situation, or refer to a picture in the physics book. Sometimes the children are invited to think of an imaginary situation.

Table 3A presents a summary of the experimental class lesson. In the introductory phase of the lesson the teacher reminds the students of the content of the previous session. In order to do that he creates an experimental situation to demonstrate that a push/pull force can be exerted even in those situations where the object may not move. He also asks the students to remember the role of the dynamometer that he uses during the whole sequence to measure forces exerted. The second phase is the main phase of this dialogue, where the teacher introduces Newton's third law (action–reaction), using as a base the explanation offered by a student who examines the situation of a man pulling a desk. This is done in order to make it possible for the students to express their possible disagreements and thus to start the negotiation of meaning process. We characterize this phase as "main" because this theme is the central theme of the lesson and is the biggest theme (21 exchanges). During the third phase, the teacher creates an experimental situation for the purpose of proving the existence of action and reaction forces. In this experiment a child on a skateboard is pulled towards the wall as she pushes the wall towards her. A dynamometer is used to measure the force exerted on the wall and the force exerted on the girl (the experiment is conducted in the class). In the next phase, the teacher uses cardboard-made vectors to represent in a concrete way action–reaction forces indicating precisely their point of origin and their direction. In the fifth and final phase the teacher uses other examples to get students to generalize the action–reaction law.

The control class dialogue can be divided into five phases. Initially, the teacher asks questions regarding the definition of molecular forces (cohesive and adhesive forces) discussed in a previous lesson. After this introductory phase, she starts with a general presentation of forces as the push and pull of objects by people. In the next phase, she asks one student to read from the book and spends the entire lesson paraphrasing explicitly what is said in the book. Phase three concerns the study of the direction of force, and also the identification of objects which exert forces. The fourth part concerns the module of force, and the fifth the study of the visual effects

Table 3
Thematic representation of experimental class exchanges and control class exchanges

Phase	Exchanges	Theme	Situation/support
(A) Experimental class exchanges			
I	1–15a	Creates an experimental situation to demonstrate that a push/pull force is exerted even when the object being pushed/pulled does not move	*Real experimental situation*: uses a rope to pull a desk that does not move. Uses a denamometer to measure exerted force
		Purpose: (a) to remind students of an established (in the previous lesson) scientific fact which is counterintuitive from the point of view of 10–12-year-old students; (b) to demonstrate the use of the dynamometer	This unit stops when students acknowledge the fact. This unit is really a repetition of a previous lesson and is used as an introduction to the theme of today's lesson which is Newton's third law
II	15b–31a	Introduces Newton's third law (action–reaction) as the opinion of a child (to make it possible for the students to disagree) and asks the students to agree/disagree	*Imaginary situation*: a child has said that when a table is pulled, the table exerts a *reaction force* on the child
		Purpose: (a) to introduce the definition of Newton's third law; (b) to negotiate its meaning with the students	This unit stops when students are able to repeat the definition of "action" and "reaction" forces
III	31b–57a	Creates an experimental situation to prove the existence of reaction force. Gets children to agree that "although it was Artemis exerting a force on the wall, the reaction of the wall was bigger". Instead of the wall coming towards her, Artemis moves towards the wall	*Real experimental situation*: a child on a skateboard is pulled towards the wall as she pushes the wall towards her using a rope. A dynamometer is used to measure the force exerted on the wall and the force exerted on the girl
		Purpose: to prove the existence of action–reaction forces	This unit stops when students are able to explain the experiment in terms of action–reaction forces
IV	57b–78a	Uses cardboard-made vectors to represent action and reaction forces demonstrated previously	*Real experimental situation*: uses previous experimental situation and cardboard-made vectors to represent forces
		Purpose: to introduce a concrete way for representing abstract unseen forces and indicate their direction	This unit stops when the cardboard vectors have been used to represent action–reaction forces correctly
V	78b–95	Generalizes the action–reaction law using other examples	*Real experimental situation*: Asks students to push walls, desks, tables, etc., and say what forces are being exerted
		Purpose: to help students generalize the action–reaction law to other situations	This unit stops when students seem able to identify action–reaction forces

(continued on next page)

Table 3 (*continued*)

Phase	Exchanges	Theme	Situation/support
(B) control class exchanges			
I	1–11a	Asks students to remember the definition of *adhesive* and *cohesive* forces which was given in the previous lesson	No situational support
		Purpose: to memorize definition of adhesive and cohesive forces	This unit stops when some students are able to repeat the definition correctly
II	11b–34	Teacher asks students to read the book and use the pictures to identify the kinds of forces exerted by one object on another (mainly push/pull forces)	Teacher uses the pictures in the physics book
		Purpose: to read the book and understand what it says; to identify push/pull forces	This unit stops when the relevant part of the book is finished
III	34–61a	Students continue to read the book and come to the section on the direction of forces. Teacher asks students to use the pictures to identify which object is exerting a force on what object (mainly push/pull forces)	Teacher uses the pictures in the physics book
		Purpose: to read the book and understand what it says; to identify the direction of push/pull forces	This unit stops when the relevant part of the book has been read and discussed
IV	61b–74a	Students continue to read the book. They come to the section that on the *intensity* of *forces*. Teacher paraphrases the book and uses a real situation (pushing a desk) and examples from everyday life to prove that forces can have different intensities	Teacher uses a real situation (force of different intensity to move a desk) and examples from everyday life to show that forces can have different intensities
		Purpose: to read the book and understand what it says; to understand that forces can have different intensities	This unit stops when the relevant part of the book has been read and discussed
V	74b–80	Students continue to read the book. The unit is on the direction of forces	Teacher uses the pictures in the book
		Purpose: to read the book and understand what it says; to understand the direction of forces	This unit stops when the relevant part of the book has been read and discussed
VI	81–103	Students continue to read the book. This section is about the effects of forces	Teacher uses the pictures in the book
		Purpose: to read the book and understand what it says; to understand that forces can cause the motion of objects and also stop the motion of objects	This unit stops when the relevant part of the book has been read and discussed

of forces exerted, such as changes in motion and the transformation of objects. During the whole dialogue the situations which serve as support and the objects of study are the pictures in the physics book where the vectors of forces have already been drawn. As can be seen in Table 3A the purpose of the teacher is at all times to help the students to read the book and understand what is said in the book.

7.3.1. The dialogue structure

First we looked at the structure of the dialogues by distinguishing main exchanges, each of which could be composed of preliminary parts and/or some initiative and reactive parts. The length of each main exchange (number of constitutive exchanges) and its complexity was noted.

As can be seen in Table 4, the experimental class dialogue consisted of fewer main exchanges than the control class (14 vs. 20). The experimental class had fewer main exchanges because the exchanges were more complex than those of the control class. If we call a main exchange with less than five exchanges simple and one more than five exchanges complex, then the experimental class dialogue had a ratio of 8 to 6 complex:simple exchanges, whereas the control class dialogue had a ratio of 6 to 14 complex:simple exchanges.

Another difference between the experimental and control class dialogues concerned their uniformity or lack of it. The control class dialogue was fairly uniform, consisting of an alternation of simple main exchanges consisting of initiative/reactive pairs of utterances. In other words, the teacher in the control class followed a strategy of asking simple, relatively unrelated questions that did not require elaborate explanations or clarification. The experimental class dialogue was less uniform because the teacher was using a variety of strategies to activate prior knowledge and to elicit what he considered more appropriate responses from his students.

7.3.2. Analysis of functional roles

The analysis of the functional roles of the teacher/students' utterances was undertaken to enable us to describe the dynamic interactions that occur in instructional dialogues. In this analysis all teacher and student utterances were assigned to a functional role. These functional roles were meant to describe the teacher and student intentions, in the context of the dialogue. Here we will look only at the functional roles of the teachers' utterances.

Table 4
Complex vs. simple exchanges for experimental vs. control class (comparison of frequencies)

	Main exchanges	Complex vs. simple*	Ratio complex:simple
Experimental	14	8 vs. 6	4:3 (1.33:1)
Control	20	6 vs. 14	3:7 (0.42:1)

*Main exchanges with less than five exchanges are called simple and those with more than five exchanges are called complex.

The teachers' utterances in the experimental and control classes were assigned to three categories of functional roles:

(a) questions asked by the teacher to the students related to the subject-matter to be taught;
(b) statements by which the teacher explained, clarified, described, or otherwise provided information to the students; and
(c) statements concerning the management of the class, such as assigning a speaker, motivational or rhetorical comments, etc.

Tables 5 and 6 show the functional roles detected of teachers' utterances in the experimental class (EC) and the control class (CC). Table 5 shows the percent functional roles for the experimental and control class in the three main functional role categories. This table shows that the experimental class differs from the control class in that the teacher spends much more time asking students questions related to the subject-matter to be taught (4.6% vs. 1.9%). A great deal of the control class teacher's time is spent on procedural management interaction. As shown in Table 6, 42.44% of the control class teacher's time is spend on the management of the interaction as compared to 27.42% of the experimental class teacher's time.

The control class teacher appears to also spend a little more time providing information than the experimental class teacher who is more likely to ask the students questions rather than to provide answers (see Table 6). More specifically, when we compare the "explanation" (Table 5.I. Asking questions, I.1. Explanation questions) and "explains" (Table 5.II. Providing information, II.1 Explains) experimental vs. control class ratios in Table 5, we have a ratio of 14.6% vs. 1.9% for "explanation questions" and 9.7% vs. 13.7% for "explains". In other words, the experimental class teacher is more likely to ask students to explain, while the control class teacher is more likely to provide the explanations.

There are other important differences between the experimental and control groups. If we look at the asking questions functional role category, we see that the experimental class teacher not only asks many more explanation questions than the control class teacher, he also further elaborates on these explanation questions by asking students to validate and clarify their explanations. This is something that the control class teacher does not do at all. The control class teacher, having the book and the illustrations in the book as a base, asks more specification and description questions than the experimental class teacher.

Both teachers ask children questions that aim to test their knowledge of institutionalized scientific facts, with the exception that the experimental class teacher tries to engage children in a critical dialogue and encourages them to express opinions of disapproval much more than the control class teacher (Table 5.I, I.5 Approves/disapproves: 19.5% experimental class vs. 7.8% control class). In contrast, if we look at the second functional roles category we see that the control class teacher is more likely to approve/disapprove the students than the experimental class teacher. In other words, the control class teacher is more likely to approve/disapprove the children themselves, whereas the experimental class teacher is more likely to ask

Table 5
Detected functional roles of teachers' utterances in the two interactions

I. Asking questions	EC	CC	II. Providing information	EC	CC	III. Management of interaction	EC	CC
I.1. Explanation questions	6/41 14.6%	1/51 1.9%	II.1. Explains	4/41 9.7%	7/51 13.7%	III.1. Assigns an activity	3/113 7.3%	5/139 3.6%
I.2. Validity of explanation questions	1/41 2.4%	0/51 0%	II.2. Clarifies	0/41 0%	4/51 7.8%	III.2. Assigns a speaker	4/113 2.65%	7/139 5.04%
I.3. Clarification questions	2/41 4.8%	0/51 0%	II.3. Specifies	2/41 4.8%	1/51 1.9%	III.3. Makes procedural comments	10/113 8.85%	15/131 0.79%
I.4. Specification questions	6/41 14.6%	9/51 17.6%	II.4. Describes	5/41 12.2%	8/51 15.7%	III.4. Makes motivational comments	1/113 0.88%	0/139 0%
I.5. Approves/ disapproves	8/41 19.5%	4/51 7.8%	II.5. Exposes scientific knowledge	2/41 4.8%	2/51 3.9%	III.5. Makes rhetorical comments	2/113 1.77%	10/139 7.19%
I.6. Knowledge of institutionalized facts	3/41 7.3%	4/51 7.8%	II.6. Presents a situation, an example	4/41 9.7%	9/51 17.6%	III.6. Makes the student(s) remember what was told	2/113 1.77%	1/139 0.72%
I.7. Description	4/41 9.7%	7/51 13.7%	II.7. Gives a hint	1/41 2.4%	2/51 3.9%	III.7. Repeats students' comments	4/113 3.54%	9/139 6.47%
			II.8. Approves/ disapproves	5/41 4.8%	5/51 9.8%	III.8. Reformulates students' comments	4/113 3.54%	8/139 5.75%
						III.9. Verifies understanding	1/113 0.88%	4/139 2.88%
Total	37.16%	21.58%	Total	30.93%	33.8%	Total	27.42%	42.44%

Table 6
Percent functional roles of teachers' utterances in the two interactions

	Asking questions	Providing information	Management of interaction
Experimental class	37.16	30.93	27.42
Control class	21.28	33.8	42.44

the students to approve/disapprove the content of his statements. As we have seen previously, the experimental class teacher at times presents the scientific information not as an institutionalized scientific fact but as the opinion of another child, in order to make it possible for the students to disagree with it.

7.3.3. Functional roles of students' utterances

The functional roles of students' utterances detected in the two dialogues were placed in two main categories: the functional roles, which constitute answers given to teachers' questions related to subject matter, and responses to classroom management interactions. In Table 7 we report the functional roles of students' utterances detected in the analysed dialogues of the experimental class (EC) and the control class (CC).

As can be seen, the most important functional role of students' utterances concerns "explanation". The utterances used by students to explain different phenomena constitute 29.16% of their total utterances. On the contrary, the students of the control class use a very small number of utterances to explain phenomena, corresponding to 1.88%. The students of the control class devote the greatest number of verbal statements to "description" of physical phenomena which corresponds to 24.52% of the total detected functional roles for this category. Finally, Table 7 shows that the control class students are much more likely to make statements related to the management of the interaction (total of 22.62% statements) than the experimental group (total of 6.24% statements).

Table 7
Detected functional roles of students' utterances in the two interactions

Answers to teacher's question	EC	CC	Management of interaction	EC	CC
I.1. Explains	14/48 29.16%	1/53 1.88%	II.1. Repeats	1/48 2.08%	0/53 0%
I.2. Clarifies	2/48 4.16%	2/53 3.77%	II.2. Reformulates	0/48 0%	1/53 1.88%
I.3. Specifies	9/48 18.75%	9/53 16.98%	II.3. Procedural questions	0/48 0%	1/53 1.88%
I.4. Exposes scientific knowledge	1/48 2.08%	4/53 7.55%	II.4. Reads (from a book)	0/48 0%	10/53 18.86%
I.5. Describes	8/48 16.66%	13/53 24.52%	II.5. Presents a situation	2/48 4.16%	0/53 0%
I.6. Approves/disapproves	9/48 18.75%	6/53 11.32%			
I.7. Affirmation/negation	1/48 2.08%	4/53 7.54%			
I.8. No answer	1/48 2.08%	0/53 0%			
Total	93.72%	79.21%	Total	6.24%	22.62%

8. Discussion

It has been argued that the design of learning environments to promote conceptual change in science must be based on systematic research on the acquisition of science concepts. Furthermore, it has been argued that the results of such research have shown that the acquisition of science concepts requires extensive reorganization of prior knowledge. What these imply for the design of learning environments is that curriculum developers and teachers understand students' initial beliefs and presuppositions and take them into consideration. Research has also shown the importance of taking into consideration students' particulate mental representations of the phenomena being taught and of using explicit models and representations during instruction. Finally, it has been argued that students are not aware of the hypothetical nature of their beliefs and presuppositions and should be encouraged through group discussions and experimentation to develop the metaconceptual awareness needed for understanding science concepts.

In this paper we show how these research findings have been taken into consideration in the design of an experimental learning environment to teach mechanics to fifth-grade students. The pre-test and post-test comparisons show statistically significant differences between the experimental group and the control group and thus confirm our hypothesis that the experimental learning environment would result in cognitive gains for the participating students.

The analysis of the interviews further confirms this finding, while the analysis of the classroom discourse and the comparison between the experimental and control classes show some of the reasons why the students in the experimental class learned more science. It is clear that at least some of the conceptual understanding gains found in the experimental class compared to the control class could be related to the teacher's asking students complex questions that require complex explanations which the students in turn provide to the teacher. Self-explanation has been found to be a powerful mechanism for promoting understanding and conceptual change (Chi & VanLehn, 1991). We could argue that explanation to others in the context of a classroom may be an even more powerful learning mechanism than self-explanation.

The complex exchanges in the experimental class dialogue are usually taking place when the students are explaining their point of view, or when the teacher is obliged to explain what he means because these is no established common language between him and the children. Another case where complex dialogue is generated is when the teacher uses empirical observations to lead children to induce theoretical abstractions. In all these cases, the teacher is going beyond the direct presentation of the scientific model, which is what the control class teacher does. He uses strategies that bring to the surface the different presuppositions and beliefs of the students so that they can be externalized and become the basis on which the negotiation of meaning process will start. This negotiation of meaning is necessary to foster the deeper understanding required for conceptual change.

The differences in the structure and function of the teachers' utterances in the two classrooms are related to obvious differences in the underlying purposes and conceptions of teaching and learning. These lead to different instructional strategies. The experimental class teacher's purposes seem to be that of making the children understand certain counterintuitive ideas about forces, as they are understood within current scientific theory. His underlying theory of learning is that learning consists of the enrichment and reorganization of existing knowledge structures. On the contrary, the control class teacher's purposes seem to be nothing more than to get the children to read and understand what is said in the book. Understanding for this teacher seems to be related to repeating, memorizing, and remembering facts and definitions.

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