The Changing Meanings of *Force*

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ABSTRACT

The research reported in this paper investigated developmental changes in the meaning of *force* in 105 children ranging in age from 4 to 15 years. The subjects attended the same school in Thessaloniki, in the North of Greece, and came from predominately middle class backgrounds. In individual interviews the children were shown 27 drawings of physical objects in combinations of different sizes and kinetic states, and were asked to determine which *forces* were being exerted on these objects, if any. Children's responses to these questions were analyzed following a methodology developed by Vosniadou & Brewer (1992, 1994). The results showed that most of the children (88.6%) made use of a small number of relatively well-defined and internally consistent interpretations of *force*. The discovered meanings of *force* varied significantly with age. The younger children thought that *force* is an internal property of objects related to their weight (*internal force* meaning) while the older children thought that *force* is an acquired property of objects that move, as the result of an agent pushing or pulling them (*acquired force* meaning). The *acquired force* meaning was well established by the age of twelve years and not substantially changed despite the systematic instruction in Newtonian mechanics that takes place in the Greek high schools. Under the influence of instruction children added the *force of push/ pull* and the *force of gravity* interpretations to the existing *acquired force* meaning creating *synthetic meanings of force*. The implications of these results for a theory of conceptual change are discussed.

INTRODUCTION

The purpose of the research reported in this paper is to investigate changes in the meaning of the word *force* as children are exposed to systematic science instruction, and to propose a theoretical framework within which these changes can be explained. This work aims at contributing further to our understanding of the development of children's knowledge about the physical world and of the learning of science concepts. There are two central theoretical issues in this investigation: The first has to do with the nature of children's initial interpretations of the word *force*. Is there a core meaning of *force* that constitutes a coherent explanatory framework or is it the case that children interpret the word *force* in a loose and logically inconsistent way, unstable over time and context? The second has to do with the nature and mechanisms of change. Is there a systematic way in which children's meaning of *force* change as they are exposed to science instruction or not, and what are the mechanisms of change?

Initial knowledge structures: There is general agreement in the science education and cognitive development literature that by the time children go to school they have acquired considerable knowledge about the physical world (a naive physics) that exerts significant influence on subsequent learning and particularly on the learning of science. Researchers disagree, however, on the exact nature of naive physics. One view, expressed by diSessa (1988), is that initial knowledge structures about the physical world consist of an unstructured collection of small and discrete knowledge elements, known as phenomenological primitives (p-prims). These pieces of knowledge are generated as abstractions of common phenomena and are activated in certain characteristic cases.

Other researchers argue that naive physics constitutes a narrow but relatively coherent explanatory framework that has the form of a theory. There are various interpretations of this proposal: One interpretation is based on the work of science educators like Novak (1977), Driver & Easley (1978), Viennot (1979), as well as McCloskey (1983). This work has shown that students bring to the science learning task alternative frameworks, preconceptions, or misconceptions that are difficult to extinguish through teaching. Misconceptions are faulty conceptions that produce systematic patterns of error and can be the result of instruction or originate prior to learning.

Another interpretation is based on the work of cognitive/developmental psychologists. This work that has shown that the knowledge acquisition process starts early on in infancy and proceeds rapidly to the construction of a conceptual system structured like a theory (e.g., Carey, 1985; Wellman & Gelman, 1992). According to this view, young children form naive theories that embody causal notions, allow distinct types of explanations and predictions, reflect basic ontological commitments, and are subject to modification and radical revision (Carey & Spelke, 1996; Gopnick, 1996; Vosniadou, 1994). Vosniadou has argued that the process of constructing a naive theory about physical objects starts early on in infancy and results in a relatively well-established "framework theory" about the physical world by the time children go to school. This framework theory is based on everyday observations and information provided by the culture, as this information is interpreted by the human cognitive system (Vosniadou, 1994; Vosniadou & Brewer 1992, 1994).

The term "theory" is used relatively freely to denote an explanatory system with some coherence. It is assumed that children's theories differ in many respects from scientific theories. They lack the systematicity of scientific theories as well as other characteristics of scientific theories such as their abstractness, and social/institutional nature. It is also assumed that children differ from scientists both in terms of the representations and in terms of the cognitive mechanisms they use. Most importantly, it is believed that children lack metaconceptual awareness of their framework theory, they do not make the explicit distinction between theory and evidence, and do not understand how theories guide the hypothesis testing process.

The framework theory consists of basic presuppositions about the way physical objects function in the world. Some of these presuppositions are, for example, that "physical objects are solid", that "space is organised in terms of the directions of up/down", that "unsupported objects fall down", that "rest is the natural state of physical objects" and "motion needs to be explained" and that "abstract entities such as force, heat, weight, etc. are properties of objects" (see also the work of Spelke, 1991 and Ballargeon, 1990). Specific explanations (or specific theories) of physical phenomena are embedded within the framework theory and are constrained by it. For example, in astronomy, there can be various specific explanations of the day/night cycle such as that the sun goes behind the mountains, or that the sun goes down to the other side of the earth. These specific explanations are embedded within a framework theory in which the earth is considered to be a physical object (as opposed to astronomical object), space is supposed to be organized in terms of the directions of up and down, and gravity to work in an up/down direction. It is assumed that it is easier to change specific explanations than the explanatory framework itself.

For the purpose of this paper, there is no need to pursue these arguments further. The important prediction is that if there is a framework theory that guides children's interpretation of the word *force*, then we should expect children to answer questions about *force* in a relatively uniform and internally consistent manner. If not, we should expect logically inconsistent responses guided by a multiplicity of fragmented interpretations of the meaning of *force*.

The students who participated in the present study were all asked if there was a *force* (or *forces*), acting on certain objects with which they were presented. Because the word *force* was always used we consider this study to be an investigation of the meaning of the word *force*. There are various theories in psychology regarding the meanings of words. In some the meaning of a word is considered to be the set of semantic features into which the world can be decomposed (e.g., Schaefter & Wallace, 1970). Others propose that the meaning of a word can be represented in the form of semantic network (e.g. Collins & Quillian, 1969), or as a concrete image (Rosch, 1976). We have adopted the position that the meaning of a word is not a semantic network, neither a concrete image, but a model[1], that consists of an interconnected set of beliefs and presuppositions and has a causal explanatory structure (see also Johnson- Laird, 1987).

Mechanisms of change. Concerning the question of change, diSessa (1988) describes it as a process of collecting and systematizing the fragments of knowledge (p-prims) into consistent wholes. This happens as p-prims change their function in order to be integrated into the scientific framework. In this framework, p-prims "can no longer be self-explanatory but must refer to much more complex knowledge structures, physics laws, etc., for justification" (diSessa, 1993).

We believe that diSessa's p-prims refer to the thousands of sensory experiences that form our experiential knowledge of the physical world (see also Vosniadou, in press). Unlike diSessa (1993) we think that children organize at least some of these experiences in narrow but relatively coherent framework and specific theories in their attempt to make sense of the physical world. As a result, the process of learning involves both the enrichment of the initial theories, as well as their major reorganization or restructuring as children become exposed to scientific information. Previous research has shown that restructuring is difficult to happen. Usually, learners assimilate aspects of the scientific explanation into their existing framework and specific theories, without changing conflicting

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[1]In the psychological literature, sometimes the term "schema" is used. We consider a schema to be an empirical abstraction that does not usually contain a causal structure and abstract entities for providing explanations. Models on the other hand have a causal explanatory structure and often employ abstract entities that are not derived on the basis of observation alone.

presuppositions, (or changing only some of them). The result is the creation of misconceptions or synthetic models (Vosniadou, 1994, Vosniadou & Brewer, 1992, 1994).

Our view of conceptual change is in some ways similar to position taken by Chi and her colleagues (Chi, 1992; Reiner, Slotta Chi, & Resnick, 2000). They argue that misconceptions arise when a person associates the wrong ontology with a scientific concept. They note, for example, that many physics concepts, such as the concept of *force* and *heat*, are wrongly associated with a *substance* ontology when in fact they belong to a *process* ontology. Chi and her colleagues seem to believe that conceptual change is a radical process that happens in a short period of time, as an individual learns the correct ontology for a given concept.

In contrast to the above-mentioned position, as well as other misconceptions-based accounts of conceptual change, we believe that conceptual change does not usually happen suddenly but is a gradual and time-consuming process. This is the case because it involves a complex network of beliefs or presuppositions that take a long time to change. While we agree with Chi and her colleagues that conceptual confusions often arise in science learning from the assignment of concepts such as force and heat to scientifically wrong ontological categories, we believe that ontological change is only one of the many changes that need to take place in the process of learning science. We also think that a more complete account needs to be provided of how ontological categories are formed and how they develop and change in the process of learning science

If our account of the knowledge acquisition process is correct, then the development of the meaning of *force* should start with a relatively coherent initial interpretation of *force* revealing aspects of the specific and framework theory within which the concept of *force* is embedded. In the process of learning science, this initial meaning should change as aspects of the scientific theory are assimilated into the specific and framework theories, creating *synthetic meanings*. This prediction is different from what the fragmentation hypothesis would predict. According to the fragmentation hypothesis, children's initial meanings of force should be unsystematic and fragmented and we should see increasing systematicity and coherence in these meanings with development and instruction.

The predictions of our theoretical framework are also different from those based on Chi’s theory. According to Chi we should see a change from assigning force to a *substance* ontology to now assigning force to a *process* ontology. On the contrary, we are not predicting a sudden change in ontological categories, but rather smaller changes in beliefs and presuppositions, that will create synthetic meanings of force, slowly bringing children’s conceptual systems closer to the conceptual system of scientifically literate adults.

In the pages that follow we will review the existing literature on the development of the concept of *force* as well as changes in the history of science in order to formulate more specific hypotheses about how the meaning of *force* may change with development and instruction.

Review of the literature

The first important attempt to study the development of the concept of *force* can be traced to the work of Piaget. In his book "Understanding Causality" Piaget (in collaboration with R. Garcia, Piaget, 1972), argues that the development of the scientific concept of *force,* as well as of other scientific concepts like weight and heat, proceeds through stages which coincide with the well known stages of his theory. More specifically Piaget (1972) traced the beginnings of the scientific concept of *force,* at the period of formal operations (12 - 15 years). He claimed that, at the formal operation stage, children recognize that when object fall they accelerate regularly, because of their weight. Therefore, we can speak of the beginning of *force* as m x a.

The first, undifferentiated, concept formed by the pre-operational child is what Piaget calls "spatio-temporal thrust". Spatio-temporal thrust is a combination of mass (which children call "weight"), speed, and distance traveled by the object. For example, when 4 to 5 years olds explain the results of a collision of a moving marble on a stationary one, they call alternatively to the size or the mass of the moving marble, to its speed, and/or to the distance traveled by it. During the next stage (5.5 to 6 years), children begin to differentiate mass from speed and distance. For example, in the above mentioned situation, they stress either the mass or the speed of the moving marble. In the next stage (7 to 8 years) they place “emphasis on the speeds and their changes that is impetus at take of” (in French: "pris d' elan" = gathering of *force*s previous to take of). This *force* or "elan" according to Piaget, is a quantity that "stays inside the movement, in the sense that the movement or the speed constitutes itself the *force*".

Therefore, as Piaget claims, during the stage of concrete operations “force” does not exist separately from movement, in the sense that every movement encompasses a “force”, in the form of an internal motor. Later (9 to 10 years), “force is differentiated from movement and represents the cause of the movement or of its changes”. It is only at the beginning of the period of formal operations (11 to 12 years) that children start to form the idea that forces continue to exist in the state of rest. As mentioned earlier Piaget also claimed that at this age children recognize that when objects fall they accelerate regularly because of their weight.

Many studies conducted during the last two decades, mainly by science educators, have confirmed Piaget’s findings that force is closely related to movement but have contradicted his claim that the two become differentiated in older children and adults. Rather it appears that children as well as adults continue to relate force to movement and to believe that there is a force within inanimate objects that have been set in motion, even when the objects have lost their contact with the original mover. It is believed that this force gradually dissipates and finally runs out as the object slows down and stops. For example, in a study conducted by (Clement, 1986) first year engineering students taking a physics course were presented with a drawing depicting a coin that was thrown upwards vertically. Clement asked the students to draw vectors to represent the forces that are exerted on the coin. Only 12% of the students (N=34) 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 last force was supposed to represent-according to 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 (N=43 and N=37) were only 28% and 30% respectively.

In another study, conducted in New Zealand, Osborne and Freyberg (1985) showed students (age 7 to 19) the 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" (13 years), "It is the force from the golf stick which slowly dies out". These responses show that the subjects thought that there should be a force in the moving object to explain its motion. The cause of this force was usually attributed to the original mover.

It can be derived from students' explanations that the hypothesized force within moving objects is proportional to the speed of the object since it is believed that this force diminishes as the object slows down. Viennot (1979) studied more systematically the relation between force and speed. English secondary school students (last year of secondary school), as well as French and Belgian university students, participated in her studies. In one of her tasks she presented the subjects

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

with a drawing depicting six balls, thrown by a juggler, at different points in their trajectories. The subjects were asked to say whether the forces acting on the six balls had equal or different magnitudes. According to Newton's second law of motion, a force exerted on an object is proportional to the acceleration that is acquired by the object, and not to its velocity. Although the six balls had different velocities, they had the same acceleration, caused by the only force exerted on them, i.e., the force of gravity. Results showed that more than half of the subjects believed that forces of different magnitudes were exerted on the six balls, and that their magnitude was always proportional to the magnitude of their velocities. Many subjects argued that no force was applied on the ball being at the top of its trajectory where its velocity equals to zero. Many students referred to this kind of force as "the force of the mass".

Children's ideas about forces exerted on objects at rest have also been studied (e.g. Ministrel, 1982; Clement, 1986; Osborne and Freyber, 1985). Many children believe that if an object is not moving there is no force exerted on it. In a study with high school students, Ministrell (1982) presented students with a drawing depicting a book being at rest on the top of a table, and asked them to draw vectors to represent the forces exerted on the book. Half of the students answered that the only force that is exerted on the book is the force of gravity, neglecting to mention an equal to it force in the opposite direction exerted by the table. Similar results have also been reported by Clement who gave the same task to college students (Clement, 1986).

Finally, in the study already mentioned conducted by Osborne and Freyberg, (1985) students, ranging in age from 7 to 19 years, were presented with a drawing depicting a man pushing a car. The students were told that the car did not move and that 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. Some common explanations were 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- etc.”.

In summary, there is much empirical evidence that supports the argument that both children and adults hold ideas about force and give explanations about motion and rest that are incompatible with the Newtonian theory of mechanics. As mentioned earlier, these results come in contrast with Piaget’s claims that the Newtonian concept of force is the product of a spontaneous conceptual reorganization that takes place during the formal operation stage. Rather, it appears that the perceived relation between force and motion is rather strong and does not go away even after years of instruction.

Force in the history of science

It is not our purpose here to give a complete description of the development of the concept of *force* in the history of science. Rather, we will use the historical evidence to make two points: 1) During the long period of its historical development the word *force* was given different meanings most of which considered *force* to be a property of physical objects. 2) before Galileo, *force* was associated with motion. There was no distinction between uniform motion and accelerated motion on the grounds that both need to be explained in terms of a *force* exerted.

The word *force* was used by Greek philosophers before Aristotle to refer to the properties (such as cold or hot, wet or dry, soft or hard, heavy or light) that characterize the four “elements” - soil, water, air, fire- out of which all material substances were supposed to be formed. Different combinations of these *force*s were believed to give specific qualities to each element and consequently to the different materials created by these elements. In this respect, a stone that is mainly composed of the element soil, which is “heavy”, has the tendency to move to the physical position of the element, which is the center of the spherical universe, the center of earth. That is why a stone left free falls to the ground, while smoke, composed by air, which is “light”, tends to move up to the periphery of the universe, the natural position of the “air” element. These two kinds of motion - up and down- are called “natural motions” because they are caused by *force*s i.e., internal properties of the objects.

Aristotle shared the above-mentioned ideas about *force*s. He also believed that there are two kinds of motions: natural and violent motions. As “natural motions” Aristotle considered all changes that happen with the passing of time, including the fall of objects towards the earth, the rising of smoke, as well as the growing of plants, or the ripening of fruits. Changes caused by external interventions were characterized as “violent motions”. According to Aristotle, the motion of a projectile in the air (e.g., an arrow) is a violent motion that has to be explained in terms of a causal agent. Aristotle argued that the agent that sets an object in motion causes the air that surrounds it to vibrate. The vibrating air has the *force* to move the object. This *force* is then transferred to the next layer of the air, which undertakes to move the object farther. However, during the transfer the corresponding *force* is diminished gradually causing the motion of the projectile to stop (Dugas, 1950).

The problem of the projectile’s motion puzzled scientists for many centuries. In the Middle Ages, an interesting theory was proposed known as the “impetus theory”. The most articulated view of the theory was that of Buridan’s (1300 - 1388). According to Buridan, when an object is set in motion an “impetus” (or “vis” and “forza” in Latin) is imparted into the object. This “impetus” keeps the object in motion for some time after it has lost its contact with the agent. As the impetus gradually dissipates, the object slows down, until it finally stops or falls to the ground due to its weight (Franklin, 1978).

Galileo conceptualized projectile motion in a completely different way. His idea was not to look for a cause that makes an object retain its motion, but for the reasons that may bring the object to a stop. The "law of inertia" explained the motion of a projectile as the result of a tendency of all objects to retain their state of motion, when no force is exerted on them. In other words, when an agent sets an object in motion the object tends to move on a straight line and in a constant speed. Frictional forces and the force of gravity are responsible for making an object stop. Although the law of inertia solved the problem of motion, there still was a lot of ambiguity about the concept of *force*. The term was used to describe, among others, muscular strength, the power of the explosion of a cannon, and the power of a bow. It was also used to express the effort exerted by someone to move a heavy object and the potential of the heavy and hard objects to react to an agent that tents to set it in motion (Westfall, 1971).

A few decades later, Newton with his law of gravity generalized the law of inertia to include celestial objects. With his three laws of motion, he founded a theory in which force is the core concept. Force is not anymore considered a property of objects but a quantity that characterizes the interaction between two objects and the cause that can change the kinetic state of the objects on which it is exerted. Correspondingly, weight is the force with which the earth attracts objects towards its center. Galileo introduced the concept of inertia to explain the uniform motion of objects in a straight line in the absence of external interventions. Therefore, in the Newtonian theoretical framework there was no need to distinguish between natural and violent motions, since all motions, (except for the uniform motion in a straight line-free fall included), were caused by some force.

It took centuries for the Aristotelian concept of force to take its present Newtonian form. These changes cannot be understood as a process isolated from the changes that happened in the framework theory in which the concept of force was embedded. Nersessian and Resnick (1989) studied in depth the similarities between students' ideas and the medieval theory. They analyzed summaries of students' protocols about projectile motion and free fall, reported in the literature, and showed that the intuitive reasoning about the above-mentioned phenomena could be generated from an underlying conceptual structure that included certain presuppositions (such as, "motion is a process" and "processes require explanations in terms of causal agency") and observations (such as, "things move by an external agent", "some bodies continue in motion after detachment from source"), that give rise to beliefs such as: "all motions require causal explanations". By examining medieval explanations of projectile motion and free fall, Nerserssian and Resnick were able to determine that the inference structure that generates the medieval explanations of motion appears to have striking similarities with the intuitive inference structure of students who provided intuitive explanations of motion. Impetus, or force, was considered by both medieval scholars and students to be a property of the moving object.

The present study

The present study used the conceptual framework and methodology developed by Vosniadou and Brewer (1992, 1994; Vosniadou, 1994) to study developmental changes in the meaning of *force*. The subjects of the study were all Greek students ranging in age from 4 to 16 years. In individual interviews they were asked to answer verbally a 27 items questionnaire developed after extensive pilot work.

Based on previous work in this area, it was hypothesized that *force* would be interpreted as a property of physical objects and that it may be related to an object's weight and size (Piaget, 1972). As mentioned earlier, much of recent science education research has shown that the currently accepted Newtonian theory of force is difficult to be acquired and that there is a persistent misconception according to which force is related to the movement of inanimate objects. On the basis of these findings, it was hypothesized that the students in the present study may also relate force to movement. Finally, based on previous work in astronomy (Vosniadou and Brewer, 1992,1994), we expected that students would assimilate aspects of the scientific concept of force (when starting systematic instruction in Newtonian theory), in their existing conceptual structures, creating synthetic meanings. We were not, however, clear about the exact form these synthetic meanings would take.

METHOD

Subjects

A total of 105 students participated in this study: 15 kindergarten students, ranging in age from 4 years and 10 months to 6 years (mean age 5 years and 5 months), 30 fourth grade students, ranging in age from 8 years and 3 months to 10 years and 1 month (mean age 9 years and 7 months), 30 sixth grade students, ranging in age from 11 years and 2 months to 12 years and 3 months (mean age 11 years and 7 months), and 30 nine grade students, ranging in age from 13 years and 8 months to 16 years and 2 months (mean age 14 years and 8 months). All the students attended the same school in Thessaloniki, a big city in the northern part of Greece, and came from predominately middle-class backgrounds. Approximately half of them were boys and half were girls.

Materials

The materials consisted of a 27-item questionnaire, based on the results of extensive pilot work (Ioannides & Vosniadou, 1989). All the questions referred to respective drawings and concerned *force*s in relation to stationary and moving inanimate objects. There were 20 simple questions and 7 comparison questions, all of which are shown in Tables 1 to 9[3].

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[3] The tables are presented in the Results section.

Simple questions inquired about the existence of *forces* on simple objects in various kinetic states (stationary or moving). The comparison questions asked children to compare *force*s applied in situations that differed in some critical respect (i.e., in the size of objects being compared, the size of the people pushing the objects, etc.). Questions about *force* were phrased either using the scientific form "*Is there a force exerted on the x? Why?*" or the colloquial form "*Is there a force on the x? Why*?" The kindergarten children were asked the questions in the colloquial form only, because they appeared to be perplexed by the scientific form and did not respond when asked. All the other children were divided in two groups: one group received the simple questions in the scientific form and the other in the colloquial.

The simple and comparison questions were grouped in five distinct sets based on the different conditions in which the objects were presented in the drawings (e.g., stationary objects, stationary objects pushed by a human agent, etc.). In what follows we will describe the five sets of questions used.

<u>Set I: Stationary objects (Table 1).</u> The four questions included in this set were designed to provide information regarding students' ideas about *force* in relation to stationary objects. Following Piaget (1972) who argued that "weight is at first a *force* with quantity and action undifferentiated", we were interested in finding out whether young children attribute *force* to stationary objects and whether this *force* is related to their *weight* and *size*.

<u>Set II: Stationary objects pushed by a human agent (Tables 2 & 4).</u> The questions in this set were designed to explore students' ideas about *force* in a situation where a human agent pushes an object and exerts a *force* on it. Previous studies (Osborne and Freyberg, 1985) have shown that children relate *force* with motion and often believe that there is no *force* on an object that is stationary although it is being pushed by an agent. Four simple questions were used in order to

provide information about how the presence of an agent who pushes the objects affects children's responses (Table 2). The two comparison questions (Table 4) were used in order to study how the hypothesized *force* is related to the size/weight of the objects or to the size/weight of the humans who push the objects. We hypothesized that in attributing *force* to these objects children may take into consideration only the weight or size of the object, while the older children may take into consideration the possible kinetic state of the objects resulting from the agent/object interaction.

Set III: Stationary objects being on the top of a hill (Tables 3 & 5). The four simple questions of this set referred to four drawings depicting different objects situated at an unstable position, on the top of a hill. We wanted to know whether the children were able to take in consideration not only the size and the weight of the objects but their position as well. Position is important because it affects the objects' kinetic state as well as its potential to act on other objects. With the comparison questions we aimed to study how factors such as the object's height from the ground and its stability affect children's ideas about *force*.

Set IV: Objects on a free fall (Tables 6 & 8). The purpose of these questions was to study children's ideas about *force* in relation to falling objects. It has been argued that students do not use the "impetus misconception" in the case of free fall. They simply refer to the weight of the object as the cause of the fall (diSessa, 1988). It was expected that these questions would give more information about this matter. A single comparison question was also used (Table 8) in which children were asked directly to compare *force*s related to two similar objects the one being at rest and the other falling to the ground.

Set V: Objects that have been thrown (Tables 7 & 9). The last four simple questions referred to drawings of different objects being thrown by a man and aimed at revealing students' ideas about *force* in relation to objects that have being thrown. In the literature, there is general agreement that this case is a typical example of a motion explained by the "impetus misconception". It was expected that the Greek children would provide explanations similar to those given by English and French speaking children. As in the case of falling objects the comparison question (Table 9) was expected to give more information about moving objects as compared to similar stationary objects.

Procedure

The students were interviewed individually for about 20 to 25 minutes. Their responses were recorded, while the experimenter also kept detailed notes. The scoring of the data was done on the basis of both the transcribed data and the experimenter's notes. Follow-up questions like "can you tell me more about this", were used to clarify the responses which the interviewer could not understand.

Scoring

Children's responses to the questions were scored twice: first for the questions comprising each of the five sets of questions (question set level, QSL) and second for all the questions combined (overall level, OL). At the first level, students' responses to each set of questions were scored as a group, on the basis of a scoring key containing a set of categories for each set of questions. Within the same set, simple and comparison questions were also scored as separate sub-sets. The scoring categories are presented in tables 1 to 9. They were designed to capture the range of specific responses obtained. Agreement between two independent judges who used the scoring key to score all the responses was high (between 90% and 95%). All disagreements were resolved after discussion.

Following the scoring at the set of questions level, we tried to see if we could find evidence in the data for the consistent use of a small number of explanatory structures or meanings of *force* by the individual subject in our sample. The scoring at this, overall level, was done on the basis of a second scoring key outlining the pattern of expected responses for each meaning. The second scoring key and the procedure for scoring the data at the overall subject level will be described later.

RESULTS

Scoring at the question set level (QSL)

In this section we will present the categories that were used to score children's responses at the question set level. We will start with questions sets I, II & III, and will continue with sets IV & V. Then we will report the results of an analysis of variance on children's responses to these question sets. Tables 1, 2 and 3 present the categories of responses for Set I (Stationary Objects - Simple questions), Set II (Stationary objects being pushed by a human agent-Simple questions), and Set III (Stationary objects being on the top of a hill-Simple questions), respectively, distinguishing between simple and comparison questions.

(Insert Tables 1, 2 and 3 about here)

Sets I, II and III - Simple questions. Responses to these three sets of questions revealed that many children believed that there is a *force* within stationary objects. We have used the term *internal force* to refer to this kind of *force* that children seem to believe is a property of stationary objects. Some children attributed an *internal force* to big objects and not to small objects. They said, for example, that "there is a *force* on the big stone/big balloon" but not "on the small stone/small balloon" (Tables 1,2,3; Category a). Others attributed such an *internal force* to the big stone only (Tables 1,2,3; Category b), while others to the stones and not to the balloons (Tables 1,2,3; Category c). All these children justified the existence of the internal *force* by saying that these objects are difficult to move or that they are big and/or heavy. Some children believed that there is a *force* on all the objects because all of them have weight. In the case of the simple questions of Set

III, some children justified the existence of *internal force* on the grounds that “if they fall down they will cause damages” or “they may hit someone” (Table 3).

Another group of students answered that there is a *force* on all the objects and that this *force* is *the force of gravity* or the attraction of the earth on the objects. (Table 1, Category e; Table 2, Category h; Table 3, Category e). Of course it is not possible from these answers to find out exactly how children interpreted gravity. A few children argued that it is the “*force* from the man” exerted on all the objects (Table 2, Category i), while some others believed that the *force* of gravity as well as the *force* from the man are exerted on all the objects (Table 2, Category g).

Finally another *force*, the *force* from the air, was also mentioned to be exerted on the four objects (Table 1, Category i and Table 3, Category h), by two students (i.e., one 6th and one 9th grader).

A number of children refused the existence of any *force* on the objects. Four different arguments, depending on the particular situation, were used by those children: (1) There is no *force* on any object because the objects are not moving (Table 1 and Table 3, Category f), or (2) because no one pushes them (Table 1, Category h; Table 3, Category i); (3) there is no *force* on any object because they are at an unstable position and they can be moved easily (Table 3, Category g), and (4) there is no *force* on the big stone because it is heavy and/or the man cannot move it, while there is a *force* on the remaining objects because the man can move them (Table 2, Category f).

<u>Sets II and III - Comparison questions</u>. Children’s responses to the comparison questions give support to our initial interpretations of their responses to the simple questions and help us to clarify them further. Tables 4 and 5 present the categories of responses for Set II (Stationary objects being pushed by a human agent - Comparison questions) and Set III (Stationary objects being on the top of a hill - Comparison questions).

(Insert Tables 4 and 5 about here)

Some children related the size of the supposed exerted *force* to the size of the objects and not to the size of the human agents who push them (Table 4, Category a) or to the position of the objects (Table 5, Category d). They justified their responses by referring only to the size and/or weight of the objects. It appears that these children believe that there is an *internal force* within stationary objects and that the size of this *force* depends on the size/weight of the objects.

Concerning children's responses to the questions of Set III a number of students were sensitive to the position of the objects. They answered that when the stones are at a more stable position "more *force* is exerted on them", or that a *force* is exerted only on the stones in such a position but not on others. All these students explained their responses by referring to the stability of the stones. Again, it appears that these children interpret *force* as an internal property of the object affected by its stability.

Some other children had a different interpretation of *force*. They believed that when it is easier for a stone to be moved (stones at the pointed top of the hill), the *force* exerted on it is greater (Table 5, Category c, and Category b). This interpretation of *force* relates *force* to *the potential of the object to be set in motion*.

In the situations where human agents try to move different stones (Set II, Table 4), some children believe that the agent exerts a *force* on the stones. There were three different categories of responses in this push/pull category of *force*. Children assigned to category b (Table 4) associated the size of the *force of push* exerted to the size of the agent. They, therefore, concluded that the same man exerts the same *force* on different stones (Table 4, Question 9), but a big man exerts more *force* than a small man (e.g., the child, Table 4; Question 10). Students grouped in category c, used the above reasoning in the second comparison question, while in the first question related the *force of push* exerted on the objects to the effort exerted from the agent. They assumed that the same man would exert more effort, and thus more *force*, to move the big stone, as compared to the small stone. Finally, the students who were grouped in category e related the *force of push* exerted by the agent to effort in their responses to both comparison questions. According to this reasoning the child must try harder to move the stone and therefore he must exert more *force* than the man, who has a bigger size (Table 4, Question 10).

No student referred to the *force of gravity* in responses to the comparison questions of Set II, while a number of students answered that there is the *force* of gravity exerted on the objects in the case of the comparison questions of Set III. These children were grouped in two categories. Children assigned to the category e (Table 5) seemed to have formed a scientifically accepted concept of gravitational *force*. Others had interpreted the *force* of gravity in ways inconsistent with the scientific view (Table 5, Category f). Three kinds of alternative interpretations of gravity have been identified. 1) the *force* of gravity is greater on the stone on the higher hill because the earth attracts it more, 2) the *force* of gravity is greater on the stone on the higher hill because the air pressure is greater, and 3) the *force* of gravity is greater on the stones on the ground or on the flattened top of the hill because there they are more stable. Finally, a few children answered that there is the *force* from the air, which is exerted on the objects (Table 5, Category h).

Some children believed that there is no *force* exerted on the stones either in the context of the comparison questions of Set II or of Set III. They gave similar explanations: The stones are not moving (Tables 4 and 5, Category f), or no one pushes the stones (Table 5, Category k). One child whose answers to the comparison questions of Set III could not be grouped in any of the above categories was assigned in category i (Table 5). This child gave contradictory responses since some of his answers were consistent with one of the categories of Table 5 and others consistent with another category.

<u>Sets IV & V - Simple questions</u>. Children's responses to the simple questions of sets IV and V were placed in categories presented in Tables 6 and 7 respectively.

(Insert Tables 6 and 7 about here)

Students whose responses were grouped in one of the first four categories (Table 6, Categories a, b, c, and d) or one of the first three categories of Table 7 (a, b, and c) answered that there is a *force* exerted on one or more objects and mainly explained their responses by referring to the size and/or weight of the objects. Some of them, also, related the existence of this *force* to the damage or noise that the objects would cause when they would fall on the ground. Again, it appears that these children think of *force* as an internal property of objects associated with their size and/or weight. As can been seen in Tables 6 and 7 these were primarily the younger children.

Some students believed that there is a *force* on all falling objects because they fall. Some of them referred to this *force* as "the kinetic *force*" (Table 6, Category i). In the case of the thrown objects (Set V), students whose responses were categorized in category d (Table 7) explained the existence of a *force* exerted on all thrown objects by saying that "it is the *force* from the man's hand" or "it is the *force* the man gave to it". It seems that all these children believed that the man gives the object a *force* that explains its movement. This notion appears to be similar to what is known as the *impetus* misconception. We have called this kind of *force acquired* to differentiate it from the internal *force*, identified earlier.

A group of students answered that it is the *force* of gravity or the attraction of the earth that is exerted on the four falling objects (Table 6, Category e). Some students also believed that it is the *force* from the air that is exerted on the falling objects (Table 6, Category h). In the case of thrown objects some students answered that there are two *force*s exerted on the objects: The *force* of gravity and the *force* given by the man's push (Table 7, Category e).

Finally, there were some students who did not believe that there is any *force* exerted on any object either falling or being thrown. Two kinds of arguments were used. Some answered that there is no *force* because no one pushes the objects. It appears that these students noted the absence of a push/pull *force* and they were grouped in category f (Tables 6, and 7). The remaining children argued that since someone was able to move the objects there must be no *force* on acting on them. We interpreted such statements to probably make reference to the absence of an *internal force* and assigned these students to category g (Tables 6 and 7). In other words we think that students of the first group thought of *force* in terms of a push/pull of a human agent, while children of the second group thought of *force* as an internal property of physical objects (related to their weight or mass).

<u>Sets IV and V - Comparison questions</u>. The categories of students' responses to the comparison questions of Sets IV and V are presented in Tables 8 and 9.

(Insert Tables 8 and 9 about here)

The interpretation of *force* as *internal force* within big/heavy objects is also present in students' responses to the comparison questions concerning moving objects. Students who held this interpretation of *force* were grouped in three different categories since they gave different responses. (1) Those who believed that equal *force*s are exerted on both stationary and moving stones, were assigned to category a (Tables 8 and 9). (2) Those who said that there is a greater *force* on the stationary stones than on the moving stones were grouped in category b (Tables 8 and 9). (3) Those who believed that there is a *force* exerted only on the stationary stones were grouped in categories b (Table 8) and g (Table 9). It appears that the first group of students did not relate the exerted *force* to the motion of the stones but to their size and or weight, while the students in the other two groups considered the fact that an object is moving as an indication that there is no *internal force* or that there is a little *internal force,* since the object could not resist the agent who set it in motion.

Many students believed that the moving stones have an additional *force,* a *force* that does not exist on the stationary stones. As mentioned earlier, we have called this *force acquired*. In the case of the falling stone, there were two categories of responses related to the interpretation of *force* as *acquired force*. The children who answered that there is a greater *force* on the falling stone than on a similar stationary one, explained their response by saying that the falling stone can cause damages or that it has more weight or that it falls with greater *force* (Table 8, Category d). A few of the older students believed that it is the *force* of gravity that is exerted on both stones but, also, that an additional impulse or a “propellant” *force* is exerted on the falling stone (Table 8, Category g).

The interpretation of *force* as *acquired force* related to motion is also present in students’ responses to the comparison question of Set V (Table 9 - Objects that have been thrown). In this case, a *force* is considered to have been given to the stone by the man who threw it in the first place. The students who believed that the *force* given by the man is the only *force* exerted on the moving stone, and that there is no *force* exerted on the stationary stone, were grouped in category c (Table 9). The students who believed that apart from the *force* given by the man to the stone there is also the *force* of the stone itself (here children are obviously talking about an *internal force* of the stones), were placed in category d. Students who considered that the *force* of gravity is exerted on both stones, while the *force* given by the man is exerted only on the moving stone were grouped in category e (Table 9). Finally, a few children thought that additionally to the *force* given by the man, the *force* from the air is also exerted on the moving stone (Table 9, Category h).

In the comparison question of Set IV, a number of students answered that it is *the force of gravity* that is exerted on both stones. Some of them believed that both *force*s are of equal size and were placed in category e (Table 8). However, a few children seemed to have developed interpretations of the gravitational *force* which are inconsistent to the scientifically accepted concept (Table 8, Category f). Three kinds of alternative interpretations of the *force of gravity* were identified. (1) There is a greater *force* of gravity on the falling stone, because it falls. (2) There is more *force* of gravity on the falling stone because it is farther from the center of the earth than the stationary stone. (3) There is more *force* on the falling stone because there is the *force of gravity* and the weight of the stone, while the stationary stone has only its weight. Finally, a few students answered that since no one pushes the stones there is no *force* exerted either on the moving or on the stationary stone (Table 8, Category h; Table 9, Category f).

Effects of age and question type on children's responses. The effects of age and question type (group I vs. group II) on students' responses were further examined using an analysis of variance on every question set, for simple and for comparison questions separately. The analyses showed no significant effect of question type (Set I: $F(1,104)=0.37$, $p>0.5$; Set II: $F(1,104)=0.34$, $p>0.5$; $F(1,104)=0.16$, $p>0.5$; Set III: $F(1,104)=0.15$, $p>0.5$; $F(1,104)=0.52$, $p>0.1$; Set IV: $F(1,104)=2.88$, $p>0.05$; $F(1,104)=4.98$, $p>0.05$; Set V: $F(1,104)=4.98$, $p>0.05$; $F(1,104)=0.12$, $p>0.5$), and no interaction between question type and age (Set I: $F(2,104)=0.28$, $p>0.5$; Set II: $F(2,104)=0.368$, $p>0.5$; $F(2,104)=0.29$, $p>0.5$; Set III: $F(2,104)=0.29$, $p>0.5$; $F(2,104)=0.42$, $p>0.5$; Set IV: $F(2,104)=0.11$, $p>0.5$; $F(2,104)=0.13$, $p>0.5$; Set. V: $F(2,104)=0.34$, $p>0.5$; $F(2,104)=0.12$, $p>0.5$). On the contrary, age was found to be a significant factor (Set I: $F(3,104)=28.41$, $p<0.00$; Set II: $F(3,104)=29.03$, $p<0.00$; $F(3,104)=6.54$, $p<0.00$; Set III: $F(3,104)=2.77$, $p<0.05$; $F(3,104)=2.85$, $p<0.05$; Set IV: $F(3,104)=13.53$, $p<0.00$; $F(3,104)=4.54$, $p<0.005$; Set. V: $F(3,104)=5.75$, $p<0.00$; $F(3,104)=4.57$, $p<0.01$). Based on these results we combined the data from group I and from group II before proceeding to further analyses. This means that the children placed in the overall meanings of *force*, presented bellow, represent the total number of children.

Scoring at the Overall Level (OL Scoring) - Meanings of *Force*

Expected Meanings of *Force*. Previous work in the area of astronomy (Vosniadou & Brewer, 1992), showed that it is possible to assign the majority of the children to the consistent use of a small number of relatively well-defined explanatory structures or models of the earth. Correspondingly we checked to see if it would be possible to also assign the majority of children in this sample to the consistent use of a small number of meanings of *force*. Indeed, the analysis of children's responses at the question level revealed four possible interpretations of *force*, which could be conceptualized as distinct explanatory structures. These were the following: a) *Internal force* an internal property of stationary objects, related to their size or weight, b) *Acquired force* an acquired property of inanimate objects that explains their motion and their potential to act on other objects, c) *Force of push or pull* the interaction between an agent (usually animate) and an (usually non-animate) object, and d) *Force of gravity* the interaction, at a distance, between physical objects and the earth. In order to look into this possibility more systematically, we generated the pattern of responses expected if the students had used each one of the expected meanings of *force* consistently to answer our questions. Table 10 presents this pattern of expected responses. In what follows we will present the criteria for deciding that a given student used one of the four expected meanings of *force*.

(Insert Table 10 about here)

Internal force. As can be seen in Table 10, the criteria we devised for the *internal force* meaning were the following: a) Responding to Sets I, II and III, Simple Questions, which refer to stationary objects, the student should say that there is a *force* on all stationary objects or only on the "big" or "heavy" objects, because they have weight or they are big or heavy (Table 1, 2, 3; Categories a , b, c, d) and not due to gravity or man's push (Set II) or their position (Set III) or any other answer. b) Concerning Set II, Comparison Questions, students should answer that there is a *force* exerted on the stones and refer to their weight/size and not to the agents' size/weight, or to their effort to move the stones, or any other answer (Table 4; Category a). c) In Set III, Comparison Questions, students using the *internal force* meaning should say that there is the same *force* exerted on all the stones because they are equally big/heavy without reference to gravity or their position (Table 5; Category d). d) In their responses to the Set IV, Simple Questions, students should say that there is a *force* exerted on all the objects or on the big/heavy objects only, because of size/weight and not because of gravity or because of their motion (Table 6; Categories a, b, c, d). e) Concerning simple questions about objects that have been thrown (Set IV), students should respond that there is a *force* exerted on all objects or on the big/heavy objects with reference to the size/weight of the objects and not to their motion or to the man's *force* or to the *force* of gravity (Table 7; a, b, c). f) Finally, students in their responses to the comparison questions of Sets IV and V should say that there is the same *force* exerted on both moving and stationary stones and refer to their equal size/weight and not to other reasons such as gravity (Table 8 and 9, Category a).

Acquired force. The criteria for deciding that students used this meaning were the following: a) in their responses to the questions concerning stationary objets on the ground (Set I) students should say that there is no *force* exerted on any object because they are not moving, (Table 1, Category f), although explanations such as "because no one pushes them" (Table 1, Category h) were also accepted. In the later case it is not clear whether these students were talking about a *force* of push/pull (and therefore they should be placed at the push/pull meaning) or about the absence of motion. The crucial criterion for differentiating students who should be assigned to the *acquired* *force* meaning from those assigned to the *push/pull meaning* was their answers to the comparison questions of Set II. b) Concerning the simple questions about objects being pushed by a human agent (Set II) they should say that there is a *force* only on those objets which the man can move (the "light" ones) (Table 2, Category f). However, responses according to which there is a *force* on all objects because the man pushes them were considered acceptable (Table 3, Category e). Since, it is not clear whether these students were talking about the *force* exerted by the man on the objects (*force* of push/pull) or an acquired *force*, we used as a safe criterion for assigning them to the *force* of push/pull meaning or to the acquired *force* meaning their responses to the comparison questions of Set II. c) In their responses to the simple and comparison questions of Set III, students should say that there is no *force* on any object because they are not moving (Table 3, Category f; Table 5, Category g) or they are not being pushed (Table 3, category g; Table 5, Category k). d) In their responses to the comparison questions of Set II, students should say that there is no *force* exerted on any stone because the man or the child cannot move them or because the stones are not moving (Table 4, Category f). e) Students should also answer that there is a *force* on all falling objects because they are falling or they gain *force* due to their fall (Table 6, Category i), and f) that there is a *force* on all objects that have been thrown by a man which is the *force* given by the man or the *force* from the man's hand (Table 7, Category d). g) Concerning the comparison questions of Sets IV and V, in order for students to be assigned to the acquired *force* meaning they should say that there is a *force* exerted only on the moving stone and not on the stationary stone either because it is falling (Table 8, Category c) or because the man gave it to the stone (Table 9, Category c) and not due to gravity or any other reason.

Force of Push/Pull. The criteria for using the *push/pull meaning of force* are also described in Table 10. a) Students should say that there is no *force* on any stationary object because no one pushes it and not because the object is not moving (Table 1, Category h; Table 3, Category i; Table 5, Category k). b) They should also say that when a human agent pushes an object he exerts a *force* on it (Table 2, Category i) regardless of whether the object moves or not (Table 4, Categories b, c, e). c) In the case of falling or thrown objects students assigned to the push/pull meaning should answer that there is no *force* exerted on them because, again, no one pushes them (Tables 6 and 7, Category f; Table 8, Category h; Table 9, Category f). In other words, these students should not consider movement as a criterion for *force* being exerted, and should show evidence in their explanations that they understand *force* as an interaction between an agent and an object.

Gravitational force. If students used this meaning they should answer that there is the *force* of gravity exerted on all the objects in all situations. More specifically according to Table 10 students should answer that: a) There is the *force* of gravity on all stationary objects on the ground or on the top of a hill, in all simple (Table 1, Category e; Table 2, Category h; Table 3, Category e) and comparison questions (Table 6, Categories e and f), and b) there is the *force* of gravity exerted on all moving objects (Sets IV and V) in simple questions (Table 6, Category e) and comparison questions (Table 8, Categories e and f). In addition, students' explanations should reveal evidence of understanding *force* as an interaction between physical objects and the (at least) earth which can occur at a distance.

Obtained Meanings of *Force*. Having defined the criteria presented in Table 10 we compared the actual responses given by the students to the pattern of expected responses. The results showed that many students appeared to use the expected meanings of *internal force,* and *acquired force* but that the expected meanings of *push/pull* and *gravitational force* were not used by the students in our sample. Moreover, a great number of students' responses could be explained if we hypothesized that they had used several *synthetic meanings of force*, consisting of combinations of the above-mentioned core explanatory frameworks.

Table 11 presents the obtained pattern of responses and the way they were categorized into meanings. In what follows we will present the criteria for assigning the students in each one of the obtained meanings of *force* presented in Table 11. Table 12 presents examples from the responses of children placed in these different meanings of *force*.

(Insert Tables 11 and 12 about here)

1. Internal Force. This meaning, which was found mostly in kindergarten and a few fourth grade students, is similar to the expected *internal force meaning*, described on p. 28. All the children using this meaning of force argue that there is a *force* either within all objects or only on objects that are "heavy" (as opposed to "light"). These children could also say that there is "more *force*" on "heavy" objects as compared to "light" objects. We have called this the *internal force meaning* because children seem to conceptualize *force* as an internal property of physical objects affected only by their weight and/or size (and not by their movement). This meaning of *force* is close to the interpretation of *force* as strength or power. A typical example of an internal *force* meaning is presented in Table 12 (Kiriaki, Kindergarten).

2. Internal Force Affected by Movement. Only four children used this meaning (two kindergartners and two fourth graders). These children believed that there is an *internal force* on all objects affected by their weight and/or size. In contrast the previous group, however, these children thought that there was *no force* or *less force* on an object if the object was in motion or in an unstable position and thus likely to move and/or fall. It appears that the movement of an object was interpreted to mean lack of internal *force* (strength or power). In some cases, lack of internal *force* was associated with the object's "failure" to resist the actions of an external agent trying to affect the object in some way. A typical example of a student who used this meaning is Katerina (Table 12), who believed that the balloon does not have *force* because "if we kick it, it will be broken", (Question 3) and that there is no *force* on the big stone standing on the pointed top of the hill because "if someone pushed it, it may fall" (Question 22), and that there is a *force* only on the second stone in Question 27 (the stationary), "because he (the man) cannot throw it".

3. Internal and Acquired Force. This was a popular meaning obtained in a total of 24 children mostly from grades 4th and 6th. The characteristic pattern of responses for children using this meaning was to say that there is a *force* on stationary objects affected by their weight/size and that these objects also acquire an additional *force* when set in motion. In other words the children interpreted the motion of an object to signify the existence of an additional *acquired force*, in contrast to the previous children who had interpreted the motion of an object to signify the absence of an internal *force*. For example Anna (this meaning) says in response to question 27 (Table 12) that there is more *force* on the first stone "because the man threw it and it leaves with great *force*", in contrast to Katerina (previous meaning) who said that there is a *force* only on the second stone because the man "cannot throw it".

The children in this group were ambivalent about how to interpret the situation where an object was in an unstable position. Most children interpreted the unstable position (and therefore the great likelihood of an object to fall) as lack of internal *force* and said, like Anna (Table 12, Grade 4, Question 17, 3a. Internal and Acquired *Force* a) that there is "no *force* on the first stone because it is not stable. There is a *force* on the second stone because it is more stable". Four children interpreted the unstable position, however, as likelihood of the object to acquire an additional *force*. For example, Michael (Table 12, Grade 4, Question 17, 3b. Internal and Acquired *Force*, b) said in response to the same question that "there is more *force* on the first stone because it may fall".

4. Acquired force. Students who used the *acquired force meaning* met all the criteria described in page 29. These students believed that there is no *force* exerted on any stationary objects at all, and clearly related *force* to motion: inanimate objects acquire a *force* when moved by an agent. This *force* disappears when the object stops. According to these students, *force* is imparted to the objects by the agent (e.g., the man) who threw them, or is acquired as a result of their fall to the ground. Two students, one of the 4th and the other of the 6th class, thought that *force* is acquired only by those objects they considered as “heavy” and not by the “light” ones (Tables 6 and 7, categories b, c). We think that this response is not really a deviation from the meaning, but that these students related the acquired *force* to the weight of the objects as well as to their motion.

The students in this group were also ambivalent about how to interpret the situation of an object placed in an unstable position. Most students focused on the lack of movement and thus assigned more *force* to the stationary stones in unstable positions (see for example Domna, Table 12, 4a. Acquired *Force* a). However, a group of five students thought that there is a *force* on all objects that are standing on the pointed top of a hill. They justified the existence of this *force* by saying that it is due to the fact that they would easily fall down the hill and thus be set in motion (Table 3, Category d). An example can be found in Pavlos (Table 12, Question 11) who says that there is a *force* “because the stone is in a high position”. He further explains that the stone “has kinetic energy. Its potential energy is transferred into kinetic energy and the stone may fall down”. The same student says in Question 22 that there is a “kinetic *force*” on the falling stone. As it becomes clear from this example, many children in this group mixed up *energy* with *force*.

5. Acquired Force and Force of Push/Pull. As in the case of the *acquired force meaning* the interpretation of *force* as *acquired force* is in the core of this meaning also. However, there is an essential difference between the students who were assigned to the present meaning compared to those assigned to the *acquired force meaning*. The students who were assigned to the present meaning said that when an agent (e.g., a man) tries to push an object he exerts a *force* on it, regardless whether the object moves or remains stationary. Therefore, for these students, the existence of a *force* exerted on an object is not related only to the motion of the object (as in the case of the acquired *force* meaning), but also to the presence of a push/pull.

Three students, one 6th grader and two 9th graders, who were placed in this meaning referred also in their responses to a *force* exerted from the air on all the objects. Elizabeth, for example, a 6th grader, in responding to question 1 which is about *force*s exerted on a stationary stone said that there is the "*force* from the air above it" that is exerted on the stone. These students also believed that in the case of moving objects the *force* from the air is added to the acquired *force*. Giannis, a 9th grader, for example, said that there are two *force*s exerted on a thrown stone: "The *force* of the man who threw it and the *force* from the air ".

It must be stressed here that the students who used this meaning were consistent in their interpretation of *force* both as *push/pull* and as acquired *force*. They used the push/pull meaning in cases where an agent pushes an object regardless of whether it moves or not and the acquired *force* in situations related to moving objects. Therefore, we can speak of a representation with internal consistency and not of a mixed category.

Finally, it should be mentioned here that it does not appear that the present students consider the *force* of push/pull as an interaction. It seems more likely that they relate the *force* of push/pull to the effort of the agent, and that they mix up *force* with *energy*.

6. Force of Push/Pull. This meaning was used only by one 9th grader. He answered that there is no *force* exerted on any objects moving or stationary, except in situations where a man tries to push an object. The responses of the child placed in this meaning are presented in Table 12

(Giorgos, 9th grade, group I). This push/pull meaning seems closer to the scientifically accepted concept compared to the previous synthetic *acquired force and force of push/pull* meaning. Nevertheless, it is again difficult to say on the basis of the available evidence exactly how the *force* of push/pull is interpreted by this student and whether is confused with effort or energy.

7. Gravitational Force and Other Forces. The OL scoring revealed that no student could be assigned to the expected *gravitational force* meaning. All students who gave gravity responses mentioned other kinds of *force*s as well. This is why they were placed in a category we called *Gravitational and Other Forces*. Their responses are described in Table 13.

(Insert Table 13 about here)

The first observation that can be made is that all students who mention the *force* of gravity also believe that in the case of thrown objects there is an additional *force* that comes from the agent who throws the object - an acquired *force*. See for example, the response to Question 27 of Andreas, Table 12, *Gravitational and Other Force*s.

Gravity appears to be associated first with falling objects (Gravity and Acquired, and Gravity, Push/pull, and Acquired a; Table 13) and then with stationary objects (Gravity, Push/pull, and Acquired b, c, d; Table 13). When gravity is assigned to stationary objects as well as falling objects, some students believe that there is “more force of gravity” exerted on falling objects or on objects placed in unstable positions (Gravity, Push/pull, and Acquired b; Table 13). Two subjects mention the co-existence of “*force* of gravity and weight” in the case of falling objects (Gravity, Push/pull, and Acquired c; Table 14). The majority of the subjects (mostly 9th graders) belong to the Gravity, Push/pull, and Acquired d sub-meaning. These students assign *force* of gravity to stationary as well as thrown/falling objects, but think that when an object is moving an additional (acquired) *force* is added to the *force* of gravity. When there is a *force of Push/pull*, gravity is usually not mentioned, except in a few cases.

We interpreted these findings to mean that the *acquired force meaning* continues to be the main meaning of *force* in this case as well. The notion of *gravity* is added to this core meaning. It is not clear exactly how gravity is understood. It is important, however to notice the similarity between the various *gravity meanings* and the *internal and acquired force meaning* where moving objects are interpreted to have "more force exerted on them" than stationary objects. It appears that some of the cases where the *internal force* meaning was used earlier are now reinterpreted in light of a *gravity meaning* of *force*.

8. Mixed (internally inconsistent). Students were assigned to a mixed category if their responses showed internal inconsistency. Table 14 shows the response categories to which each one of these students was placed in the different sets of questions used in this study. As can be seen in all, except the last two students, the inconsistency can be traced in their ambivalence regarding *force*s in objects placed in unstable positions, in falling objects and in thrown objects. More specifically, all these students believe that there is a *force* in stationary objects affected by weight/size and cannot decide how to interpret movement as in meaning 2 (movement means less or no *force* exerted) or as in meaning 3 (movement means more *force* exerted). The last two students in Table 15 show greater inconsistency in their responses and cannot be placed in a consistent category.

(Insert Table 14 about here)

Effects of age and question type on meanings of *force*

An analyses of variance showed that there was a significant effect of age on students' responses ($F(3,104)=3.28$, $p<0.05$), while there was no significant effect of question type

($F(1,104)=1.38$, $p>0.05$). There was also no interaction between question type and age ($F(2,104)=1.101$, $p>0.05$). Table 15 shows the frequencies and percent of meanings of force as a function of grade.

(Insert Table 15 about here)

As can be seen, the younger children used almost exclusively only the first four meanings. The kindergarten children tended to use meanings 1, 2 and 3, while the older elementary school children tented to use meanings 3 and 4. Meaning 5, was used by the 6th and 9th graders, while meanings 6 and 7 were used almost exclusively by high school children.

DISCUSSION

Meanings of *force*

The analysis revealed that it was possible to explain the responses given by 88.6% of the students by assuming that they were consistent in using one out of a small number of meanings of *force*. The observed meanings can be grouped in two categories: Those that appear to be based on everyday experience and show no influences from Newtonian theory, and those that have been influenced by the scientific theory. Following Vosniadou and Brewer (1992, 1994) we will call the first group of meanings "initial" and the later "synthetic". In this study we discovered two kinds of initial meanings of *force*, not influenced by instruction: the *internal force* meaning and the *acquired force* meaning. We also discovered some combinations of the *internal* and *acquired* meanings that will be called *hybrid*. There were no meanings of *force* in the present sample that showed a complete understanding of the Newtonian framework.

Initial meanings. There seemed to be two initial meanings of force: *internal force* and *acquired force*. As was mentioned earlier, most of the kindergarten children (46.7%) used the *internal force meaning*, according to which *force* is exerted either on all objects because they have weight, or only on "heavy or big objects"[4]. There is also an additional interpretation according to which there is more *force* exerted on heavier objects. In all these interpretations, *force* is conceptualized as an internal property of physical objects, affected only by their weight and/or size.

A description of the hypothetical conceptual structure underlying this meaning of *force* appears in Figure 1. We hypothesize that students interpret observations such as that big/heavy people/objects can cause damage on other people/objects, or can resist the push/pull of other objects, and relate these descriptions to the presence of *force*. This interpretation of force is embedded within a framework theory of physical objects with force being considered as a property of physical objects. It appears that the meaning of *force* for these students is closer to what is expressed by the word *strength.*

(Insert Figure 1 about here)

The results showed that between the ages of 8 to 12, the *internal force meaning* is replaced by the *acquired force* meaning. In the *acquired force* meaning the criterion for deciding whether a *force* has been exerted or not, is *movement*. The students talk about objects being pushed/pulled by agents but they do not assign a *force* to them unless they move. The a*cquired force* meaning, which is the most stable interpretation of *force* in the students in our sample, is similar to the "internal motor" idea of *force* reported by Piaget (1972), to the "*force* of mass" reported by Viennot (1979), and to the "impetus" notion reported by McCloskey (1983), Clement (1982), and diSessa (1988).

Figure 2 presents the hypothesized conceptual structure that underlies the a*cquired force* meaning. This structure is based on Nersessian and Resnick's (1989) analysis of the impetus misconception. According to this analysis *force* is tied to motion in an explanatory framework in which the motion of an inanimate object requires explanation in terms of a causal agent (this causal

[4] This is a qualitative not a quantitative understanding of "heavy" or "big".

agent being *force*). *Force* is not considered any more an inherent property of inanimate objects although we assume that this continues to be true in the case of animate objects. Rather, it is an *acquired property* of those inanimate objects that move, in the context of the explanatory framework mentioned earlier, that is, that the push/pull of an agent is what usually causes the inanimate object to move. It appears that the children who adopted this meaning of force had differentiated *force* from *weight*.

(Insert Figure 2 about here)

Hybrid meanings of *force* not influenced by instruction. The change from the *internal* to the *acquired force* meaning observed in the present study is a change in explanatory framework that appears to happen *spontaneously* without influence from instruction. How can this change happen during a relatively short period of time?

The presence of the hybrid meanings *internal force affected by movement* and *internal and acquired force,* provide information regarding the process of conceptual change. It appears that students become sensitive to movement and the relationship between movement and *force* early on[5], but have difficulty explaining this relationship. In the context of the *internal force* meaning, the natural interpretation of the movement of an inanimate object is to consider it as “weakness”, i.e., as a failure of this object to resist to the push/pull of other objects, and thus to lack of *force*, or less *force* (see the hypothesized conceptual structure for the *internal force meaning* described in figure 1). This is exactly the interpretation of movement present in the hybrid meaning, *internal force affected by movement*. On the other hand, from the point of view of the *acquired force* meaning, the movement of an inanimate object is an indication that a *force* is being exerted. In this context, the presence of movement implies an additional force, which when combined with *internal force*

[5] About half of the kindergarten children were placed in one of these two synthetic meanings (see Table 15).

produces "more force". This is exactly the interpretation of movement in the hybrid meaning *internal and acquired force.*

There is, however, an internal inconsistency that characterizes this interpretation of force. If we think of an object that has been set in motion by an agent as having an *acquired force*, such an object cannot be thought of as having an *internal force* also, because if it did, the agent should not have been able to move it (following the logic of the argument given by the students placed in the *internal force* meaning). It is maybe the realization of the internal inconsistency implicit in the attempt to combine the internal and acquired interpretations of *force*, that this hybrid meaning is eventually abandoned in favor of the a*cquired force meaning*. To have an *internal force* means that an object cannot be moved, while *acquired force* is related to moving objects only. Therefore, *acquired* and *internal force* cannot coexist. It is not uncommon in the developmental literature to have cases where conceptual change occurs from the need to solve internal inconsistencies (e.g., Vygotsky, 1962; Karmiloff-Smith, & Inhelder, 1974).

In the *acquired force meaning*, it appears that *force* has been differentiated from *weight*, at least in the case of inanimate objects. Weight remains an internal property, but *force* is now considered an acquired property related to the push/pull of an agent (usually animate), when that push/pull causes the inanimate object to move. Similar cases where two concepts are differentiated from a parent concept, have been reported by Piaget (1972) and Smith, Carey & Wiser (1985), and are, of course, common in the history of science (Kuhn, 1977).

It is interesting to observe that most of the students placed in the mixed category did so because they were caught between *the internal* and *acquired force meanings* and were unsure about how to interpret movement. Ten of the twelve students placed in the mixed category sometimes interpreted movement in the context of the *internal force meaning* - as an indication of "less" *internal force* - and sometimes in the context of the *acquired force meaning* - as an indication for the application of an external *force* (Table 14 presents all cases of inconsistency obtained).

Synthetic meanings of *force.* We have argued that while the first four meanings of *force* do not show an influence of the Newtonian theory presented through instruction, the remaining three do show such an influence. As in the case of the astronomy studies conducted earlier (Vosniadou & Brewer, 1992; 1994) these synthetic meanings result from the assimilation of scientific information into the existing explanatory framework.

The students who used the *acquired force* and *force of push/pull* meaning interpreted *force* as an acquired property of moving inanimate objects but added to it the *force* of *push/pull* (in the case where an animate agent was shown to exert a *push/pull force*). These students showed some progress towards the scientifically accepted meaning, to the extent that they interpreted the push/pull action of an animate agent as *force* exerted, regardless of whether the push/pull results in the movement of the affected object or not. The hypothetical conceptual structure that underlies the a*cquired force meaning* (see Figure 2) could be part of the underlying structure of this synthetic meaning of force also with the exception that *force* is now considered to be exerted not only when the object moves but also when an agent simply pushes or pulls it.

This meaning is synthetic because the *force of push/pull* is added to the existing *acquired force meaning*. Moreover, the *push/pull force* does not appear to be conceptualized in ways consistent with the scientific theory (*force* as interaction between two objects), but in ways that show a confusion between *force, effort*, and *internal strength or energy*. Although, it was not the purpose of this study to investigate the students' confusion between *force, effort* and *energy* it was clear from students' statements that such a confusion existed. For example, in response to question 9 (where a man of the same size pushes a big stone and a small stone), Vasilis, a 9th grader says that in pushing the first stone "the man *consumes* more *force* because the stone is bigger", showing a confusion between *force, effort* and *energy*. On the other hand, Haralambos (grade 9) says in response to question 10, that "the child exerts more *force* than the man (to move the same stone) because he is weaker and has less *force* than the man", implying a confusion between *force* and *internal strength/energy*. It was common for students to use terms like "*kinetic force*" (to characterize the movement of an object being pushed by a man) or "*dynamic force*" (to characterize the potential energy of an object in an unstable position) and in general to attribute *force* in the cases where the scientific concept of energy should be used. Characteristic are the responses of Manolis who says in response to questions 9 and 10 that *there is no force* exerted on the stones because *there is no energy*. These apply to all occasions where *the push/pull meaning of force* is used.

As mentioned in the Results section, there were two students who used this meaning but also mentioned the *force* of the air to be exerted on all the objects. We consider this to be another case of assimilation of new information into existing knowledge structures. It appears that these students were informed, probably in school, about the atmospheric pressure exerted on all objects being inside the atmosphere. This information does not contradict any of their prior beliefs: A *force*, such as the *force* from the air, can be exerted on an object without causing it to move (the same is true for the *force* of push/pull exerted on stationary objects). Thus, in their responses, these students simply added the "*force* from the air" to the meanings of *acquired force* and the *force of push/pull*. Instead of answering that no *force* is exerted on the stationary objects they said that it is the *force* from the air that is exerted on them, and in the case of thrown objects the "*force from the air*" was added to the already acquired *force*.

Finally, another synthetic meaning is the *gravitational and other forces* meaning. As it is shown in Table 13, the *gravity meaning of force* starts to appear first in the case of falling objects (Question 22) and thrown objects (Question 27 - with *acquired force*) and then generalizes to stationary objects as well. In the majority of the responses in our sample, gravity was mentioned as a *force* that operates both in the case of moving and of stationary objects, except in the case of push/pull. It appears that in the later case students focus on the push/pull action and forget about gravity.

In summary, it appears that students start with a meaning of *force* not differentiated from weight (*force* as an internal property of big/heavy objects). This meaning is eventually replaced by a different meaning according to which *force* is the acquired property of objects that move (*acquired force* meaning). The *acquired force* meaning is well in place in the conceptual system of the 11-12 year old child (6th grader) and is not substantially changed through instruction until the age of 15 (9th grade). Under the influence of instruction, students add the *force of push/pull* and the *force of gravity* to the already existing *acquired force* meaning creating various synthetic meanings.

Relationship to prior research

The relationship between *force* and *weight* has been mentioned by Piaget (1972) but has not been reported in more recent studies with English-speaking subjects. One reason could be that these studies have used older subjects than the ones used in our sample. There may be also important linguistic and/or cultural differences. As mentioned earlier, in the Greek language there is only one word for *force*, the word “dynamis” that denotes not only *force* but also *strength* and *power*. The *internal force* meaning appears to be closer to the "strength" meaning of the Greek word "dynamis". A cross-cultural study comparing Greek to English speaking students could provide some answers to this question.

The most stable interpretation of *force* in our sample was that of the *acquired force* meaning. As mentioned earlier, this meaning is similar to the impetus idea of *force* identified by many science educators, as well as o the "internal motor" idea reported by Piaget (1972). Unlike Piaget's claims that the formal operational child spontaneously differentiates *force* from *motion*, this did not happen in the older students in our sample, despite the fact that considerable instruction in mechanics takes place in the Greek high school.

The confusion between *force* and *energy* has been noted in previous studies. Piaget (1972) reported that some students at the stage of formal operations spoke of a *suspended force* on marbles which were ready to go down a slope, something "that brings to mind the idea of energy, but which is as yet only the generalization of the idea formed at this stage, namely, that *force*s continue to exist in the immobile state" (Piaget, 1972, p. 49). Many students in the present study were likely to attribute a *force* to a stationary stone in an unstable position (Questions 11 and 17), clearly showing a confusion between *energy* and *force* in this case (Note, for example, Katerina's response to Q11 "Yes, dynamic (*force*). Because it is not stable and it may easily fall", Table 16). The relationship between *force* and *energy* is currently the subject of an ongoing investigation (Megalakaki, Ioannides and Vosniadou, in preparation).

Another difference between the present study and previous studies has been the finding that many students reported an *acquired force* in the case of falling objects (Question 22) as well as in the case of objects thrown (Question 27). This finding does not agree with diSessa's findings with American students and comes in conflict his claim that the impetus misconception is not applied in the case of free fall because students mention the *force of gravity* as the cause of this motion (diSessa, 1988). A possible explanation for this discrepancy may be that diSessa's data come from subjects older than 10 years. Indeed, in the present study also the older students mentioned the *force of gravity* to account for free fall.

Towards a theory of conceptual change in childhood

In what follows we will discuss some of the theoretical implications of this study with respect to the two main questions raised at the beginning of this paper: (a) the nature of childrens' initial knowledge structures and (b) the mechanisms of conceptual change.

Initial Knowledge Structures. The results of this study do not agree with diSessa's (1988; 1993) position that initial knowledge about the world consists of an unstructured collection of small and discrete knowledge elements. On the contrary our findings showed that the majority of even the youngest children in our sample had collected their intuitive observations and information they received from the culture to form either a) one of two initial meanings of force-the *internal force* and the *acquired force meanings*-or, b) two hybrid meanings showing a transition from the *internal force* to the *acquired force*. These two meanings of force represent two distinct explanatory frameworks consisting of a complex network of beliefs, presuppositions, observations, and causal relations that go beyond what is immediately perceived.

The results of the present study are in general agreement with the position developed by Chi and her colleagues (Chi, 1992; 1994; Reiner et al, 2000) in that *force* is associated with the "wrong" ontology. Indeed it appears that in the conceptual system of children (as well as lay adults) *force* is categorized either as a property of physical objects (*internal force*) or as an acquired property of inanimate physical objects that move (*acquired force*). Unlike Chi, however, we do not believe that conceptual change consists simply of adopting a different ontology. Rather, the conceptual system is a dynamic one with changes in representations and beliefs taking place all the time preparing the ground for more radical re-organization in ontology or epistemology. More specifically, the meaning of *acquired force* is a different explanatory framework for interpreting the situations where *force* has been exerted, than that of *internal force* different both in terms of the specific theory adopted and in terms of the framework theory. It is a different explanation, addressed to different phenomena (e.g., the motion of inanimate objects), and where the individual concepts have been radically modified (differentiation between *force* and *weight*) [6]. Nevertheless, this conceptual change still happens in the context of an explanatory framework where *force* continues to be categorized as a *property* of physical *objects*, rather than as a process.

Mechanisms of Change. Unlike our previous studies in astronomy, where the observed changes in the concept of the earth and in explanations of the day/night cycle were the product of instruction, the findings of the present study show that considerable change can happen prior to the beginnings of systematic instruction. The effects of instruction, while considerable, do not succeed in producing radical changes in the established *acquired force meaning*. The results of the present study show that the meanings of *gravitational force* and *force of push/pull* are added on to the existing explanatory framework, destroying its coherence instead of restructuring it. The finding is contrary to predictions of the diSessa (1993) position that the learning of science should be associated with the creation of greater systematicity and coherence. Rather, the results of the present study support those of previous experiments showing that conceptual change is a slow and gradual affair[7] that proceeds by destroying rather than increasing the coherence of childrens' initial

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[6] We know on the basis of research with infants that the distinction between mechanical and psychological causality develops during the first years of life (e.g. Leslie, 1988). What we are claiming here is not that children understand that the movement of inanimate objects is caused by an agent pushing or pulling them, but that they associate the word *force* with this explanatory structure.

[7] Although cross-sectional data seriously constraints the kinds of inferences that can made about the knowledge acquisition process, the age effects on the use of the different meanings of *force* and the existence of synthetic meanings provide strong support to the argument that conceptual change is slow and gradual.

explanatory framework, thus preparing the ground for a new restructured conception that may or may not be finally achieved.

The present findings show that the mechanisms of conceptual change are in many respects similar in the case of spontaneous change as in the case of change produced through instruction. In both cases, a new representation appears in a specific context of use to explain a limited phenomenon (e.g., *gravity* to explain free fall, *acquired force* to explain the motion of inanimate objects, etc.) but is otherwise assimilated to the existing explanatory framework. It may then proceed to generalize its contexts of use within the same framework, as in the case of gravity in the present study, remaining a synthetic meaning. Or, it may overtake the previous meanings of *force*, creating a new explanatory framework that amounts to radical conceptual change. This is what happens when the explanatory framework behind the meaning of *acquired force* overtakes that of the *internal force*, causing a differentiation between *weight* and *force* and a distinction between inanimate and animate objects as far as the application of *force* is concerned.

It should not be surprising that the development of the meaning of force is a gradual and time-consuming process. It took hundreds of years to develop the current theory of mechanics in which force is considered an interaction between two objects. What is most interesting is that the *term force* has been used both in the history of science and by children to express similar meanings: As an internal property of inanimate objects expressing the potential of the objects to act or react on other objects, and as an agent that makes an object move or retain its motion

There also seem to be some similarities between children and scientists in the way conceptual change is achieved. For example, the spontaneous change from the *internal* to the *acquired force* meaning, where a new meaning of the term force replaces an existing one, seems to be motivated by issues of explanatory coherence. Explanatory coherence seems to be a major cause of revolutions in science (see Thagard, 1992). Moreover, the addition and deletion of concepts, the differentiation of concepts, the absorption of a new theory into an old framework, have all been observed in the historical process of theory change in science (Thagard, 1992). Although, evidence for similar processes has been found in the present study, we cannot claim that the students in our sample are metaconceptually aware of these theory change processes, or that they are in any way engaged in systematic hypothesis testing. It appears that such changes are produced by an adaptive cognitive system designed to incorporate new information into existing conceptual structures, while at the same time aiming at keeping these structures as free from internal contradictions as possible.

Conclusions

The present study investigated aspects of the development of the meaning of *force* in students ranging in age from 4 to 15 years. The results showed that students are consistent in their interpretation of the situations in which a *force* is supposed to be exerted, and that these interpretations vary significantly with age producing different meanings of *force*. Only a small number of meanings of *force* were obtained. It appears that students start with a meaning of *force* as an *internal property* of physical objects related to their weight and change to a meaning of *force* as an *acquired property* of inanimate objects that explains their motion. This becomes the major explanatory framework for interpreting *force* until the age of 15. By that time, as a result of instruction, various synthetic meanings of *force* have been created through assimilation of the notions of *gravitational force* and the *force of push/pull* to the existing explanatory framework resulting in increases in fragmentation.

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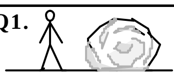
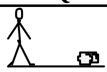
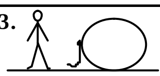
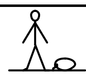
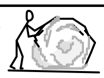
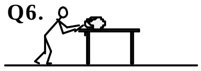
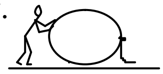
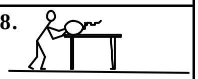
Table 1. Categories of responses for
Set I: Stationary objects - Simple questions (QSL Scoring)

	Questions			
Response categories	**Q1.**  **The stone is standing on the ground. -Is there a force exerted on the stone? Why?**	**Q2.**  **The stone is standing on the ground. -Is there a force exerted on the stone? Why?**	**Q3.**  **The balloon is standing on the ground. -Is there a force exerted on the balloon? Why?**	**Q4.**  **The balloon is standing on the ground. -Is there a force exerted on the balloon? Why?**
a. Force only on the big stone and big balloon. (K: 26.7%, 4th: 6.7%, 6th: 0%, 9th: 0%)*	Yes. Because it is big and/or heavy and/or you cannot move it.	No. Because it is small and/or light, and/or you can move it easily.	Yes. Because it is big and/or heavy and/or you cannot move it.	No. Because it is small and/or light and/or you can move it easily.
b. Force only on the big stone. (K: 73.3%, 4th: 43,3%, 6th: 10%, 9th: 0%)	Yes. Because it is big and/or heavy and/or you cannot move it.	No. Because it is, light and/or you can move it easily.	No. Because it is light and/or you can move it easily.	No. Because it is small and/or light and/or you can move it easily.
c. Force only on the big and small stone. (K: 0%, 4th: 13.3%, 6th: 13.3%, 9th: 0%)	Yes. Because it is big and/or heavy and/or you cannot move it easily.	Yes. Because it is heavy or it has weight.	No. Because it is light and/or you can move it easily.	No. Because it is small and/or light and/or you can move it easily.
d. Force on all the objects. (K: 0%, 4th: 6.7%, 6th: 16.7%, 9th: 3.3%)	Yes. Because it is big and/or heavy or it has weight.	Yes. Because it has weight.	Yes. Because it has weight.	Yes. Because it has weight.
e. Force of gravity on all the objects. (K: 0%, 4th: 10%, 6th: 6.7%, 9th: 43.3%)	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.
f. No force on any object because they are not moving. (K: 0%, 4th: 0%, 6th: 0%, 9th: 26.7%)	No. Because it is not moving.	No. Because it is not moving.	No. Because it is not moving.	No. Because it is not moving.
g. Force on the balloons and the small stone, no force on the big stone. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 3.3%)	No. Because it is heavy and/or no one can move it easily.	Yes. Because it is light and/or you can move it easily.	Yes. Because it is light and/or you can move it easily.	Yes. Because it is light and/or you can move it easily.
h. No force on any object because no one pushes them. (K: 0%, 4th: 20%, 6th: 46.7%, 9th: 20%)	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.
i. Force from the air on all the objects. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 6.7%)	Yes. It is the force from the air above it.	Yes. It is the force from the air.	Yes. It is the force from the air.	Yes. It is the force from the air.

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

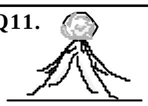
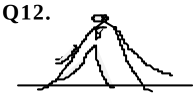
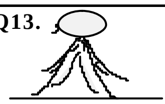
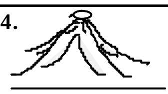
Table 2. Categories of responses for Set II: Stationary objects being pushed by a human agent - Simple questions (QSL Scoring)

	Questions			
Response categories	**Q5.**  **A man is pushing the stone. -Is there a force exerted on the stone? Why?**	**Q6.**  **A man is pushing the stone. -Is there a force exerted on the stone? Why?**	**Q7.**  **A man is pushing the balloon. -Is there a force exerted on the balloon? Why?**	**Q8.**  **A man is pushing the balloon. -Is there a force exerted on the balloon? Why?**
a. Force only on the big stone and big balloon. (K: 26.7%, 4th: 6.7%, 6th: 0%, 9th: 0%)*	Yes. Because it is big and/or heavy and/or the man cannot move it.	No. Because it is small and/or light and/or the man can move it easily.	Yes. Because it is big and/or heavy and/or the man cannot move it.	No. Because it is small and/or light and/or the man can move it easily.
b. Force only on the big stone. (K: 73.3%, 4th: 40%, 6th: 6.7%, 9th: 0%)	Yes. Because it is big and/or heavy and/or the man cannot move it.	No. Because it is, small and/or light and/or the man can move it easily.	No. Because it is light and/or the man can move it easily.	No. Because it is small and/or light and/or the man can move it easily.
c. Force only on the big and small stone. (K: 0%, 4th: 16.5%, 6th: 13.4%, 9th: 0%)	Yes. Because it is big and/or heavy and/or the man cannot move it.	Yes. Because it is heavy or it has weight.	No. Because it is light and/or the man can move it easily.	No. Because it is small and/or light and/or the man can move it easily.
d. Force on all the objects. (K: 0%, 4th: 10%, 6th: 13.4%, 9th: 3.3%)	Yes. Because it is heavy and/or it has weight and/or the man has less force than the stone.	Yes. Because it has weight.	Yes. Because it has weight.	Yes. Because it has weight.
e. Force on all the objects because the man pushes them. (K: 0%, 4th: 6.7%, 6th: 36.5%, 9th: 6.7%)	Yes. Because the man pushes it.	Yes. Because the man pushes it.	Yes. Because the man pushes it.	Yes. Because the man pushes it.
f. No force on the big stone, force on the remaining objects. (K: 0%, 4th: 13.4%, 6th: 6.7%, 9th: 3.3%)	No. Because it is heavy and/or the man cannot move it.	Yes. Because it is light and/or the man can move it.	Yes. Because it is light and/or the man can move it.	Yes. Because it is light and/or the man can move it.
g. Force from the man and force of	Yes. It is the force from	Yes. It is the force from	Yes It is the force from	Yes. It is the force from

gravity. (K: 0%, 4th: 6.7%, 6th: 0%, 9th: 33.4%)	the man and the force of gravity.	the man and the force of gravity.	the man and the force of gravity.	the man and the force of gravity.
h. Force of gravity on all the objects. (K: 0%, 4th: 0%, 6th: 0%, 9th: 3.3%)	Yes. It is the force of gravity.	Yes. It is the force of gravity	Yes. It is the force of gravity.	Yes. It is the force of gravity.
i. Force from the man on all the objects. (K: 0%, 4th: 0%, 6th: 23.3%, 9th: 50%)	Yes. It is the force from the man or it is the kinetic force from the man.	Yes. It is the force from the man or it is the kinetic force from the man.	Yes. It is the force from the man or it is the kinetic force from the man.	Yes. It is the force from the man or it is the kinetic force from the man.

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

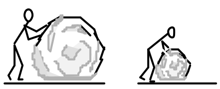
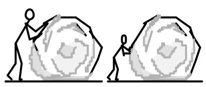
Table 3. Categories of responses for
Set III: Stationary objects being on the top of a hill - Simple questions (QSL Scoring)

	Questions			
Response categories	**Q11.**  **The stone is standing on the top of the hill, but it is not stable. If someone pushed it, it would fall down. -Is there a force exerted on the stone? Why?**	**Q12.**  **The stone is standing on the top of the hill, but it is not stable. If someone pushed it, it would fall down. -Is there a force exerted on the stone? Why?**	**Q13.**  **The balloon is standing on the top of the hill, but it is not stable. If someone pushed it, it would fall down. -Is there a force exerted on the balloon? Why?**	**Q14.**  **The balloon is standing on the top of the hill, but it is not stable. If someone pushed it, it would fall down. -Is there a force exerted on the balloon? Why?**
a. Force only on the big stone and big balloon. (K: 26.7%, 4th: 0%, 6th: 3.3% , 9th:3.3%)*	Yes. Because it is big and/or heavy and/or if it falls it can cause damages.	No. Because it is small and/or light and/or it is more stable so it cannot fall.	Yes. Because it is big and/or heavy and/or if it falls it can cause damages.	No. Because it is small and/or light and/or it is more stable.
b. Force only on the big stone. (K: 40%, 4th: 20%, 6th: 6.7%, 9th: 3.3%)	Yes. Because it is big and/or heavy and/or if it falls it can cause damages.	No. Because it is, small and/or light.	No. Because it is light and/or the wind can move it and/or if it falls it cannot cause damages.	No. Because it is small and/or light and/or the wind can make it move.
c. Force only on the big and small stone. (K: 0%, 4th: 3.3%, 6th: 13.3%, 9th: 0%)	Yes. Because it is big and/or has weight and/or it will fall with impetus/force.	Yes. Because it has weight.	No. Because it is light.	No. Because it is small, light.
d. Force on all the objects. (K: 0%, 4th: 16.7%, 6th 20%, 9th: 6.7%)	Yes. Because it is heavy or it has weight and/or it is not stable.	Yes. Because it has weight and/or it is not stable.	Yes. Because it has weight and/or it is not stable.	Yes. Because it has weight and/or it is not stable.
e. Force of gravity on all the objects. (K: 0%, 4th: 10%, 6th: 3.3%, 9th: 43.3%)	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.

f. No force on any object, because they are not moving. (K: 0%, 4th: 13.3%, 6th: 26.7%, 9th: 26.7%)	No. Because it is not moving.	No. Because it is not moving.	No. Because it is not moving.	No. Because it is not moving.
g. No force on any object, because they are not stable. (K: 33.3%, 4th: 36.7%, 6th: 6.7%, 9th: 0%)	No. Because it is not stable or it can be moved easily.	No. Because it is not stable or it can be moved easily.	No. Because it is not stable or it can be moved easily.	No. Because it is not stable or it can be moved easily.
h. Force from the air on all the objects. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 3.3%)	Yes. It is the force from the air above it.	Yes. It is the force from the air.	Yes. It is the force from the air.	Yes. It is the force from the air.
i. No force on any object because no one pushes them. (K: 0%, 4th: 0%, 6th: 16.7%, 9th: 13.4%)	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.

- Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

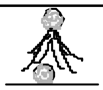
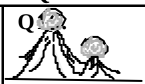
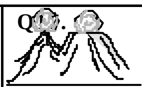
Table 4: Categories of responses for Set II: Stationary objects being pushed by a human agent- Comparison questions (QSL Scoring)

	Questions	
Response categories	**Q9.**  **The same man is trying to move two different stones. He cannot move either. - Is there a force exerted on these stones? Why? (If "yes":) - Is the force exerted on the stones the same? (If "no":) - Which of the two forces is greater? Why?**	**Q10.**  **A man and a child are trying to move two similar stones. They both fail. -Is there a force exerted on these stones? Why? (If "yes":) - Is the force exerted on the stones the same? (If "no":) - Which of the two forces is greater? Why?**
a. Force related to the size of the stones. (K: 100%, 4th: 66.7%, 6th: 33.4%, 9th: 6.7%)*	Greater force on the bigger stone. Because the first stone is bigger, heavier.	Same force on both stones. Because the two stones are similar.
b. Force from the human agent. (K: 0%, 4th: 6.7%, 6th: 3.3%, 9th: 36.7%)	Same force on both stones. Because it is the same man and he cannot move either.	Greater force on the stone being pushed by the man. Because the man is bigger, has greater force, is pushing with greater force.
c. Force from the human agent related to his effort and "supply " of force. (K: 0%, 4th: 0%, 6th: 23.4%, 9th: 36.7%)	Greater force on the bigger stone. Because the stone is bigger and the man is trying harder to move it.	Greater force on the stone being pushed by the man. Because the man is bigger, has greater force, is pushing with greater force.
d. Force of resistance misunderstood. (K: 0%, 4th: 0%, 6th: 0%, 9th: 6.7%)	Greater force on the bigger stone. It is the resistance of the stone to the man's force. Because the stone is greater its resistance is greater as well.	Greater force on the stone being pushed by the man. It is the resistance of the stone. Because the man is pushing with greater force the resistance will be greater as well.

e. Force from the human agent related to his effort. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 3.3%)	Greater force on the bigger stone. Because the stone is bigger and the man is trying harder to move it.	Greater force on the stone been pushed by the child. Because the child must try harder to move the stone.
f. No force on any stone. (K: 0%, 4th: 26.6%, 6th: 36.7%, 9th: 9.9%)	No force on any stone. Because the man cannot move the stones, the stones are not moving.	No force on any stone. Because they cannot move the stones, the stones are not moving.

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

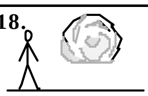
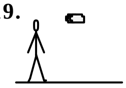
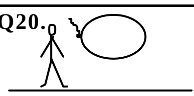
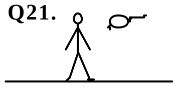
Table 5. Categories of responses for Set III: Stationary objects being on the top of a hill - Comparison questions (QSL Scoring)

	Questions		
Response categories	**Q15.**  **These two stones are similar. The first stone is standing on the top of a hill, but it is not stable. If someone pushed it , it would fall down. The other stone is standing on the ground. -Is there a force exerted on these stones? Why? (If "yes":) - Is the force exerted on the stones the same? (If "no":) - Which of the two forces is greater? Why?**	**Q**  **These two stones are similar. Each one of them is standing on the top of a hill. The first hill is higher than the second. Neither stone is stable. If someone pushed them they would fall down. -Is there a force exerted on these stones? Why? (If "yes":) - Is the force exerted on the stones the same? (If "no":) - Which of the two forces is greater? Why?**	**Q.**  **These two stones are similar. Each one of them is standing on the top of a hill. The first stone is not stable. If someone pushed it, it would fall down. The second stone is very stable. -Is there a force exerted on these stones? Why? (If "yes":) - Is the force exerted on the stones the same? (If "no":) - Which of the two forces is greater? Why?**
a. Force on the stable stones, less force or no force on the unstable stones. (K: 53.3%, 4th: 53.3%, 6th: 20%, 9th: 3.3%)*	Force only or greater force on the stone on the ground Because the stone on the hill will fall easily if someone pushed it.	No force or the same force on both stones. Because they will fall easily if someone push them.	Force only or greater force on the stone on the second hill. Because the stone on the first hill will fall easily if someone pushed it.
b. Force on the unstable stones only. (K: 0%, 4th: 16.7%, 6th: 13.4%, 9th: 6.7%)	Force only on the stone on the hill. Because it will easily fall down.	Force only or greater force the stone on the higher hill. Because they will both fall or the stone on the higher hill will fall more forcefully.	Force only the stone on the first hill. Because it will easily fall down.

c. Force on all the stones but greater force on the unstable stones. (K: 6.7%, 4th: 3.3%, 6th: 10%, 9th: 3.3%)	Greater force on the stone on the hill. Because it is easier to be moved by someone.	Greater force on the stone on the higher hill. Because it will fall more forcefully.	Greater force on the stone on the first hill. Because it is easier to be moved by someone.
d. Same force on all the stones. (K: 40%, 4th: 13.4%, 6th: 3.3%, 9th: 0%)	Same force on both stones. Because they are similar, equal big, equally heavy.	Same force on both stones. Because they are similar, equally big, equally heavy.	Same force on both stones. Because they are similar, equally big, equally heavy.
e. Force of gravity on all the stones: Same force on all stones or greater force on the stones at a lower position. (K: 0%, 4th: 3.3%, 6th: 0%, 9th: 33.3%)	Same force or less force on the stone on the hill It is the force of gravity. Similar stones therefore equal forces or less force of gravity on the stone at a greater distance from the centre of earth.	Same force or less force on the stone on the higher hill. It is the force of gravity. Similar stones therefore equal forces or less force of gravity on the stone being at a greater distance from the centre of the earth.	Same force on the stone on the hill. It is the force of gravity. Similar stones therefore equal forces. Similar stones and equal distance from the centre of the earth therefore, equal forces.
f. Alternative interpretations of the force of gravity. (K: 0%, 4th: 0%, 6th: 6.7%, 9th: 10%)	Greater force of gravity on the stone on the hill. Because is at a higher position and earth attracts it more. Greater force of gravity on the stone on the ground, because it is more stable.	Greater force of gravity on the stone on the higher hill. Because earth attracts it more or because the air pressure is greater.	Greater force of gravity on the first stone, because it will fall easily. Greater force of gravity on the second stone because it is more stable.
g. No force on any stone because they are not moving. (K: 0%, 4th: 13.3%, 6th: 26.4%, 9th: 26.4%)	No force on any stone. Because they are not moving.	No force on or into any stone. Because they are not moving.	No force on any stone. Because they are not moving.
h. Force from the air on both stones. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 6.7%)	Greater force from the air on the stone on the ground, because there is more air above it.	Greater force from the air on the stone on the lower hill, because there is more air above it.	Same force on both stones because they are at the same height.
i. Mixed category: Contradictory answers and explanations. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 0%)	Same force on both stones. Because they are similar.	Greater force on the stone on the higher hill. Because it is at a higher position.	Greater force on the second stone. Because it is more stable.
k. No force on any stone because no one pushes them. (K: 0%, 4th: 6.7%, 6th: 13.4%, 9th: 6.7%)	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

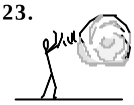
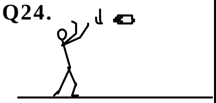
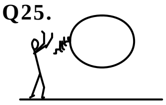
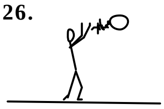
Table 6. Categories of responses for Set IV: Free falling objects - Simple questions (QSL Scoring)

	Questions			
Response categories	**Q18.**  **The stone is falling to the ground. -Is there a force exerted on the stone? Why?**	**Q19.**  **The stone is falling to the ground. -Is there a force exerted on the stone? Why?**	**Q20.**  **The balloon is falling to the ground. -Is there a force exerted on the balloon? Why?**	**Q21.**  **The balloon is falling to the ground. -Is there a force exerted on the balloon? Why?**
a. Force only on the big stone and the big balloon. (K: 33.3%, 4th: 3.3%, 6th: 0%, 9th:0%)*	Yes.. Because it is big and/or heavy and it will cause damages/noise.	No. Because it is small and/or light and it will make no damages/noise.	Yes. Because it is big and/or heavy and it will make damages/noise.	No. Because it is small and/or light and it will make no damages/noise.
b. Force only on the	Yes.	No.	No.	No

big stone. (K: 53.3%, 4th: 33.3%, 6th: 3.3%, 9th:0%)	Because it is big and/or heavy and it will cause damages.	Because it is small and/or light.	Because it is light or it is full of air.	Because it is small and/or light or it is full of air.
c. Force only on the big and the small stone. (K: 0%, 4th: 16.7%, 6th: 16.7%, 9th:3.3%)	Yes. Because it is big and/or heavy and it will cause damages.	Yes. Because it is heavy or it has weight.	No. Because it is light and/or you can move it easily.	No. Because it is small and/or light and/or you can move it easily.
d. Force on all the objects, due to object's weight. (K: 0%, 4th: 20%, 6th: 6.7%, 9th: 0%)	Yes. Because it has weight.	Yes. Because it has weight.	Yes. Because it has weight.	Yes. Because it has weight.
e. Force of gravity on all the objects. (K: 0%, 4th: 10%, 6th: 3.3%, 9th: 56.8%)	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.	Yes. It is the force of gravity or the earth's attraction.
f. No force on any object, because no one pushes it. (K: 0%, 4th: 3.3%, 6th: 0%, 9th: 3.3%)	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.	No. Because no one pushes it.
g. No force on any object, because someone pushed it. (K: 6.7%, 4th: 3.3%, 6th: 6.7%, 9th: 0%)	No. Because someone pushed it and it fell.	No. Because someone pushed it and it fell.	No. Because someone pushed it and it fell.	No. Because someone pushed it and it fell.
h. Force from the air on all the objects. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 6.7%)	Yes. It is the force from the air.	Yes. It is the force from the air.	Yes. It is the force from the air.	Yes. It is the force from the air.
i. Force on all the objects due to motion. (K: 6.7%, 4th: 10%, 6th: 60%, 9th: 30%)	Yes. Because it falls or it falls with force or it gains force as it falls or it is the kinetic force.	Yes. Because it falls or it falls with force or it gains force as it falls or it is the kinetic force.	Yes. Because it falls or it falls with force or it gains force as it falls or it is the kinetic force.	Yes. Because it falls or it falls with force or it gains force as it falls or it is the kinetic force.

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

Table 7. Categories of responses for Set V: Objects that have been thrown - Simple questions (QSL Scoring)

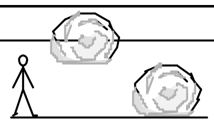
	Questions			
Response categories	**Q23.**  **The man threw the stone.** **-Is there a force exerted on the stone? Why?**	**Q24.**  **The man threw the stone.** **-Is there a force exerted on the stone? Why?**	**Q25.**  **The man threw the balloon** **-Is there a force exerted on the balloon? Why?**	**Q26.**  **The man threw the balloon.** **-Is there a force exerted on the balloon? Why?**

a. Force only on the big stone and the big balloon. (K: 26.7%, 4th: 3.3%, 6th: 0%, 9th: 0%)*	Yes. Because it is big and/or heavy and it will cause damages/noise.	No. Because it is small and/or light and it will make no damages/noise.	Yes. Because it is big and/or heavy and it will make damages/noise.	No. Because it is small and/or light and it will make no damages/noise.
b. Force only on the big stone. (K: 46.6%, 4th: 26.7%, 6th: 0%, 9th: 0%)	Yes. Because it is big and/or heavy and it will cause damages.	No. Because it is small and/or light.	No. Because it is light or it is full of air.	No. Because it is small and/or light or it is full of air.
c. Force only on the big and small stone. (K: 6.7%, 4th: 16.7%, 6th: 10%, 9th: 3.3%)	Yes. Because it is big and/or heavy and it will cause damages.	Yes. Because it is heavy or it has weight.	No. Because it is light and/or you can move it easily or the wind will take it away.	No. Because it is small and/or light and/or you can move it easily or the wind will take it away.
d. Force from the man on all the objects. (K: 6.7%, 4th: 36.6%, 6th: 83.4%, 9th: 56.6%)	Yes. It is the force the man gave to it or the force from the man's hand or because it will fall with great force.	Yes. It is the force the man gave to it or the force from the man's hand.	Yes. It is the force the man gave to it or the force from the man's hand.	Yes. It is the force the man gave to it or the force from the man's hand.
e. Force from the man and force of gravity on all the objects. (K: 0%, 4th: 6.7%, 6th: 0%, 9th: 26.7%)	Yes. It is the force of gravity and the force from the man's hand /the force the man gave to it.	Yes. It is the force of gravity and the force from the man's hand/the force the man gave to it.	Yes. It is the force of gravity and the force from the man's hand/the force the man gave to it.	Yes. It is the force of gravity and the force from the man's hand/the force the man gave to it.
f. No force on any object, because no one pushes them. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 6.7%)	No. Because no one is pushing it.	No. Because no one is pushing it.	No. Because no one is pushing it.	No. Because no one is pushing it.
g. No force on any object, because they have been pushed. (K: 13.3%, 4th: 10%, 6th: 0%, 9th: 0%)	No. Because the man threw it away so it must not be so heavy.	No. Because it is light and/or the man threw it away.	No. Because it is light and/or the man threw it away.	No. Because it is light and/or the man threw it away.
h. Force from the man and force from the air on all the objects. (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 6.7%)	Yes. It is the force from the man and the force from the air.	Yes. It is the force from the man and the force from the air.	Yes. It is the force from the man and the force from the air.	Yes. It is the force from the man and force from the air.

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

Table 8. Categories of responses for
Set IV: Free falling objects - Comparison questions (QSL Scoring)

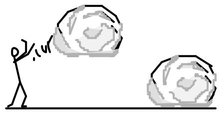
	Question 22



Response categories	**The two stones are similar. The one is falling, the other is stationary on the ground.** **-Is there a force exerted on these stones? Why?** **(If "yes":) - Is the force exerted on the stones the same?** **(If "no":) - Which of the two forces is greater? Why?**
a. Same force on both stones. (K: 46.6%, 4^{th}: 13.3%, 6^{th}: 0%, 9^{th}: 0%)*	Same force on both stones. Because they are similar, they are both heavy.
b. Greater force on the stationary stone or force only on the stationary stone. (K: 13.4%, 4^{th}: 13.4%, 6^{th}: 6.7%, 9^{th}: 0%)	Greater force on the stationary stone, because people cannot move it. No force on the falling stone, because someone pushed it and it fell down.
c. Force only on the falling stone. (K: 0%, 4^{th}: 16.7%, 6^{th}: 50%, 9^{th}: 23.3%)	Force only on the falling stone. Because it is falling, it can cause damages.
d. Greater force on the falling stone. (K: 40%, 4^{th}: 43.3%, 6^{th}: 36.7%, 9^{th}: 10%)	Greater force on the falling stone. Because it can cause damages, it is heavier, has more weight than the stationary, it falls with greater force.
e. Force of gravity on both stones. (K: 0%, 4^{th}: 3.3%, 6^{th}: 0%, 9^{th}: 6.7%)	Same force on both stones. It is the force of gravity, the earth's attraction.
f. Alternative interpretations of the force of gravity. (K: 0%, 4^{th}: 6.7%, 6^{th}: 3.3%, 9^{th}: 36.7%)	Force of gravity/earth's attraction only on the falling stone, because it falls. -Greater force of gravity/earth's attraction on the falling stone, because it is farther from the centre of the earth. - Greater force on the falling stone because it is the force of gravity and its weight.
g. Greater force on the falling stone: Force of gravity and a propellant force. (K: 0%, 4^{th}: 0%, 6^{th}: 0%, 9^{th}: 13.3%)	Greater force on the falling stone. Because it is the force of gravity and an impulse, a propellant force because it falls.
h. No force on any stone. (K: 0%, 4^{th}: 3.3%, 6^{th}: 0%, 9^{th}: 3.3%)	No force on any stone. Because no one is pushing them.
i. Force from the air on the falling stone. (K: 0%, 4^{th}: 0%, 6^{th}: 3.3%, 9^{th}: 6.7%)	There is the air resistance only on the falling stone. - Greater force on the stationary stone. It is the force from the air above the stones.

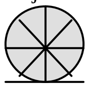
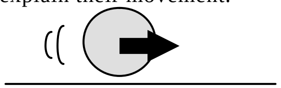
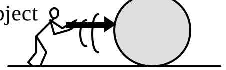
* Percent responses for Kindergarten, 4^{th} grade, 6^{th} grade, and 9^{th} grade respectively.

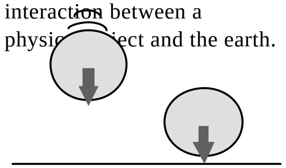
Table 9. Categories of responses for Set V: Objects that have been thrown - Comparison questions (QSL Scoring)

	Question 27
Response categories	 **These two stones are similar. The man has thrown the first stone. The other is standing on the ground.** **-Is there a force exerted on these stones? Why?** **(If "yes":) - Is the force exerted on the stones the same?** **(If "no":) - Which of the two forces is greater? Why?**
a. Same force on both stones. (K: 53.4, 4^{th}: 13.3%, 6^{th}: 0%, 9^{th}: 0%)*	Same force on both stones. Because they are similar, they are both heavy.
b. Greater force on the stationary stone. (K: 13.3%, 4^{th}: 10%, 6^{th}: 3.3%, 9^{th}: 0%)	Force only on the stationary stone or greater force on the stationary stone. Because the man could not move it.
c. Force only on the moving stone. (K: 6.7%, 4^{th}: 43.4%, 6^{th}: 63.4%, 9^{th}: 33.4%)	Force only on the moving stone. Because it is moving, it is the force from the man.
d. Greater force on the moving stone: The force of the stone and the force from the man are exerted on the moving stone, the force of the stone on the stationary stone. (K: 13.3%, 4^{th}: 20%, 6^{th}: 23.4%, 9^{th}: 3.3%)	Greater force on the moving stone. Because the moving stone has its own force and the force the man gave to it, because it can cause damages.
e. Greater force on the moving stone: Force from the man and force of gravity on the moving stone, only the force of gravity on the stationary stone. (K: 0%, 4^{th}: 3.3%, 6^{th}: 3.3%, 9^{th}: 50%)	Greater force on the moving stone. Because it is the force of gravity and the force from the man. There is only the force of gravity on the stationary stone.
f. No force on any stone. (K: 0%, 4^{th}: 0%, 6^{th}: 3.3%, 9^{th}: 6.7%)	No force on any stone. Because no one is pushing the stones.
g. Force only on the stationary stone. (K: 13.3%, 4^{th}: 10%, 6^{th}: 0%, 9^{th}: 0%)	No force on the moving stone. Because the man is able to move it.
h. Force from the man and force from the air on the moving stone, only the force from the air on the stationary stone. (K: 0%, 4^{th}: 0%, 6^{th}: 3.3%, 9^{th}: 6.7%)	Greater force on the moving stone. Because it is the force from the air on both stones and the force from the man only on the moving stone.

* Percent responses for Kindergarten, 4^{th} grade, 6^{th} grade, and 9^{th} grade respectively.

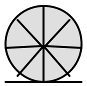
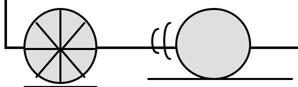
Table 10. Meanings of force: Expected pattern of responses

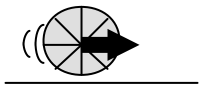
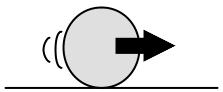
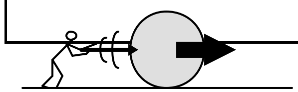
Meanings of force	**Set I: Stationary objects - Simple questions (Table 1)**	**Set II: Stationary objects which are pushed by a human agent - Simple questions (Table 2)**	**Set III: Stationary objects on the top of a hill - Simple questions (Table 3)**	**Set II: Stationary objects which are pushed by a human agent – Comparison questions (Table 4)**	**Set III: Stationary objects on the top of a hill - Comparison questions (Table 5)**	**Set IV: Falling objects - Simple questions (Table 6)**	**Set V: Objects thrown by a man - Simple questions (Table 7)**	**Set IV: Falling objects - Compariso n questions (Table 8)**	**Set V: Objects thrown by a man - Comparison questions (Table 9)**
1. INTERNAL FORCE: Force is an internal property of physical objects. 	F on big stone and big balloon (**a**)***,** F on both stones (**b**)**,** F on big stone (**c**)**,** F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**)**,** F on both stones (**b**)**,** F on big stone (**c**)**,** F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**)**,** F on both stones (**b**)**,** F on big stone (**c**)**,** F on all objects (**d**), because they have weight or are big/heavy.	F related to the size of the objects and not to the size of the agents (**a**).	Same F on all the stones because they are equally big/heavy (**d**).	F on big stone and big balloon (**a**)**,** F on both stones (**b**)**,** F on big stone (**c**)**,** F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**)**,** F on both stones (**b**)**,** F on big stone (**c**)**,** because they have weight or are big/heavy.	Same F on both stones (**a**).	Same F on both stones (**a**).
2. ACQUIRED FORCE: Force is an acquired property of physical objects that explain their movement. 	No F on any object because they are not moving (**f**). - No F on any object because no one pushes them (**h**).	F on small/light objects only (**f**). - F on all objects because the man pushes them (**e**).	No F on any object because they are not moving (**f**). - No F on any object because no one pushes them (**i**).	No F on any stone, because the man/child cannot move the stones (**f**).	No F on any stone because they are not moving (**g**). - No F on any stone because no one pushes them (**k**).	F on all objects because they fall (**i**).	The force from the man's hand on all the objects (**d**).	F on the falling stone only because it falls (**c**).	F on the moving stone only because the man gave it (**c**).
3. FORCE OF PUSH/PULL: Force is the interaction between an agent and an object 	No F on any object because no one pushes them (**h**).	F from the man on all the objects (**i**).	No F on any object (**i**).	F from the human agent **(b, c, e**).	No F on any stone because no one pushes them (**k**).	No F on any object because no one pushes them (**f**).	No F on any object because no one pushes it (**f**).	No F on any stone because no one pushes them (**h**).	No F on any stone because no one pushes them (**f**).

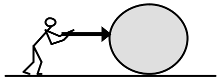
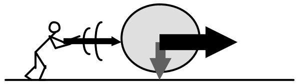
4. GRAVITATIONAL FORCE: Force is the interaction between a physical object and the earth. 	F of gravity on all the objects (**e**).	F of gravity on all the objects (**h**).	F of gravity on all the objects (**e**).	F of gravity on both stones.	F of gravity on all the objects (**e**). - F of gravity on all the objects- alternative interpretations of gravity (**f**).	F of gravity on all the objects (**e**).	F of gravity on all the objects.	F of gravity on both stones (**e**). - F of gravity on both stones - alternative interpretations of gravity (**f**).	F of gravity on both stones.

* Categories of students' responses for Sets I to V, described in Tables 1 to 9. The letters refer to the response categories.

Table 11. Meanings of force: Obtained pattern of responses

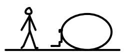
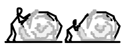
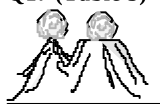
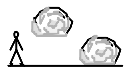
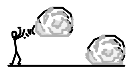
Meanings of force	**Set I: Stationary objects - Simple questions (Table 1)**	**Set II: Stationary objects which are pushed by a human agent - Simple questions (Table 2)**	**Set III: Stationary objects on the top of a hill - Simple questions (Table 3)**	**Set II: Stationary objects which are pushed by a human agent - Comparison questions (Table 4)**	**Set III: Stationary objects on the top of a hill - Comparison questions (Table 5)**	**Set IV: Falling objects - Simple questions (Table 6)**	**Set V: Objects thrown by a man - Simple questions (Table 7)**	**Set IV: Falling objects - Comparison questions (Table 8)**	**Set V: Objects thrown by a man - Comparison questions (Table 9)**
1. INTERNAL FORCE 	F on big stone and big balloon (**a**)*****, F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.	F related to the size of the objects and not to the size of the agents (**a**).	Same F on all the stones because they are equally big/heavy (**d**).	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), because they have weight or are big/heavy.	Same F on both stones, because they are similar in size/weight (**a**).	Same F on both stones, because they are similar in size/weight (**a**).
2. INTERNAL FORCE AFFECTED BY MOVEMENT 	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone	No F on any object because they are not stable (**g**).	F related to the size of the objects and not to the size of	F on the stable stones only or less F on the unstable stones	No force on any object because someone	No force on any object because they have been	F on the stationary stone only or greater F on	F only on the stationary stone (**g**).

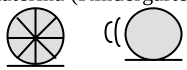
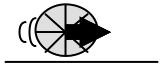
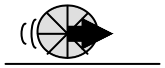
	(**c**), F on all objects (**d**), because they have weight or are big/heavy.	(**c**), F on all objects (**d**), because they have weight or are big/heavy.		the agents (**a**).	(**a**).	pushed them (**g**).	pushed (**g**).	the stationary stone (**b**).	
3. INTERNAL and ACQUIRED FORCE 	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy.- No F because they are unstable (**g**).	F related to the size of the objects and not to the size of the agents (**a**).	F on the stable stones only or less F on the unstable stones (**a**). - F on all the stones, greater on the unstable (**c**).	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), F on all objects (**d**), because they have weight or are big/heavy. - F on all objects due to motion (**i**).	F on big stone and big balloon (**a**), F on both stones (**b**), F on big stone (**c**), because they have weight or are big/heavy). - F from the man (**d**).	Greater F on the falling stone (**d**).	Greater F on the moving stone (**d**).
4. ACQUIRED FORCE 	No F on any object because they are not moving (**f**). - No F on any object because no one pushes them (**h**).	F on small/light objects only (**f**). - F on all objects because the man pushes them (**e**).	No F on any object because they are not moving (**f**). - No F on any object because no one pushes them (**i**). - F on all the objects because they are not stable (**d**).	No F on any stone, because the man/child cannot move the stones (**f**).	No F on any stone because they are not moving (**g**). - No F on any stone because no one pushes them (**k**). - F on the unstable stones only (**b**).	F on all objects because they fall (**i**). - F only on the big stone (**b**). - F only on the big and small stone (**c**).	The force from the man's hand on all the objects (**d**). -F only on the big stone (**b**). - F only on the big and small stone (**c**).	F on the falling stone only because it falls (**c**).	F on the moving stone only because the man gave it (**c**).
5. ACQUIRED FORCE and FORCE OF PUSH/PULL 	No F on any object because they are not moving (**f**). - No F on any object because no one pushes them (**h**).-	F from the man on all the objects (**i**).	No F on any object because they are not moving (**f**). - F from the air (**h**).	F from the human agent (**b, c, e**). - F of resistance misunderstood (**d**).	No F on any stone because no one pushes them (**k**). - F from the air (**h**).	F on all objects because they fall (**i**).- F from the air (**h**).	The force from the man's hand on all the objects (**d**). - F from the	F on the falling stone only, because it falls (**c**). - F from the air (**i**).	F on the moving stone only because the man gave it (**c**). - F from

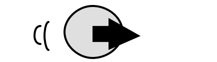
	F only on balloons/small stone (**g**).- F from the air (**i**).						man and F from the air (**h**).		the man and F from the air on the thrown stone - F from the air on the stationary stone (**h**).
6. FORCE OF PUSH/PULL 	No F on any object because no one pushes them (**h**).	F from the man on all the objects (**h**).	No F on any object (**i**).	F from the human agent (**b, c, e**).	No F on any stone because no one pushes them (**k**).	No F on any object because no one pushes them (**f**).	No F on any object because no one pushes it (**f**).	No F on any stone because no one pushes them (**h**).	No F on any stone because no one pushes them (**f**).
7. GRAVITATIONAL and OTHER FORCES 	F of gravity on all the objects (**e**).	F from the man and F of gravity on all objects (**g**).	F of gravity on all objects (**e**).	F from the man related to size of stone and "F supply"(**b**). - F from the man related to "F supply" (**c**). - F from the man related to effort (**e**).	F of gravity on all stones (**e**). - Alternative interpretation of the F of gravity (**f**).	F of gravity on all the objects (**e**).	F from the man and F of gravity on all objects (**e**).	F of gravity on both stones (**e**). - F of gravity misunderstoo d (**f**). - F of gravity and a propellant F on the falling stone (**g**).	F from the man and F of gravity on the moving stone (**e**).

* Categories of students' responses for Sets I to V, described in Tables 1 to 9. The letters refer to the response categories.

Table 12. Examples of the responses of children who used different meanings of force to a set of critical questions

Subjects	**Q1 (Table 1)** 	**Q3 (Table 1)** 	**Q9 (Table 4)** 	**Q10 (Table 4)** 	**Q11 (Table 3)** 	**Q17 (Table 5)** 	**Q22 (Table 8)** 	**Q27 (Table 9)** 
1. INTERNAL FORCE Kiriaki (Kindergarten) 	Yes, because it is heavy and the children cannot hold it.	No, it is light. It is a balloon not a stone.	There is more force on the first stone. Because it is bigger.	It is the same force. Because they are similar.	Yes, but it is not stable because there is not much ground.	It is the same force. Because they are similar.	It is the same force. Because the stones are similar.	The force is the same. Because they are two but it does not matter that it falls dawn.

2. INTERNAL FORCE AFFECTED BY MOVEMENT Katerina (Kindergarten) 	Yes, because it is big.	No, because if we kick it, it will be broken.	More force on the first stone, because it is bigger.	It is the same. Because they are similar.	No, because if someone goes up there, it will fall dawn.	No force on the first stone. There is a force on the second because it is stable.	No force on the first stone, because someone may pushed it and the stone fell down. There is a force on the second because he cannot push it and make it fall.	No force on the first stone because he put all his strength and threw it up. There is a force on the second stone because he cannot throw it.
3a. INTERNAL and ACQUIRED FORCE (a) Anna (4th grade, group I) 	Yes, because the stone is very strong and it may sink in the ground.	No, because it is only air and it is very light like a feather.	More force on the first, because it is bigger.	Same force, because they are similar.	No. It is on the hill and it may easily fall dawn, because it is not stable.	No force on the first stone because it is not stable. There is a force on the second because it is more stable.	There is more force on the first stone because it falls with great force and it may sink in the ground.	More force on the first stone. Because the man threw it and it leaves with great force.
3b. INTERNAL and ACQUIRED FORCE (b) Michael (4th grade, group II) 	It has force because the man cannot push it.	No, because it is light.	More force on the first stone, because it is bigger.	Same force on both stones because they are similar.	Yes, because it is big and it will fall down.	More force on the first stone because it may fall.	More force on the first stone because it will fall and make a lot of noise.	More force on the first stone because the man threw it with force.

4a. ACQUIRED FORCE (a**)** Domna (6th grade, group I) 	No, because it is not moving.	No, it is not moving.	No. Because he does not give a force to push them.	No. They do not give a force to push them.	No. Because there is no one to give a force and make it fall.	No. Because no one pushes them.	Yes, there is a force on the first stone because it gives a force, it falls, it has some force. There is no force on the second stone	Yes, there is a force on the first stone because he gives some force to throw it and the stone goes with some force. There is no force on

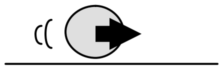
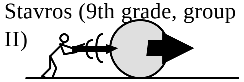
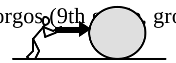
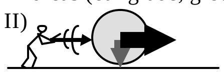
							because it is not moving.	the second stone because it is not moving.
4b. ACQUIRED FORCE (b**)** Pavlos (6th grade, group II) 	No, because things on the ground cannot move.	No. It doesn't move.	No, because the man does not move them.	No because they cannot move them.	There is a force because it is in a high position. It has kinetic energy. Its potential energy is transferred to kinetic and the stone falls down.	Force on the first stone only, because it may fall.	There is a kinetic force on the fist stone.	There is a kinetic force on the first stone only.
5. ACQUIRED FORCE and FORCE OF PUSH/PULL Stavros (9th grade, group II) 	No, since it is not moving.	No, it is not moving.	Yes, since the man is trying, there has to be some force (on the stones). The force is the same, because it is the same man (who pushes).	More force on the fist stone, because the man is bigger and he has more force.	No, because it is not moving.	No because they are not moving.	Yes, (on the first stone) since it falls it has some force. There is no force on the second stone because it is not moving.	Yes, the man exerts a force on the stone. There is no force on the second stone because it is not moving.
6. FORCE OF PUSH/PULL Giorgos (9th [illegible], group I) 	No. The man is not pushing it.	No. The man is not pushing it.	Yes, there is a force from the man. The same force because it is the same man.	The first (exerts) more force because he is bigger.	Not this moment. There is no one to push it.	No. No one pushed them.	No force is exerted from anybody.	No. No one pushes them now. The man pushed the first stone and it is leaving now.
7. GRAVITATIONAL and OTHER FORCES Andreas (6th grade, group II) 	I think it has gravity. The earth attracts it.	Not much. The balloon is light.	It is the same force. Because the man is the same.	More force on the first stone. The man gives more force.	There is a force. --*What kind of force?* Dynamic. It is due to gravity.	The same force. They are at the same height.	The earth attracts them. More force on the falling stone. Because the earth's attraction is bigger.	There is more force on the first stone because he threw it. There is only the force of gravity on the second stone.

Table 13. Sub-categories of "Gravitational and other forces meaning"

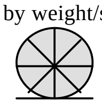
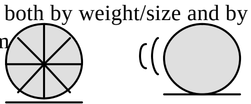
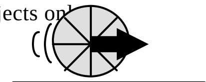
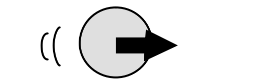
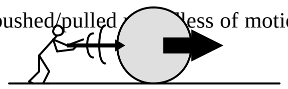
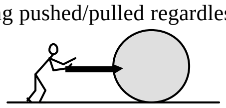
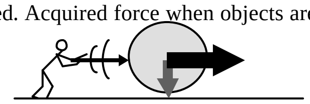
Sub-Categories of Gravitational and Other Forces Meaning	**Set I**: Stationary objects - Simple questions (Table 1)	**Set II:** Stationary objects being pushed by a human agent - Simple questions (Table 2)	**Set III:** Stationary objects being on the top of a hill (Tables 3, 5)	**Set II:** Stationary objects being pushed by a human agent -Comparison questions (Table 4)	**Set IV:** Free falling objects (Tables 6, 8)	**Set V:** Objects that have been thrown (Tables 7, 9)
Gravity and Acquired (K: 0%, 4th: 3.3%, 6th: 0%, 9th: 3.3%)	No force	No force	No force +/- Acquired	No force	Gravity	Gravity + Acquired
Gravity, Push/pull and Acquired (a) (K: 0%, 4th: 0%, 6th: 0%, 9th: 6.7%)	No force	Push/pull	No force	Push/pull	Gravity	Gravity + Acquired
Gravity, Push/pull and Acquired (b) (K: 0%, 4th: 0%, 6th: 3.3%, 9th: 6.7%)	Gravity	Push/pull	Gravity More gravity at higher position	Push/pull	Gravity More gravity on falling	Gravity + Acquired
Gravity, Push/pull and Acquired (c) (K: 0%, 4th: 0%, 6th: 0%, 9th: 6.7%)	Gravity	Gravity + Push/pull	Gravity More gravity at lower position	Push/pull	Gravity + Weight	Gravity + Acquired
Gravity, Push/pull and Acquired (d) (K: 0%, 4th: 3.3%, 6th: 0%, 9th: 26.4%)	Gravity	Push/pull + /- Gravity	Gravity + More gravity at lower position or same gravity	Push/pull	Gravity + Acquired	Gravity + Acquired

* Percent responses for Kindergarten, 4th grade, 6th grade, and 9th grade respectively.

Table 14. Mixed category

Subject	Set I: Stationary objects - Simple questions (Table 1)	Set II: Stationary objects being pushed by a human agent - Simple questions (Table 2)	Set III: Stationary objects being on the top of a hill (Tables 3, 5)	Set II: Stationary objects being pushed by a human agent -Comparison questions (Table 4)	Set IV: Free falling objects (Tables 6, 8)	Set V: Objects that have been thrown (Tables 7, 9)
Voula Kinder garten	Internal	Internal	Internal More force on stable	Internal	Acquired More force on moving	Internal More force on stable
Giannis Kinder garten	Internal	Internal	No force	Internal force on stable stones	Acquired More force on moving	No force
Petros 4th grade, group II	Internal	Internal	Internal Force on stable stone only	Internal	Internal + Acquired	Internal More force on stable
Vasilis 4th grade, group II	Internal	Internal	Internal Force on stable stone only	Internal	Internal More force on stationary	Acquired
Kostas 6th grade, group II	Internal	Internal	Internal More force at higher-stable position	Internal	Internal + Acquired	Internal + Acquired
Zoi 4th grade, group I	Internal	Internal	Internal More force on stable stone	Internal	Internal + Acquired	Internal More force on stable
Pegy 4th grade, group I	Internal	Internal	No force on unstable	Internal	Internal More force on stationary	Internal Same force
Manolis 6th grade, group I	Internal	Push/pull	Internal More force on stable stone	Push/pull	No force	Internal + Acquired
Asteris 6th grade, group I	Internal	Push/pull	Internal More force on unstable stone	Push/pull	No force	No force
Dimitra 6th grade, group I	Internal	Internal	Internal Force on unstable stone only	Push/pull	Internal + Acquired	No force
Makis 4th grade, group II	Acquired Force on light objects only	Gravity + Push/pull	No force	No force	No force No one pushes	Acquired
Nikos 4th grade, group I	Gravity	No force	Gravity	No force	Gravity	Acquired

Table 15. Frequencies and percent of *meanings of force* as a function of grade

Meanings of force	**Kind/ garten**	**4th grade**	**6th grade**	**9th grade**	**Total**
1. INTERNAL FORCE: There is an internal force within objects affected by weight/size only. 	7 (46.7%)	4 (13.3%)	-	-	11 (10.5%)
2. INTERNAL FORCE AFFECTED BY MOVEMENT: There is an internal force within objects affected both by weight/size and by position/movem 	2 (13.3%)	2 (6.7%)	-	-	4 (3.8%)
3. INTERNAL and ACQUIRED FORCE: There is an internal force affected by weight/size and/or position. In addition there is an acquired force within moving objects on 	4 (26.7%)	10 (33.3%)	9 (30%)	1 (3.3%)	24 (22.9%)
4. ACQUIRED FORCE: There is an acquired force within moving objects only. 	-	5 (16.7%)	11 (36.7%)	2 (6.7%)	18 (17.1%)
5. ACQUIRED FORCE and FORCE OF PUSH/PULL: There is an acquired force within moving objects. There is a force exerted on all objects being pushed/pulled [illegible]less of motion. 	-	-	5 (16.7%)	10 (33.3%)	15 (14.3%)
6. FORCE OF PUSH/PULL: There is a force only on objects being pushed/pulled regardless of motion. 	-	-	-	1 (3.3%)	1 (1%)
7. GRAVITATIONAL and OTHER FORCES: Force of gravity. Force of push/pull when objects are being pushed/pulled. Acquired force when objects are moving 	-	3 (10%)	1 (3.3%)	16 (53.3%)	20 (19%)

8. Mixed	2 (13.3%)	6 (20%)	4 (13.3%)	-	12 (11.4%)
Total	15 (14,3%)	30 (28.6%)	30 (28.6%)	30 (28.6%)	105 (100%)

Figure 1. Hypothetical conceptual structure for the interpretation of force as an internal property of physical objects

Presuppositions of the Framework Theory

Observations and Information Received in the Cultural Context (Specific Theory)

Ontolo

There are physical objects, which can be animate or inanimate.

Physical objects have properties.

There are states (e.g. rest) and processes (e.g. motion)

Epistemologi

States (like rest) do not need explanation.

Processes (like motion) need to be explained.

Processes (like motion) need to be explained in terms of a causal agent

Big and heavy people/objects can cause changes/damage in other people/objects.

Big and heavy people/objects can resist the push/pull of other objects or people.

Beliefs

Physical objects have force. Force is what makes physical objects cause changes to other physical objects or resist the push/pull of other physical objects. Force maybe affected by the weight and/or size of the object.

Meaning of Force

Force is an internal property of physical objects related to their weight and/or size.

Figure 2: Hypothetical conceptual structure for the interpretation of force as an acquired property of moving inanimate objects

Presuppositions of the Framework Theory

Ontological

There are physical objects, which can be animate or inanimate.

Physical objects have properties.

There can be *internal* properties and *acquired* properties.

There are states (e.g. rest) and processes (e.g. motion).

Epistemological

States (like rest) do not need explanation.

Processes (like motion) need to be explained.

Processes (like motion) need to be explained in terms of a causal agent.

Observations and Information Received in the Cultural Context (Specific Theory)

Animate objects move by themselves.

Inanimate objects move only when pushed/pulled by an agent.

When an agent pulls/pushes an inanimate object a force is exerted.

Belief

Inanimate objects move when a force has been exerted by an agent.

Meaning of Force

Force is an acquired property of physical objects which move.

Figure captions

Figure 1. Hypothetical conceptual structure for the interpretation of force as an internal property of physical objects

Figure 2. Hypothetical conceptual structure for the interpretation of force as an acquired property of moving inanimate objects