Sci & Educ
DOI 10.1007/s11191-013-9640-3

Conceptual Change from the Framework Theory Side of the Fence

Stella Vosniadou · Irini Skopeliti

Abstract We describe the main principles of the framework theory approach to conceptual change and briefly report on the results of a text comprehension study that investigated some of the hypotheses that derive from it. We claim that children construct a naive physics which is based on observation in the context of lay culture and which forms a relatively coherent conceptual system—i.e., a framework theory—that can be used as a basis for explanation and prediction of everyday phenomena. Learning science requires fundamental ontological, epistemological, and representational changes in naive physics. These conceptual changes take a long time to be achieved, giving rise to fragmentation and synthetic conceptions. We also argue that both fragmentation and synthetic conceptions can be explained to result from learners' attempts assimilate scientific information into their existing but incompatible naive physics.

1 Introduction

For a number of years now we have been involved in a program of research that attempts to provide detailed descriptions of the development of children's knowledge in various areas of the physical sciences, such as observational astronomy[1], mechanics (Ioannides and Vosniadou 2002), geology (Ioannidou and Vosniadou 2001), biology (Kyrkos and Vosniadou 1997), and more recently in mathematics (Vosniadou and Verschaffel 2004; Vamvakoussi and Vosniadou 2010). Our research involves mostly cross-sectional developmental studies investigating the knowledge acquisition process in subjects ranging from 5 years of age to adults. We have also conducted some instructional interventions the results of which have been used to develop instructional materials for science education (Vosniadou et al. 2001). This research has led to the development of the framework theory

[1] See for example Vosniadou and Brewer (1992, 1994), Vosniadou and Skopeliti (2005), Vosniadou et al. (2004, 2005), Samarapungavan et al. (1996).

S. Vosniadou (✉) · I. Skopeliti
Cognitive Science Lab, Department of Philosophy and History of Science, National and Kapodistrian University of Athens, University Town, A. Ilisia, 15771 Athens, Greece
e-mail: svosniad@phs.uoa.gr

Published online: 11 August 2013

approach to conceptual change (Vosniadou 2013; Vosniadou et al. 2008). In the pages that follow we outline the basic principles of this approach and answer some frequently asked questions about it. We argue that major ontological, representational and epistemological changes are required in the learning of science because currently accepted scientific concepts and theories are counter-intuitive and violate basic principles of naïve physics based on everyday experience and lay culture. Fundamental to our understanding of these conceptual changes is the idea that naïve physics does not consist of fragmented knowledge pieces but forms a relatively coherent explanatory framework—a framework theory. The framework theory approach to conceptual change claims that the ontological, representational and epistemological changes that need to take place to learn science are slow and gradual and give rise to fragmentation and synthetic conceptions which result from the assimilation of scientific information into the framework theory.

2 Three Basic Principles of the Framework Theory Approach to Conceptual Change

2.1 Naïve Physics is a Framework Theory

At the heart of the framework theory is the idea that young children start the knowledge acquisition process by developing a naïve physics which does not consist of fragmented observations but forms a relatively coherent explanatory system—a framework theory. This principle is based on the results of cognitive developmental research showing that infants organize the multiplicity of their sensory experiences under the influence of lay culture into narrow but relatively coherent domains of thought from early on.[2] For example, it appears that infants use the criterion of self-initiated movement to distinguish animate from inanimate entities, thus creating two fundamentally different ontological domains—naïve psychology and naïve physics. Naïve physics and naïve psychology are also distinguished in terms of their causality. Naïve physics obeys the laws of mechanical causality while naïve psychology is governed by intentional causality. Once categorized as a physical or psychological object, an entity inherits all the characteristics and properties of the other entities that belong to the same category. Knowledge acquisition proceeds from a very broad and relatively explanatory weak set of structures to more detailed and explanatory rich categorizations with better fit to the world (see also Keil 1981).

2.2 Learning Science Requires Fundamental Conceptual Changes in Students' Ontological and Epistemological Commitments and in Their Representations

When children start being exposed to science they have already constructed a naive physics which allows them to provide explanations of everyday phenomena and to make predictions about the behavior of physical objects. For example, in the case of observational astronomy, children categorize the Earth as a physical object distinct from solar objects like the sun, the Moon and the Stars. They attribute to the earth all the characteristics of physical objects such as solidity, stability and lack of self-initiated movement. They also organize space in terms of the directions of up and down and believe that the Earth and physical objects on the Earth behave in terms of an up/down gravity principle.[3]

[2] Baillargeon (1995), Carey (2009), Carey and Spelke (1994), Gelman (1991).

[3] See, for example, Nussbaum (1979), Nussbaum and Novak (1976), Sneider and Pulos (1983), Vosniadou and Brewer (1992, 1994).

Understanding the scientific concept of the Earth requires that children re-categorize the Earth from the ontological category 'physical object' to the ontological category 'physical-astronomical object'. Vosniadou and Skopeliti (2005) have shown that such re-categorizations happen in the conceptual system of elementary school children between 3rd and 5th grade. The re-categorization of the Earth as an astronomical object is accompanied with significant representational changes. The astronomical Earth is a spherical, rotating planet in space as opposed to a flat, solid and stable physical object with the sky and solar objects above its top. While this new representation is often constructed with the help of external models and artifacts, such as the globe, it nevertheless depends crucially on the development of children's perspective taking abilities and epistemological sophistication. In order to understand the scientific concept of the Earth, children must realize that the Earth can appear flat from the perspective of someone on the earth but spherical from the perspective of someone who views the Earth from the Moon or somewhere else in space. These developments in turn require epistemological sophistication–the ability to make distinctions between 'appearance' and 'reality', to understand that things are not always as they appear to be, and that what seems real maybe constructed, hypothetical, and subject to falsification.

Analogous ontological, epistemological and representational changes must take place in children's naïve physics in order to understand scientific concepts in practically all of the domains of science. The concepts of force, energy, heat, undergo fundamental ontological re-categorizations in the process of learning science from entities or substances in the initial conceptual system of novices to processes or interactions in the conceptual system of experts (Chi 2008; Wiser and Smith 2008; Ioannides and Vosniadou 2002). These ontological changes are accompanied by representational and epistemological changes. The epistemological knowledge necessary to make sense of the atomic matter theory, for example, includes the nature of scientific models and their relation to observed objects and events, as well as the understanding that many macroscopic properties of matter are emergent (Wiser and Smith 2008). In recent years a number of experimental studies have shown high correlations in students' performance in conceptual change tasks and epistemic belief tasks.[4]

2.3 The Achievement of These Conceptual Changes is a Slow Process During Which Fragmentation and Synthetic Conceptions Can be Created

The above mentioned ontological, representational and epistemological changes do not happen overnight. They are achieved gradually producing, in the process, fragmentation and misconceptions. A detailed examination of students' misconceptions and fragmented responses has revealed that they can be explained if we assume that constructive, enrichment-types of learning mechanisms are used to synthesize scientific information with initial conceptions in the context of the framework theory (Vosniadou and Brewer 1992, 1994). More specifically, fragmentation can be produced when learners use the scientific information to enrich their naive physics without concern for internal consistency and coherence. For example, many children who believe that night is caused because the sun goes down behind the mountains simply add the scientific information that the Earth turns around itself to their original but incompatible explanation thus creating an internally inconsistent, fragmented response (Vosniadou and Brewer 1994). Misconceptions are

[4] See for example Mason and Gava (2007), Mason et al. (2008), Stathopoulou and Vosniadou (2007a, b), Kyriakopoulou and Vosniadou (2012).

formed when students distort the scientific information. Many misconceptions are synthetic constructions that provide incorrect but nevertheless creative solutions to the problem of incommensurability between initial conceptions and scientific information.

Synthetic conceptions are produced when learners, in the search for coherence and internal consistency, incorporate the scientific information to their incompatible prior knowledge distorting it and creating an alternative conception or model which however has some internal consistency and explanatory value. For example, many elementary school children form a model of the day/night cycle according to which the sun and the moon are stationary and located at opposites sides of the Earth. As the Earth turns around, it is day for the side opposite the sun and night for the side opposite the Moon (Vosniadou and Brewer 1994). This synthetic model allows students to reconcile the scientific information with their initial belief that the Moon is causally implicated in the day/night cycle.

To sum up, the framework theory is based on cognitive/developmental research and attempts to provide a broad theoretical basis for understanding how conceptual change is achieved in the process of learning science. It claims that young children start the knowledge acquisition process by developing a naïve physics that does not consist of fragmented observations but forms a relatively coherent explanatory system—a framework theory. Learning science requires fundamental ontological, epistemological and representational changes in naïve physics. After all, currently accepted science is the product of a long historical process characterized by radical theory changes which have restructured our representations of the physical world. Synthetic conceptions and fragmentation can be produced when learners use constructive, enrichment types of learning mechanisms to assimilate scientific information to an incompatible prior knowledge.

3 Frequently Asked Questions About the Framework Theory

3.1 Why Use the Term 'Theory'?

We acknowledge that the use of the term 'theory' may be misleading. What we mean by 'framework theory' is a skeletal conceptual structure that grounds our deepest ontological commitments in terms of which we understand the world. A framework theory is very different from a scientific theory. It is not explicit, well formed, and socially shared, it lacks the explanatory power and internal consistency of scientific theories, it is not subject to metaconceptual awareness, and it is not systematically tested for confirmation or falsification. Nevertheless, we have chosen to call it a 'theory' because it is a principle-based system which is characterized by a distinct ontology and causality and which is generative in that it can give rise to prediction and explanation. When an entity like 'force' is categorized as a property of physical objects, it inherits all the characteristics of this category at once. Categorization is the most fundamental learning mechanism, a mechanism which most of the time promotes learning but which, in cases where conceptual change is required, can inhibit it.

3.2 What are the Similarities and Differences Between 'Naïve Physics' and a 'Framework Theory of Physics'?

The term 'naïve physics' has been used in the literature to refer to the beliefs, ideas, explanations of physical phenomena given by children or adults who have not been exposed to science. We claim that this pre-scientific body of knowledge known as naïve physics (and sometimes as 'folk physics' or 'intuitive physics') constitutes a framework theory—i.e., a relatively coherent system with some limited predictive and explanatory power. In other words we consider these two to be tautological. The term 'framework theory' was first used by Wellman (1990), Wellman and Gelman (1992) to refer to an abstract knowledge structure that outlines the ontology and basic causal devices in a domain and to which several 'specific theories' can be attached. There can be different framework theories and a distinction can be made between a framework theory of physics and a framework theory of psychology.

3.3 What Exactly is the Explanatory Power of a Framework Theory?

The explanatory power of the framework theory of physics is derived from its ontological and causal structure. Research with infants has shown that they make ontological distinctions based on everyday experience in the context of lay culture, such as the distinction between physical objects and psychological beings. When an entity is categorized in an ontological category it immediately inherits all the properties and characteristics of the category. Ontological mis-categorizations are not rare in early childhood. For example, young children often think that the Sun belongs to the ontological category of psychological entities because it is perceived to move by itself. As a result they often attribute to the Sun intentional causality and other characteristics of animate beings (for example they explain the day/night cycle on the grounds that the Sun is tired and goes to sleep at night). Framework theories specify the ontological categories that children form early on in the context of a realist epistemology. These framework theories need to be restructured when scientific concepts are introduced. Science learning requires conceptual change precisely because it contradicts the framework theory of physics.

3.4 Some Theories of Conceptual Change that Claim that Conceptual Change Requires Ontological Shifts Without Reference to Framework Theories. Why Do We Need to Posit the Existence of a Framework Theory to Account for Conceptual Change Processes and More Specifically for Ontological Shifts?

Chi (2008, 2013) has advanced a theory of conceptual change in which ontological shifts play an important role. More specifically, she argues that certain misconceptions are robust and difficult to change because they have been assigned to an inappropriate ontological category (2013). Chi (2013) explains that an analysis of students' misconceptions for a variety of science concepts which she and her collaborators have undertaken (e.g., Reiner et al. 2000), has shown that many students mistakenly assign concepts such as heat, force, electricity and light, to the ontological category 'Entities' when they should be assigned to the scientifically correct ontological category 'Processes'. She continues:

> this is why some misconceptions are so robust – because the naïve conceptions are mis-categorized into an ontologically distinct tree. Such entity-based misconceptions not only occur for a variety of concepts across a variety of disciplines, but they are held across grade levels, from elementary to college students (Chi et al. 1994) as well as across historical periods (Chi 1992, 2013, p. 56–57).

We agree with Chi that ontological shifts are required in the process of conceptual change. However, the observation that students assign scientific concepts to the 'wrong' ontological category does not explain why students so frequently behave in this way, neither does it explain why such mis-categorizations are so robust. In other words, Chi (2013) offers a description of the problem and not an explanation of the problem. The framework theory approach on the other hand uses evidence from cognitive developmental research to argue that students' initial knowledge about the physical world is organized in ontological categories that are different from those accepted by science, to describe these ontological categories, and to explain why children categorize concepts like the Earth and force to them. We argue, for example, that the Earth is categorized as a physical object rather than an astronomical object because it has the characteristics of physical objects (solidity, stability, lack of self-initiated movement) when judged on the basis of the everyday experience available to a child. Similarly, a concept like force, or heat is categorized as a 'property of physical objects' as this is the only possible way to understand these concepts in the limited conceptual repertoire of a young child. In other words, the framework theory approach to conceptual change attempts to explain *why* students categorize concepts in ontological categories different from those assigned to by scientific theories and why these ontological categories are difficult to change (because they are not fragmented but embedded in a complex and systematic network of concepts—a framework theory)

In contrast to Chi, we do not see these ontological categories as wrong, incorrect, or misconceived. On the contrary, we argue that they are absolutely justified considering that a) they are based on experience and are continuously confirmed by it; b) are supported by a lay culture which further supports and solidifies this experience; and c) are consistent with a naive epistemology, based on inferences from perceived appearance. Ontological shifts such as the ones required when learning science are difficult because these early ontological categories are not isolated, knowledge pieces, but consist of large and systematic networks of concepts. In other words, they constitute a framework theory. This is why conceptual change is required and what makes conceptual change difficult.

3.5 What is the Predictive and Explanatory Power of the Framework Theory Approach to Conceptual Change?

A particular strength of the framework theory approach to conceptual change is that it provides an account of the transition process from an initial to a more sophisticated understanding of counter-intuitive concepts, predicting that it will be slow and gradual and that it will give rise to fragmentation and the generation of synthetic conceptions. The prediction that students will create synthetic conceptions tests the assumption of the theory that students rely mainly on enrichment type, constructive, mechanisms to add new information to prior knowledge. Although a synthetic conception is incorrect from a scientific point of view, it nevertheless enables the student to move on in the knowledge acquisition process. Moreover, the framework theory allows us to go even further and predict not only that fragmentation and synthetic conceptions will occur but also when and where they are likely to occur—i.e., when there is incompatibility between the new, scientific information and existing beliefs and presuppositions in the context of the framework theory—and thus it can potentially prove very useful in informing instruction.

3.6 Is There a Cognitive Mechanism Involved?

A number of different cognitive mechanisms could model the process of conceptual change we have described. One possible mechanism is the gradual re-interpretation of the beliefs and presuppositions of the framework theory, as new information comes in, allowing the construction of new ontological categories and new representations, until full conceptual change has been achieved. Although most of the evidence we have at our disposal comes from cross-sectional developmental studies, the developmental pattern suggested is clear. For example, our studies of children's ideas about the shape of the earth have shown that children usually start with the initial model of a square, rectangular or disc shaped Earth which is supported, stable, and flat, where gravity operates in an "up-down" fashion, and where the sky and solar objects are located above the top of the earth. This initial model is what one would expect assuming that the Earth is originally categorized as a physical, non-astronomical, object (as shown by Vosniadou and Skopeliti 2005). The models of the hollow sphere and the truncated sphere, on the other hand, which are more sophisticated and are formed usually by older children who have been exposed to some science instruction, show that some of the above-mentioned presupposition have been lifted or re-interpreted. The model of the hollow sphere, for example, is constrained by the belief that people live on flat ground and that gravity operates in an up/down fashion. However, this flat ground is now conceptualized to belong to a spherical earth in space rather than to a flat, supported physical object. Similarly, the up/down gravity presupposition constrains the understanding of the spherical Earth in children who have constructed a flattened or truncated sphere, who also believe that people live on flat ground, not inside but at the upper side of the spherical earth in space. In other words, all of these children have accepted the scientific view that the Earth is an astronomical object in space but continue to believe that people live on flat ground and that gravity operates in an up/down fashion. These beliefs are, however, re- interpreted in the context of this new conceptualization leading to the creation of different alternative models and representations.

3.7 Why Does the Framework Theory Claim that Students Always Cohere When the Empirical Evidence Clearly Shows that They Do Not?

A common mistake often made about the framework theory is to interpret it as claiming that students always form internally consistent scientific or alternative conceptions. This is not the case. The framework theory accepts that students often give internally inconsistent, fragmented, responses and explanations. However, the presence of fragmentation is explained differently in the framework theory compared to other approaches. One source of fragmentation springs from the looseness of the framework theory itself. The framework theory is a very skeletal structure that imposes only some general constrains on students' explanation of a physical phenomenon leaving a degree of freedom for variation and for adjusting to different contextual situations. For example, before they are exposed to science, young children may explain the day/night cycle by saying, for example, that the sun goes down behind the mountains, or that clouds come and block the sun, or that the sun goes far away to another country. Despite their differences, all these explanations are consistent with the ontological categorization of the Earth as a solid and stable physical object with they sky and solar objects above its top, and where the day/night cycle is caused by the movement and change of the solar objects, such as the sun, the moon, and the clouds.

Second, and most important, we argue that fragmentation is often produced as the result of initial instruction. As discussed earlier, when exposed to science concepts and explanations, students often use the new, scientific, information to enrich their naive physics without considering the incompatibility between the two kinds of information. For example, children can add the information that the earth turns around itself to their previous explanation that night happens because the sun goes behind the mountains, thus creating an internally inconsistent and fragmented response.

3.8 What Exactly are the Differences Between the Framework Theory and the 'Knowledge in Pieces' Approach to Conceptual Change?

The framework theory is consistent with many aspects of the knowledge-in-pieces approach, including the view that we need to focus on rich knowledge systems that are composed of many constituent elements, p-prims being one of them. Arguably, many components of children's initial concepts are experientially based, building on the multiplicity of perceptual and sensory experiences obtained via observation and interaction with physical objects. But it is assumed that most of these are integrated from early on into larger conceptual structures under the influence of lay culture and language. In other words, from the point of view of the framework theory, to the extend that knowledge elements such as p-prims could be postulated to operate in our conceptual system, they become organized in conceptual structures much earlier than it is claimed by the knowledge in pieces approach. Let us take for example the Ohm's p-prim that more effort leads to more effect and more resistance leads to less effect. This p-prim schematizes a phenomenological experience but it is not divorced from other similar experiences. On the contrary, it operates in a larger explanatory system where effort, for example, is assumed to be exercised only by animate agents, or by inanimate agents when they are pushed or pulled, and where resistance can be exerted both by animate or inanimate agents, etc. In other words, p-prims operate in a larger system where other p-prims are also organized forming a relatively coherent naïve physics.[5]

We also differ from diSessa (1993, 2008) in that we claim that fragmentation and inconsistency can often be the product of initial instruction, particularly in cases where a rather coherent, but incompatible, initial structure is already established. In other words, unlike diSessa (1993, 2008), who argues for a learning process that proceeds from fragmentation to coherence under the influence of instruction (see for example diSessa 1993), where it is posited that top-down coherence is triggered by students' exposure to symbolic and verbal knowledge system as presented via instruction and texts, we believe that the need and search for coherence is more an initial condition of the cognitive system. Of course, like Smith et al. (1993), we do not expect students to hold unitary, isolated, and context-independent conceptions. Students often create situational models and explanations, constructed on the spot to deal with the demands of specific situations. Although we expect these conceptions to have some minimal internal consistency and explanatory power, we might still find that students change them depending on the affordances of the specific contexts to which they are exposed. Finally, we agree with diSessa (2008) that the individual student's personal learning history is unique—there are probably no two students with the exact same understanding across contexts.

3.9 What Exactly is the Difference Between a Fragmented Conception and Synthetic Models?

We have used two criteria in our empirical studies to distinguish synthetic models from fragmentation: Internal consistency and explanatory adequacy. Internal consistency is determined by examining students' protocols to see if they use the same explanation in an internally consistent manner – i.e., throughout the interview. If the student says at all times in the interview that day/night happens because the sun goes behind the mountains we score

[5] There are a number of other attempts to reconcile the framework theory approach with the knowledge-in-pieces approach, such as those described by Brown and Hammer (2013) and Clark and Linn (2013).

this as an internally consistent response. If at another point in the interview the student says that it is because the Earth revolves around the Sun we score this as an inconsistent response. If the explanation provided explains the phenomenon even in a very rudimentary way, we score it as explanatory adequate. For example the explanation that day/night happens because the Earth revolves around the sun every 24 h is wrong but has some explanatory adequacy. A synthetic model must have both internal consistency and explanatory adequacy. Mixed, internally inconsistent and ad hoc responses are considered fragmented.

Despite the existence of the above-mentioned criteria to distinguish synthetic from fragmented conceptions, the distinction between these two types is not a dichotomous one but rather a continuum with clear cases at the end and some difficult to distinguish cases in the middle (as everyone who has been involved in scoring students' responses to interviews or questionnaires knows). This is one of the reasons why there is often disagreement on the exact number of students who can be assigned to internally consistent models of the Earth or of 'force' (diSessa et al. 2004; Clark et al. 2011; Ozdemir and Clark 2009).[6]

Is this disagreement problematic for the framework theory approach to conceptual change? In every theory it is important to have well defined criteria for the distinctions the theory proposes. The distinction between fragmentation and synthetic models is important in that the presence of synthetic models demonstrates that even very young children are sensitive to the issues of consistency and empirical adequacy of explanation. As mentioned earlier, according to the framework theory, the search for coherence is assumed to be an initial condition of the cognitive system. If, as we propose, initial instruction can destroy the loose coherence of the framework theory, we should expect that students should be bothered by conceptual inconsistencies, to the extent that they can understand then, and that they will try to remedy the situation by creating a synthetic conception. At present we do not have much information about when and why a learner may create such synthetic conceptions. Maybe there are individual differences when it comes to sensitivity to coherence. It is possible that this sensitivity is related to age, intelligence, or epistemological sophistication. Maybe it is an issue of time and amount of exposure to information. This is indeed an important area for future research.

3.10 How is the Framework Theory Different From the Classical Approach to Conceptual Change?

According to the approach developed by Posner et al. (1982) students come to the task of learning science with alternative theories often resembling earlier theories in the history of science. Students need to realize the inadequacy of their ideas so that they will be motivated to replace them with the correct scientific view. According to this view, conceptual change is the result of a rational process of theory replacement by learners who behave more or less like scientists. This conceptual replacement is supposed to happen quickly, resembling something like a gestalt-type restructuring, and to be facilitated by cognitive conflict.

Unlike the classical approach, the framework theory approach to conceptual change does not treat students' alternative conceptions as unitary faulty conceptions but makes an important distinction between *initial conceptions*, which are constructed *before students are exposed to school science* and which are based on everyday experience and lay culture, and *synthetic conceptions* which are constructed *after students have been exposed to school science* and which result from students' constructive attempts to reconcile scientific

[6] Some of the other reasons are differences in methodology, data collection and scoring criteria (see also Clark and Linn 2013).

information with their initial conceptions. Unlike the classical approach, the framework theory does not claim that conceptual change can be achieved through some kind of sudden replacement of the initial conception with a scientific concept when students become dissatisfied with it. Rather, it is a slow process where constructive enrichment-types of learning mechanisms produce synthetic conceptions and fragmentation.

According to the framework theory, conceptual change is usually a slow process not only because it involves a large network of interrelated concepts that change slowly through the creation of fragmentation and synthetic conceptions, but also because it requires the creation of new ontologies and new representations and the ability to flexibly move amongst them. In addition learning science requires the ability to understand that the same phenomenon can be explained from different perspectives and some of these perspectives have greater explanatory power than others. As mentioned earlier, this is an area where the framework theory also differs from another influential approach to conceptual change, the one proposed by Chi and her colleagues (Chi 1992, 2008; Chi et al. 1994). From our point of view, the framework theory is not a wrong, misconceived theory. On the contrary, it is a very useful interpretation of everyday experience, which allows us to navigate in the physical environment. Some recent experimental evidence indeed shows that naïve physics co-exists with scientific theories even in experts, suggesting that scientific knowledge does not replace naïve physics but creates new conceptual structures in the context of continuous representational and epistemological growth.

To sum up, the framework theory approach to conceptual change meets all the criticisms of the classical approach made by different researchers and can also account for fragmentation (Smith et al. 1993). First, we are not describing unitary, faulty conceptions but a knowledge system consisting of many different elements organized in complex ways. Second, we make a distinction between initial explanations prior to instruction and those that result after instruction some of which are synthetic models. Synthetic models are not stable but dynamic and constantly changing as children's developing knowledge systems evolve. Our theoretical position is a constructivist one that shows how constructive types of mechanisms can create fragmentation and misconceptions when scientific information is built on existing but incompatible knowledge structures. Finally, we argue that conceptual change is not a replacement of an inadequate naive physics but involves the creation of new ontologies in the context of continuous representational and epistemological growth.

4 Extensions of the Framework Theory to Other Areas of Research

One important aspect of the framework theory approach to conceptual change is the possibility of extending it to other subject matter domains, such as the domain of mathematics. In Vosniadou and Verschaffel (2004) we argued that learning mathematics can be seen from a conceptual change point of view because children's knowledge of mathematics in the early years develops around a concept of number which resembles the mathematical concept of natural number. Natural number knowledge forms something like a framework theory of number which can then stand in the way of understanding more advanced mathematical concepts and operations such as the concept of rational number and the transition from arithmetic to algebra causing fragmentation and synthetic conceptions, similar in kind to those found in the domain of physics.[7]

[7] See Stafylidou and Vosniadou (2004), Vamvakoussi and Vosniadou (2010, 2012) but also Ni and Zhou (2005), Van Hoof, et al. (in press).

Recently a series of studies in our lab have examined whether the framework theory approach can help us understand students' difficulties with science text and more specifically to investigate the hypothesis that the reading a counter-intuitive scientific explanation can cause fragmented and synthetic conceptions in students when conceptual change is required (Vosniadou and Skopeliti submitted). One of the studies involved texts presenting an explanation of the day/night cycle. Previous research has shown that young children a) create initial explanations of the day/night cycle which are incompatible with the scientific explanation; b) that understanding the scientific explanation requires conceptual change (i.e., requires ontological, representational and epistemological changes such as the ones described earlier; and c) that many children create fragmented and synthetic conceptions in this process.[8] Two texts were written which explained the day/night cycle from the point of view of a hypothetical child (e.g., 'Paul said that….') and not as the 'correct' explanation: The *initial text* agreed with the initial explanation that day/night happens because the sun goes down behind the mountains and the moon comes up, while the *scientific text* stated that day/night happens because the Earth turns around itself. The two texts were of similar lengths (114 and 120 words respectively) and readability levels. The participants were 79 3rd and 5th grade children from an elementary school in a middle-class suburb of Athens who were randomly assigned to one of two experimental groups. All the children took a written pretest in which they were asked to provide a verbal and pictorial explanation of the day/night. They then read one of the texts and were asked to recall it. At posttest all the children provided another written explanation of the day/night cycle.

As expected, the children produced initial explanations of the day/night cycle at pretest similar in kind and content to the explanations obtained in previous developmental research. Most of these were initial explanations of the day/night cycle. Only 7 (out of 79) children knew the scientific explanation. The analysis of the children's recalls showed that the children recalled less information and produced more erroneous inferences from reading the scientific text compared to the initial text. The initial text was easy to recall even for the students who gave the scientific explanation at pretest regardless of the fact that the initial text provided an explanation incompatible with their own. The difficulties occurred only in the case of the children with initial explanations of the day/night cycle at pretest who read the scientific text. For these children the comprehension of the scientific text required conceptual change. All but one of these children distorted the information presented in the scientific text creating erroneous inferences similar in kind to the synthetic or fragmented conceptions obtained in the previous cross-sectional developmental studies. The results supported the hypotheses of the framework theory that conceptual change is slow and gradual and that the use of constructive mechanisms produces fragmentation and synthetic conceptions during text comprehension.

Figure 1 presents some examples from children's recalls and posttest explanations. In the first example, Ethan did not change his explanation from pretest to posttest despite the fact that he had a relatively good recall of the scientific text. In the second example, Peter simply added the information that the Earth turns, thus creating an internally inconsistent—fragmented—construction in his recall and posttest explanation (the earth turns around and the sun goes to another country). Katherine created the synthetic model according to which both the sun and the moon are causally implicated in the day/night cycle. In the fourth example, Irene changed to a correct verbal explanation (the earth turns around itself) but retained her original drawing in her posttest showing the moon

[8] See for example Nussbaum (1979), Nussbaum and Novak (1976), Sadler (1987), Samarapungavan et al. (1996), Sneider and Pulos (1983), Vosniadou and Brewer (1994), Vosniadou et al. (2004).

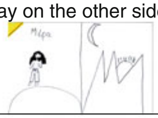
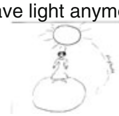
Pretest	Recall	Posttest
	Ethan, 3rd Grade	
The Sun shines and then the moon and the stars come. 	The Earth is round and it changes from day to night because the Earth turns around. The Sun is on one part of the Earth and so does the night.	The Sun shines and then the moon and the stars come. 
	Peter, 3rd Grade	
When the Sun goes behind the mountains it's getting dark and then the Moon and the stars come up on the sky. 	The Earth turns around itself. When the Earth turns around, the Sun goes to another country that previously had night. The other side that previously had day now has night.	When the Earth turns around itself the Sun moves and goes to another country. This other country that previously had night, now has day. 
	Katherine, 5th Grade	
It changes from day to night because the scientists have used a special material that does that. 	The Earth turns around itself. The Sun shines on one part of the earth and it has day and when the sun does not shine there, the moon is there and it is night.	The earth turns around itself. When the one side has day, the Sun is found there. When the other has night, the moon is there. 
	Irene, 3rd Grade	
The Sun goes to the other side of the Earth to shine on that side. When we have day on this side, there is the Moon on that side. When it is night on our side it is day on the other side. 	The Earth is round and turns around itself and that's how it changes from day to night.	It changes from day to night because the Earth turns around itself. 
	Anne, 5th Grade	
The Sun goes to the other side of the Earth and this side does not have light anymore. 	The Earth is round and turns around itself. The Sun shines on one side the one that is turned towards the Sun. The places that are not seen from the Sun have night. Those found in between have afternoon.	Earth turns around itself and the side that is turned towards the sun has day and the other side has night. 

Fig. 1 Examples of internally inconsistent and synthetic constructions found in children's recalls and posttest explanations of the day/night cycle

implicated in the day/night cycle. In the last example, Anne was one of the two children who changed to a correct scientific explanation in the posttest.

The results of these text comprehension studies are important because they confirm the predictions of the framework theory and clearly demonstrate how the use of constructive learning mechanisms can lead to fragmentation and the creation of synthetic models when a counter-intuitive scientific explanation is presented to children who do not have the prerequisite prior knowledge. It is clear from the examples provided above that the children tried as best as they could to incorporate the scientific information to their previous, initial, explanation of the day/night cycle but created inferential errors leading to the formation of misconceptions in the process.

5 Implications of the Framework Theory Approach to Conceptual Change for Instruction

Learning requiring conceptual change poses considerable problems for a constructivist theory because constructivist theory tells us that it is important to build on what students already know but conceptual change research tells us that what students know is in conflict with scientific theories and explanations. Different approaches to conceptual change have dealt with this problem in different ways. The classical approach (Posner et al. 1982) has favored dissonance-producing strategies such as cognitive conflict, which, however, have been criticized as non-constructivist, while the knowledge-in-pieces approach has emphasized the integration of students' fragmented conceptions but without telling us how to deal with the problem of change.

The framework theory approach is a constructivist approach which claims that constructive types of mechanisms can bring about the gradual revision of prior knowledge leading towards conceptual change. However, fragmentation and synthetic conceptions are almost unavoidably formed in the process. We argue that in order to reduce fragmentation and synthetic conceptions we must design student-centered curricula which take into consideration students' initial beliefs and explanations in the context of naïve physics, carefully identifying the productive areas of students' prior knowledge on which the new scientific information can be built, while at the same time highlighting the areas that need to be revised. This often requires taking a long-term perspective in curricula design, planning the sequence of concepts to be taught and the areas where particular attention needs to be paid. Developmental studies such as the studies of the development of the concept of the Earth and of force (Vosniadou and Brewer 1992, 1994; Ioannides and Vosniadou 2002) provide a great deal of information about students' initial beliefs that constrain the learning of science and which need to be addressed for instruction to be successful.

In previous work (Vosniadou et al. 2001) we described in detail the design principles and the sequence of concepts and instructional interventions used in planning a 2-year science curriculum and instruction for 5th and 6th graders. In Table 1 we present an example of the sequence of concepts taught to 5th graders in an 8-week astronomy unit. As can be seen, the first column states the concepts that need to be taught, the second column identifies students' entrenched beliefs that need to be addressed, and the third volume describes the kinds of instructional interventions that can be used [which include the construction of models (C), questions that need to be answered (Q), instructional media to be used (IM), and experiments to be conducted (E)]. The idea of using research on children's learning of science to improve curricula and instruction is in line with more recent efforts to specify learning progressions in different disciplines based on research syntheses in order to improve national standards and assessment (Smith et al. 2006; Schwarz et al. 2009; Lehrer et al. 2013).

Probably the most common type of intervention for conceptual change once an initial conception is identified is to tell students that their belief is incorrect or that the concept in question has been assigned to the wrong ontological category (e.g., Chi 2013) and should be changed. Our position is that it is more fruitful to design instruction to help students

Table 1 Design of curricula and instruction in observational astronomy for 5th graders

Sequence of Concepts to be taught	Entrenched Beliefs	Instructional Interventions
Earth Shape	Perceived flatness	C: Model of earth
		Q: Perception of flatness
		IM: Globe, video demonstrations
		E: Toy ship on the globe
Earth Shape and Gravity	Up/down gravity	C: Drawing of a man in Australia
		Q: Life at "bottom" of the earth
		E: Magnetic globe
Earth, Moon and Sun	Relation between size and distance	C: Models of earth, sun, moon
		Q: Perception of sun/moon
		IM: Scale models
		E: Balloons near/far
Solar System and Gravity	Geocentric solar system	C: Drawing of the solar system
		IM: Slides, video, maps
		E: Demonstration of revolution of earth using a toy car (earth) and a ball (sun)
Earth Movements, Day-Night Cycle and Change of Seasons	Movement of earth, sun, moon	Q: Explanation of day/night cycle and of the change of seasons
	Moon–earth distance	C: Acting out the movements of the earth
	Tilt of the axis of earth	E: Demonstration of day/night cycle and seasons using a flashlight and a globe

understand that scientific explanations represent a different perspective with greater explanatory power compared to their initial conceptions, than to tell them that their ideas are wrong and need to be replaced. For example, usual instruction in observational astronomy often consists of telling young children that the Earth is not flat but 'round like a ball' and to show them a globe. This type of instruction is not satisfactory, however, because it does not explain to the children how it is possible for the Earth to be round when they perceive it to be flat and how it is possible for people to live on a round Earth without falling 'down'. In the instruction we have used various demonstrations, models, experiments, and videos to help children understand how the Earth appears to be different from different perspectives: From the perspective of someone on the Earth, the Earth appears to be flat. However, from the perspective of an astronaut in space or on the Moon, the Earth appears to be round. It is important to also demonstrate to the children how a very big round object can appear to be flat from the perspective of some who is on it (Vosniadou et al. 2001). In this way children understand that their belief that the Earth is flat is not a wrong belief but a belief that represents only one possible perspective.

Instruction for conceptual change must enable students to become aware of the limitations of their points of view and to understand the advantages of other perspectives and of course of scientific theories and explanations. This type of awareness is usually achieved through some kind of explicit or implicit cognitive conflict.[9] There is a large and controversial literature on the effects of cognitive conflict (Clement 2008; Guzzetti and Glass

[9] Group or class discussion and collaboration are often implicit uses of cognitive conflict.

1993; Jonassen 2008; Limon 2001). While some researchers are very critical of cognitive conflict on the grounds that it is not a constructivist approach (Smith et al. 1993), others believe that the combination of dissonance with knowledge building strategies can be fruitful (Clement 2008; Inagaki and Hatano 2003; Vosniadou and Mason 2011). Inagaki and Hatano (2003) reported that introducing a controversial experiment into a class discussion and asking students to make a prediction can be helpful in promoting discussion and can lead to deeper comprehension of scientific concept.

It is in fact almost impossible to avoid some uses of dissonance when designing instruction to produce conceptual change. Even instructional programs that are specifically designed to promote knowledge integration, such as the Web-based Inquiry Science Environment (WISE) by Linn and her collaborators (Linn and Eylon 2011) present inquiry activities to help students *distinguish* among their ideas using valid evidence. Many of these inquiry activities for distinguishing ideas are in fact subtle uses of cognitive conflict. For example, students are asked to provide their ideas to explain the seasons and then to evaluate their explanations against evidence designed to demonstrate that some of the explanations are wrong.

However, dissonance producing instructional interventions work only to the extent that the learner *notices* the discrepancy between their beliefs and the scientific information. One of the problems with instructional uses of cognitive conflict is that it does not guarantee that the students will actually experience the intended, external conflict as internal cognitive dissonance (Chan et al. 1997; Chinn and Brewer 1993), not to mention changing his or her prior conceptions. From the point of view of the framework theory approach to conceptual change we argue that one of the reasons students are often unaware of the limitations of their points of view and cannot really experience cognitive conflict is because they do not have the necessary epistemological and representational prerequisites to do so. As we discussed earlier, conceptual change does not require only ontological shifts but depends crucially on developing the epistemological sophistication required to understand that appearances may deceive us and that phenomena can be explained from more than one perspective. Increased representational capacity and model-based reasoning are needed to understand counter-intuitive and abstract models that do not have a simple one-to-one relationship with what they represent. Conceptual change requires considerable metacognitive, epistemic and representational abilities as well as the understanding that our beliefs about the physical world are hypotheses that can be tested and falsified (Sinatra and Pintrich 2003; Wiser and Smith 2008; Vosniadou 2003).

In Kyriakopoulou and Vosniadou (this volume) we discuss the results of a number of experiments which have shown that elementary school children have trouble forming multiple, flexible representations of a same situation in the world and do not understand that their representations may be different from their phenomenal interpretations of experience. We argue that the first steps towards this understanding take place in the social-interpersonal realm, as children develop a theory of mind, and that instruction can be designed to use theory of mind to promote conceptual change in science. Many other researchers emphasize the importance of epistemological development, argumentation, model-based reasoning and hypothesis testing as means of developing students' learning and appreciation of science (Chinn, and Malhotra 2001, 2002; Duschl et al. 2007; Mason and Boscolo 2004).

Finally, instruction for conceptual change cannot be achieved without considerable social support in the form of dialogical interaction, collaboration, classroom discussion, etc. As Hatano and Inagaki (2003) have argued classroom discussion and argumentation can be effective because they ensure on the one hand that students understand the need to revise their beliefs deeply instead of engaging in local repairs (Chinn and Brewer 1993), and on the other that they spend the considerable time and effort needed to engage in the conscious and deliberate belief revision required for conceptual change to be achieved.

6 Conclusions

We argued that naive physic does not consist of fragmented observations but forms a relatively coherent explanatory system based on everyday experience. Learning science requires fundamental ontological, representational and epistemological changes in naive physics. Fragmentation and synthetic models are formed when students try to reconcile scientific information with naive physics. In order to foster conceptual change we can consider the design of curricula and instruction aiming at reducing the gap between students' expected initial knowledge and the to-be-acquired scientific information, so that learners can use their usual constructive, enrichment types of learning mechanisms successfully. However, it is also important to develop in students the necessary epistemological and representational sophistication and the hypothesis testing skills that will prepare them for intentional, meaningful, life-long learning. Instruction for conceptual change must thus foster not only the acquisition of new explanations and theories but also the acquisition of new modes of learning and reasoning. The above cannot be accomplished without substantial sociocultural support.

References

Baillargeon, R. (1995). A model of physical reasoning in infancy. In C. Rovee-Collier & L. Lipsitt (Eds.), *Advances in infancy research* (vol. 9, pp. 305–371). USA: Ablex.

Brown, D., & Hammer, D. (2013). Conceptual change in physics. In S. Vosniadou (Ed.), *The International handbook of conceptual change* (2nd ed., pp. 121–137). New York: Routledge.

Carey, S. (2009). *The origin of concepts*. New York: Oxford University Press.

Carey, S., & Spelke, E. (1994). Domain-specific knowledge and conceptual change. In L. A. Hirschfeld & S. A. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture*. Cambridge: Cambridge University Press.

Chan, C., Burtis, J., & Bereiter, C. (1997). Knowledge building as a mediator of conflict in conceptual change. *Cognition and Instruction, 15*, 1–40.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive models of science: Minnesota studies in the philosophy of science* (pp. 129–186). Minneapolis: University of Minnesota Press.

Chi, M. T. H. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 61–82). New York: Routledge.

Chi, M. T. H. (2013). Two kinds and four sub-types of misconceived knowledge, ways to change it, and the learning outcomes. In S. Vosniadou (Ed.), *The international handbook of conceptual change* (2nd ed., pp. 49–70). New York: Routledge.

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*, 27–43.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*, 1–49.

Chinn, C. A., & Malhotra, B. A. (2001). Epistemologically authentic scientific reasoning. In K. Crowley, C. D. Schunn, & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings* (pp. 351–392). Mahwah, NJ: Erlbaum.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic reasoning in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*, 175–218.

Clark, D. B., D'Angelo, C., & Schleigh, S. (2011). Comparison of students' knowledge structure coherence and understanding of force in the Philippines, Turkey, China, Mexico, and the United States. *Journal of the Learning Sciences, 20*(2), 207–261.

Clark, D., & Linn, M. (2013). Promoting conceptual change through inquiry. In S. Vosniadou (Ed.), *The international handbook of conceptual change* (2nd ed., pp. 520–538). New York: Routledge.
Clement, J. (2008). The role of explanatory models in teaching for conceptual change. In S. Vosniadou (Ed.), *The international handbook of research on conceptual change* (pp. 417–452). New York: Routledge.
diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2/3), 105–225.
diSessa, A. A. (2008). A bird's-eye view of the "pieces" vs. "coherence" controversy (from the "pieces" side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 35–60). New York: Routledge.
diSessa, A. A., Gillespie, N., & Esterly, J. (2004). Coherence vs. fragmentation in the development of the concept of force. *Cognitive Science, 28*, 843–900.
Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (Eds.). (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: National Academies Press.
Gelman, R. (1991). Epigenetic foundations of knowledge structures: Initial and transcendent constructions. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 293–322). Erlabaum: Hilldale, NJ.
Guzzetti, B. J., & Glass, G. V. (1993). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly, 28*, 116–159.
Hatano, G., & Inagaki, K. (2003). When is conceptual change intended? A cognitive-sociocultural view. In G. M. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change* (pp. 407–427). Mahwah, NJ: Lawrence Erlbaum Associates.
Inagaki, K., & Hatano, G. (2003). Conceptual and linguistic factors in inductive projection: How do young children recognize commonalities between animals and plants? In D. Genter & S. Goldin-Meadow (Eds.), *Language and thought in mind: Advances in the study of language and thought* (pp. 313–333). Cambridge, MA: MIT Press.
Ioannides, C., & Vosniadou, S. (2002). The changing meanings of force. *Cognitive Science Quarterly, 2*(1), 5–62.
Ioannidou, I., & Vosniadou, S. (2001). The development of knowledge about the composition and layering of the earth's interior. *Nea Paedia, 31*, (in Greek), 107–150.
Jonassen, D. (2008). Model building for conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 676–693). New York: Routledge.
Keil, F. C. (1981). Constraints on knowledge and cognitive development. *Psychological Review, 88*, 197–227.
Kyriakopoulou, N., & Vosniadou, S. (2012). *The Relation between conceptual change in physical science, theory of mind and personal epistemology and implication for science instruction*. Paper presented at the 8th international conference on conceptual change. 1–4 September, Trier, Germany.
Kyriakopoulou, N. & Vosniadou, S. (this volume). Using theory of mind to promote conceptual change in science, science & education.
Kyrkos, C., & Vosniadou, S. (1997). *Mental models of plant nutrition: A study of conceptual change in childhood*. Poster presented at the Seventh European Conference for Research on Learning and Instruction, Athens, Greece.
Lehrer, R., Jones, S., Pfaff, E., & Shinohara, M. (2013). *Modeling data: A learning progression for supporting the development of statistical reasoning*. Paper presented at the 2013 annual meeting of the American Educational Research Association, Building Learning Progressions for Science and Math Learning, San Francisco, CA: Vanderbilt University.
Limon, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: A Critical appraisal. *Learning and Instruction, 11*, 357–380.
Linn, M., & Eylon, B. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration*. New York: Routledge.
Mason, L., & Boscolo, P. (2004). Role of epistemological understanding and interest in interpreting a controversy and in topic specific belief change. *Contemporary Educational Psychology, 29*, 103–128.
Mason, L., & Gava, M. (2007). Effects of epistemological beliefs and learning text structure on conceptual change. In S. Vosniadou, A. Baltas, & X. Vamvakoussi (Eds.), *Reframing the conceptual change approach in learning and instruction* (pp. 165–196). Oxford, UK: Elsevier.
Mason, L., Gava, M., & Boldrin, A. (2008). On warm conceptual change: The interplay of text, epistemological beliefs, and topic interest. *Journal of Educational Psychology, 100*(2), 291–309.
Ni, Y., & Zhou, Y.-D. (2005). Teaching and learning fraction and rational numbers: The origins and implications of whole number bias. *Educational Psychologist, 40*(1), 27–52.

Nussbaum, J. (1979). Children's conception of the earth as a cosmic body: A cross-age study. *Science Education, 63*, 83–93.
Nussbaum, J., & Novak, J. D. (1976). An assessment of children's concepts of the earth utilizing structured interviews. *Science Education, 60*, 535–550.
Ozdemir, G., & Clark, D. (2009). Knowledge structure coherence in Turkish students' understanding of force. *Journal of Research in Science Teaching, 46*, 570–596.
Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Towards a theory of conceptual change. *Science Education, 66*, 211–227.
Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naïve physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction, 18*(1), 1–34.
Sadler, D. R. (1987). Specifying and promulgating achievement standards. *Oxford Review of Education, 13*, 191–209.
Samarapungavan, A., Vosniadou, S., & Brewer, W. F. (1996). Mental models of the earth, sun, and moon: Indian children's cosmologies. *Cognitive Development, 11*, 491–521.
Schwarz, C.V., Reiser, B. J., Davis, E. A., Kenyon, L., Acher, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632–654.
Sinatra, G. M., & Pintrich, P. R. (Eds.). (2003). *Intentional conceptual change*. Mahwah, NJ: Erlbaum.
Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences, 3*, 115–163.
Smith, C., Wiser, M., Anderson, C. W., & Krajcik, J. (2006). Implications for children's learning for assessment: A proposed learning progression for matter and the atomic molecular theory. *Measurement, 14*(1&2), 1–98.
Sneider, C., & Pulos, S. (1983). Children's cosmographies: Understanding the earth's shape and gravity. *Science Education, 67*, 205–221.
Stafylidou, S., & Vosniadou, S. (2004). The development of students' understanding of the numerical value of fractions. In L. Verschaffel, S. Vosniadou (Eds.), *Conceptual change in mathematics learning and teaching,* Special Issue of *Learning and instruction 14*, 5, 503–518.
Stathopoulou, C., & Vosniadou, S. (2007a). Conceptual change in physics and physics-related epistemological beliefs: A relationship under scrutiny. In S. Vosniadou, A. Baltas, & X. Vamvakoussi (Eds.), *Reframing the conceptual change approach in learning and instruction* (pp. 145–163). New York: Elsevier.
Stathopoulou, C., & Vosniadou, S. (2007b). Exploring the relationship between physics-related epistemological beliefs and physics understanding. *Contemporary Educational Psychology, 32*, 255–281.
Vamvakoussi, X., & Vosniadou, S. (2010). How many decimals are there between two fractions? Aspects of secondary school students' reasoning about rational numbers and their notation. *Cognition and Instruction, 28*(2), 181–209.
Van Hoof, J., Lijnen, T., Verschaffel, L., & Van Dooren, W. (in press). Are secondary school students still hampered by the natural number bias? A Reaction time study on fraction comparison tasks. *Research in Mathematics Education*.
Vosniadou, S. (2003). Exploring the relationships between conceptual change and intentional learning. In G. M. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change* (pp. 377–406). Mahwah, NJ: Lawrence Erlbaum Associates.
Vosniadou, S. (2013). Conceptual change in learning and instruction: The framework theory approach. In S. Vosniadou (Ed.), *The international handbook of conceptual change* (2nd ed., pp. 11–30). New York: Routledge.
Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535–585.
Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science, 18*, 123–183.
Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., & Papademetriou, E. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction, 11*, 381–419.
Vosniadou, S., & Mason, L. (2011). Conceptual change induced by instruction: A complex interplay of multiple factors. In K. R. Harris, S. Graham, & T. Urdan (Eds.), *APA educational psychology handbook* (Vol. 2, pp. 221–246). Washington, DC: American Psychological Association.
Vosniadou, S., & Skopeliti, I. (2005). Developmental shifts in children's categorization of the earth, In B. G. Bara, L. Barsalou, & M. Bucciarelli (Eds.), *Proceedings of the XXVII Annual Conference of the Cognitive Science Society*, pp. 2325–2330.

Vosniadou, S. & Skopeliti, I. (submitted). Children's erroneous inferences in the comprehension of counter-intuitive science text. *Learning and Instruction*.
Vosniadou, S., Skopeliti, I., & Ikospentaki, K. (2004). Modes of knowing and ways of reasoning in elementary astronomy. *Cognitive Development, 19*, 203–222.
Vosniadou, S., Skopeliti, I., & Ikospentaki, K. (2005). Reconsidering the role of artifacts in reasoning: Children's understanding of the globe as a model of the earth. *Learning and Instruction, 15*, 333–351.
Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3–34). New York: Routledge.
Vosniadou, S., & Verschaffel, L. (2004). Extending the conceptual change approach to mathematics learning and teaching. In L. Verschaffel, & S. Vosniadou (Eds.), *Conceptual change in mathematics learning and teaching. Special Issue of Learning and Instruction, 14*(5), pp. 445–451.
Wellman, H. M. (1990). *The child's theory of mind*. Cambridge, MA: MIT Press.
Wellman, H. M., & Gelman, S. A. (1992). Cognitive development: Foundational theories of core domains. *Annual Review of Psychology, 43*, 337–375.
Wiser, M., & Smith, C. L. (2008). Learning and teaching about matter in grades K-8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.), *The international handbook of research on conceptual change* (pp. 205–239). New York: Routledge.