

A new educational perspective for teaching gravity

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A New Educational Perspective for Teaching Gravity

Introduction

Research on teaching the phenomenon of falling bodies has generally revolved around students' conceptions before they are taught this lesson in school. These naive understandings are often shown to be erroneous. Bar, Zinn, and Rubin (1997) found that, for Israeli students ages 9 to 17 years, the source of the earth's attraction is often a magnetic force that requires a medium -- air -- to be propagated from the earth to the object. Watts (1982) showed that, for 12-year-old English students, gravity is "selective" in that it does not apply to bodies at rest or bodies thrown up into the air. Palmer (2001) found that 11- to 16-year-old Australian students think attraction is a phenomenon that only occurs on earth. On other celestial bodies, such as the moon, bodies do not to fall but float because they are in a vacuum, and the fact that bodies fall is often ascribed to the presence of the atmosphere. This author also noted that students' conceptions are highly resistant, changing little with age when conventional teaching methods are used.

The present article looks at how these initial conceptions evolve in French ninth graders (age 15) as they learn about this phenomenon in school. After a description of what is already known about such conceptions and about conceptual change in general, a few specific hypotheses will be set forth regarding ninth graders' conceptions of falling bodies and the potential evolution of those conceptions. Next, the current teaching approach and the problems it poses will be analyzed. Then a "new educational perspective" which takes students' initial conceptions and their evolution into account will be proposed. Finally, the effectiveness of two teaching approaches, one based on the current method and the other based on the new perspective, will be compared.

The Research Literature: Conceptions and Conceptual Change

The notion of a "conception" has been in use for about thirty years in research on science teaching, and its definition changes as new studies are conducted. Conceptions are students' conceptual bases prior to teaching, or as Givry and Tiberghien (2005) called them, their "ideas". They serve as a frame of reference for understanding the world and acting within it. Watts (1982) contended that conceptions about a given knowledge domain are not isolated pieces of knowledge, but are combined into an overall structure with its own logic. Vosdianou (1994) added that conceptions are emergent parts of broader and more complex cognitive constructions, which she called "presuppositions" (p. 46) and which diSessa (1988) called "phenomenological primitives" or "p-prims" (p. 4). According to Minstrell (1992) and Palmer (2001), conceptions have several facets that one might call "explanatory systems". Depending on the situation, one or another of the explanatory systems underlying a given conception is activated. Vosdianou (*ibid*) suggested that conceptions have a certain amount of "plasticity", which makes them virtually impossible to destroy but easier to change. Although, following Bachelard (1938), conceptions were long regarded as obstacles that had to be eliminated, they are seen today as modifiable. Two theoretical approaches to conceptual change can be envisaged. Kang, Scharmann, and Noh's (2004) approach extends Piaget's view by emphasizing the role of cognitive conflict in conceptual change. A cognitive conflict arises for a student when he/she is dissatisfied with an existing conception and the experiment at hand. For these authors, the presentation of a discrepant event (i.e., information or an experiment that is inconsistent with the student's conceptions) is "the major source of initial dissatisfaction" (Kang et al., 2004, p. 73) and "could promote the first step in the process of conceptual change" (Kang, Scharmann, Noh, & Koh, 2005, p. 1039). These ideas deepen our

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2
3 understanding of the link between the effectiveness of this process and the cognitive and
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5 motivational variables of students. However, for several other authors, the mere presentation
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7 of a discrepant event is not enough to induce proper conceptual change. According to
8
9 Vosdianou (*ibid*), such a change results from a continuous process that takes place gradually
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11 as already-constructed knowledge is reinterpreted. When a conceptual change occurs, one
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13 conception is not necessarily replaced by another; it can be the result of the greater use of a
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15 scientifically correct conception that makes sense to the student. Thus, along with Palmer
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17 (2001), Givry and Tiberghien (2005), and also Strike and Posner (1992), instead of directly
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19 attacking an erroneous explanatory system, one could attempt to reduce its use by increasing
20
21 the domain of validity of a correct explanatory system already possessed. Givry and
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23 Tiberghien (*ibid*) suggested that extending the domain of validity of a correct explanatory
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25 system is the most frequent road to conceptual change. Several studies (e.g., Akerson, Flick,
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27 & Lederman, 2000; Justi, Souza, & Ferreira, 2005) have demonstrated the effectiveness of
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29 using analogies to trigger this type of change. The analogy approach implies pointing out the
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31 similarities between a situation that students understand and know how to explain, and a new
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33 situation that resembles it. Students can then transfer what they know to the new situation.
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43 In sum (1) conceptions are composed of several explanatory systems or facets, (2) conceptions
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45 about a knowledge domain are linked into an overall system that has its own logic, (3)
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47 conceptions are backed by deeper cognitive structures, (4) they exhibit a certain degree of
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49 plasticity that promotes their evolution, and (5) conceptual change usually either occurs
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51 following a discrepant event that triggers a cognitive conflict, or involves a generalization of a
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53 valid explanatory system.
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59 The next section looks more specifically at students' conceptions about the physical
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phenomenon of falling bodies.

Initial Conceptions of Falling Bodies

Past research on conceptions about falling bodies among 15-year-old students (Baldy & Aubert, 2005) has shown that students at this age rely on several explanatory systems to account for this phenomenon, depending on the place where it occurs. The explanation that bodies fall due to attraction is reserved for events occurring on earth. On the moon or in space, where there is no atmosphere, bodies float because they are in a vacuum. For students, then, the phenomenon of falling -- i.e., gravity -- is not universal, and the earth is treated as a special case: it seems to occupy a privileged place that is not part of space. As soon as an event no longer happens on earth, students have incorrect conceptions regarding both the facts (bodies float or bodies fall) and the explanations given of them (attraction, atmosphere, etc.). Vosdianou (1994) showed that until the end of elementary school, Greek pupils do not see the earth as a planet, but as a physical body that obeys laws of its own, and Baldy and Aubert (*ibid.*) found that such a distinction still exists in 15-year-old students. This "*presupposition*" -- in Vosdianou's (*ibid.*) sense of the term -- is comparable to an idea that was shared by many scholars up through the Middle Ages, namely, that the earth is separate from "the heavens". In fact, it was Galileo who first considered terrestrial and celestial phenomena in the same way.

These observations suggest that one way to enable students' conceptions about falling bodies to evolve would be to try to eliminate the distinction between phenomena on earth and phenomena at other locations in the universe. In other words, students should be led to generalize the physical event "bodies fall", and the correct explanatory system "bodies fall because of attraction", to all places in the universe. Gravity must become a universal phenomenon.

The Current Educational Approach to Teaching Gravity

Knowledge taught in school is never an exact copy of scholarly knowledge as it is elaborated by the scientific community. Due to its complexity, the latter type of knowledge is usually inaccessible to students. To become teachable it must be transformed, and this requires making choices. In 1993, the school curricula in France (and in most other countries) recommended using Newton's theory of the interaction of bodies at a distance to teach students the connection between the earth's attraction and weight. In this theory, all bodies that have a mass are attracted to each other, and the attraction between bodies is proportional to their mass and inversely proportional to the square of the distance between them. This theory is based on the concept of force, defined as an action exerted on an object. It is introduced in ninth grade, right before students are taught the concept of weight.

In practice, this approach has proven unsatisfactory. It raises a large number of questions about the nature of the force exerted by the earth on falling bodies. Students do not understand this force -- is it magnetic, is it magic, ..? Why do we say that bodies are attracted to each other when everyday experience shows that they do not spontaneously start moving toward each other? Newton himself was unable to explain what he called the "force of the earth's attraction" and gave it a divine origin.

Note that in the course of history, theories have not been adopted by the sheer strength of their arguments. The same holds true of learning in class; students do not adhere to a theory simply because they are told to do so. According to Posner, Strike, Hewson, and Gertzog (1982), a new theory must meet several conditions to be accepted by students: it must be understandable, plausible, and effective for solving problems. The theory of bodies interacting at a distance does not fulfill these conditions: students do not understand the nature of matter's

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3 mysterious force of attraction, and they have trouble believing the theory because their
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5 everyday experience seems to contradict it (bodies do not move toward each other).
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10 Newton's theory was taken out of the French curriculum in 1998, but the new teaching
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12 approach omits the physical side of the phenomenon and considers only its mathematical side.
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15 The concept of weight is not explained but is simply defined as a force due to the attraction of
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17 the earth (or the moon). The lessons focus solely on the mathematical calculation of this force,
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19 using the formula $W = mg$ (where W stands for weight, m for mass, and g for local
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21 gravitational acceleration). Once teachers have introduced this formula, they tend to assume
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23 that their students are capable of manipulating it correctly, and of understanding the physical
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25 phenomenon it represents. Unfortunately, this is far from being the case. Presented as such,
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27 the formula is not connected to the conceptual field of the physical phenomenon of falling, nor
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29 to the mathematical knowledge needed to use it. Students do not relate this new knowledge
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31 ($W = mg$) to the old knowledge they already possess (correct, incorrect, or perhaps even
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33 contradictory). Some students are capable of learning the formula, remembering it, and
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35 reciting it, but without understanding the concepts or physical phenomenon it models.
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43 Neither of these approaches takes students' prior knowledge into account, nor the results of
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45 research on how student conceptions change. They both propose a teaching method derived
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47 from a theory that is four centuries old and is clearly outdated. Today, our scholarly
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49 knowledge of physical phenomena, and our understanding of the cognitive functioning of
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51 students, have evolved. Hence, teaching methods should do likewise, not only for this subject
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53 but for all disciplines taught in school. In biology, for example, the fast pace of recent
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55 discoveries in genetics calls for regular updating of teaching programs. What about new
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57 perspectives for teaching physics?
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A New Educational Perspective for Teaching Gravity

The new approach to teaching gravity proposed here attempts to update both the knowledge taught and the method of teaching it. Regarding the knowledge itself, an "analogical" version of Einstein's theory is presented, with explanations of the phenomenon of falling bodies based on the time-space topology that follows from the general theory of relativity. Recall that Newton devised this theory in the 17th century, i.e., about three centuries before Einstein. Today, Einstein's more recent theory is acknowledged by the scientific community as a good approach for explaining the phenomenon of gravity. France's popular science magazines for youth have presented it several times and consider it accessible to adolescents (*Sciences & Vie Junior*, No. 140 May 2001, No. 171 December 2003, and Special Issue No. 59 January 2005). Yet current teaching curricula do not include an introduction of Einstein's theory -- not even a simplified one -- to explain the concept of gravity and weight, probably because experts deem it to be too complex. Yet, as Galili (2001) suggested, the "too-complex" view of modern physics deprives us of a good opportunity for helping students obtain a clearer understanding of the concepts of gravity and weight. According to this author, the failures noted with current methods of teaching gravity should prompt teachers to change strategies: *"Though based on ideas of modern physics, the material is far from being too formally complex for the average student"* (p. 1081).

Einstein's theory offers some answers to the didactic issues and contradictions that the interacting-bodies theory does not resolve. For example, it gets rid of the problem of force at a distance, which according to Vosdianou (1994) and Bar, Zinn, and Rubin (1997), ninth graders do not understand. Einstein's theory gives a geometric explanation of falling bodies without relying on the force of attraction. Hopefully, students will be able to see that bodies do not possess some mysterious property of attraction but "simply" have the effect of

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3 "deforming" the space-time that surrounds them, and that this deformation changes their
4 trajectory as they pass near each other. While it appears as though bodies are mutually
5 attracted to each other, they in fact merely continue along their path in a deformed space-time,
6 under the effect of inertia.
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15 In the new approach used in this study, Einstein's theory is introduced to students via the so-
16 called "pillow" model: the pillow represents space, and steel balls of different sizes and
17 masses are used to represent celestial bodies. When a marble representing a body is placed
18 next to a ball, it falls into the dip in the pillow created by the ball. And if the marble is rolled
19 fast enough, it deviates from its normal trajectory in the vicinity of the ball. Whenever two
20 balls on the pillow are close enough to each other, the area between them is deformed by each
21 one. It is clear that the deformation of space-time is not confined to a deformation of space,
22 but this analogy was chosen here because this is how Einstein himself described his theory
23 when addressing an audience of non-specialists. This is also the way it is found in all physics
24 textbooks and scientific and lay journals, including the ones mentioned above. **Although well-**
25 **known to physicists, the pillow analogy has not, to our knowledge, been used in secondary-**
26 **school teaching.** Furthermore, studies by Brown (1992), Akerson, Flick, and Lederman
27 (2000), Duit and Treagust (2003), and Justi, Souza, and Ferreira (2005) have all shown that
28 conceptual change in students takes place more readily when the teaching method is based on
29 an analogy.
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52 In our earlier work (Baldy & Aubert, 2005), we noted that students often confused the g of
53 local gravitational acceleration with the g of gram. In traditional curricula, the concept of local
54 gravitational acceleration (along with its symbol " g ") is introduced and defined as the
55 coefficient of proportionality between weight and mass. Local gravitational acceleration has
56 no physical existence in this case. In the transposition of Einstein's theory proposed here, the
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3 relation between the weight of a body, its mass, and local gravitational acceleration in a given
4 location, along with the corresponding physical phenomenon, are simultaneously addressed
5 and explained via the pillow analogy. This model gives a concrete and intuitive dimension to
6 gravitational acceleration. The weight of a body is said to depend on its mass and on the slope
7 of the cavity where the body is located. The notion of local gravitational acceleration is
8 characterized in terms of the slope. Near the ball, where the slope is the steepest, the
9 gravitational acceleration is greater than farther away from the center of the cavity. With this
10 image-based presentation, local gravitational acceleration "g" has a physical definition that is
11 easier for students to understand.
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27 We know that some students separate those phenomena that take place on earth from those
28 that occur in space, as if the earth were a special body that isn't really part of space. In fact,
29 students' initial conceptions about what happens on earth are often correct -- bodies fall
30 because of the earth's attraction -- while being incorrect for the rest of the universe. In the
31 analogy used here, all bodies are represented by balls of variable size and mass that create
32 cavities in the pillow. The falling of a body is due to the slope of the cavity, and all bodies
33 make slopes that extend far beyond their centers. The fact of having every ball act in the same
34 manner, no matter where it is located on the pillow, should help students generalize the
35 phenomenon of gravity to all points in space (whether near to or far from a celestial body).
36 Generalization of this phenomenon should lead to less diversity in the explanatory systems
37 and thereby enable students to see gravity as a universal phenomenon.
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55 The aims of the present study were to test the effectiveness of this "new educational
56 perspective" with respect to (1) how students' conceptions evolve and (2) how well students
57 understand g. Einstein's theory answers the question of why bodies are attracted to each other.
58 It must therefore be introduced after students are taught the notion that bodies fall because
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3 they are attracted by a celestial body. For students who think that bodies float in a vacuum,
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5 this theory shows that the only determining factor in whether a body will fall is the presence
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7 or absence of mass.
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10 11 12 13 14 15 **Effectiveness of the New Perspective**

16 17 *Method and Sample*

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19 The effectiveness of our new approach based on Einstein's theory of space-time deformation
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21 was tested on 102 ninth graders who were compared to a control class of 21 ninth graders
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23 being taught via Newton's theory (bodies interacting at a distance). **The notions of weight and**
24
25 **mass are usually taught in reference to Newton's theory. The advantages and disadvantages of**
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27 **this approach in high school (Baldy & Aubert, 2005) and at the university (Mildenhall &**
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29 **Williams, 2001) are well-known. A control group of only one class thus seems sufficient. On**
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31 **the other hand, introducing Einstein's theory is a new approach at this level. To obtain reliable**
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33 **results, then, a large experimental group seemed necessary (approximately a hundred**
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35 **students).** In both approaches, the lessons were always given in the classroom by the same
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37 teacher, with the experimenter present. All participating students were selected from the same
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39 junior high school so as to reduce potential effects of the teacher or social class. Any
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41 performance differences across approaches could thus be ascribed to differences in the
42
43 effectiveness of the teaching approaches. Given their age (15), the students who participated
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45 had already acquired the concept of weight and its conservation (Piaget, 1972; Galili & Bar,
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1997).

57 The first session in both approaches (described in Figure 1) was a joint session aimed at
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59 helping students see that bodies fall on earth and on the moon because of the attraction of
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celestial bodies and not the atmosphere. Our working hypothesis here was that grasping this

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3 notion is a prerequisite to understanding each of the two theories proposed in the next session.
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5 For the second session of the Newton approach, Newton's theory of the interaction between
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7 bodies was presented; for the second session of the Einstein approach, the theory of space-
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9 time deformation was presented. The first session began with a questionnaire that allowed
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11 students to think individually about a simple situation: Why does a stone fall when it is
12
13 dropped? The students wrote their answers down, after which the teacher discussed the
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15 problem with the whole class. Next, the students stated their own hypotheses and offered
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17 arguments for and against, for approximately ten minutes. With the teacher's help, they then
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19 proposed various experiments to validate or refute their hypotheses. For example, they
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21 watched a piece of chalk fall in a vacuum bell, which served as a discrepant event (in the
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23 Kang et al. sense, 2004) that was inconsistent with their prior conception that "bodies float in
24
25 a vacuum". This method was likely to trigger a cognitive conflict leading to conceptual
26
27 change. For the second session, the teacher presented a new theory to the students (Newton's
28
29 or Einstein's) that could help them answer the question just raised. The students asked
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31 questions throughout the presentation. The two sessions lasted the same amount of time, both
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33 requested student participation in the same way, and in both cases, the observations were
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35 summarized using diagrams.
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Insert Figure 1 here

The evolution of each individual student's conceptions about falling bodies was assessed three times during the sequence, via three tests: initial test, intermediate test (between the two sessions), and final test. After the entire sequence, their understanding of the concept of local gravitational acceleration and its variations (final test) was analyzed. Each test consisted of

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3 five or six short-answer questions, sometimes accompanied by drawings (planets, a rocket,
4 etc.). In illustration, the first column of Figure 2 presents the most characteristic questions.
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8 This procedure allowed us to collect a relatively large number of responses to specific
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10 questions in a reasonable amount of time, and thus to compile reliable empirical data for
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12 inferring the students' underlying conceptions.
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29 Results

30 *Coding the Responses*

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33 The students' conceptions were inferred from their answers on the three tests (initial,
34 intermediate, and final) by two judges who worked independently (inter-judge agreement
35 88.7%). Disagreements were discussed until an agreement was reached. The questions asked
36 covered three areas: interplanetary space, the moon, and the earth. Figure 2 above lists the
37 most typical answers given to the characteristic questions, for each type of explanatory
38 system.
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50 A complete analysis of the students' responses showed that they considered two events: bodies
51 floating and bodies falling. They relied on three explanatory systems to account for
52 why bodies fall: the presence of an atmosphere, the presence of an attraction, and the
53 idea that they return to their place of origin (Aristotelian explanation). The following
54 seven conceptions were inferred from the students' test answers, in decreasing order of
55 correctness (from the most complete and most correct, to the most incorrect).
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1. Generalized attraction (GA): there is attraction on earth and on the moon, and more generally at any point in space.
2. Celestial body attraction (CBA): objects fall down on earth and on the moon because they are attracted by the celestial body.
3. Earth's attraction only (EA): attraction is a phenomenon that takes place only on earth.
4. Attraction on the earth and atmosphere on the moon (EA&Atmos): two explanatory systems are used, one for the earth and one for the moon. On earth, falling is due to the earth's attraction, whereas on the moon, objects float because there is no air.
5. Atmosphere (Atmos): falling is due to the atmosphere.
6. Aristotelian explanation on earth and atmosphere on the moon (Arist&Atmos): two explanatory systems are used, one for the earth and one for the moon. On earth, objects fall because they return to the ground, their original place. On the moon, objects float because there is no atmosphere.
7. Aristotle (Arist): the Aristotelian conception of falling applies on both the earth and the moon.

The first three conceptions are correct from the standpoint of the reason why bodies fall (attraction), but for CBA, the students think that the attraction of a celestial body is present only near its surface, and for EA they think the earth is the only celestial body that attracts. The fourth conception, AE&Atmos, is correct for the earth but incorrect for the moon. The last three conceptions are based on incorrect explanatory systems regarding why bodies fall. Note that GA, CBA, EA, Atmos, and Arist are homogeneous in the sense that students use the same explanatory system no matter what place is at stake. AE&Atmos and Arist&Atmos are

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3 mixed conceptions to the extent that students rely on different explanatory systems for
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5 different places.
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10 *Results of the Control Classes Taught Using the Newton Approach*

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12 Table 1 presents the evolution of the conceptions of students taught using the Newton
13 approach. The upper panel of the table (N1) shows how the conceptions evolved during the
14 first session (joint session for both teaching approaches); the middle panel (N2) shows how
15 they evolved during the second session (Newton); and the lower panel (N3), how they evolved
16 for the entire Newton sequence.
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36 We can see in the upper panel (N1) that the most common conception before the lesson was
37 EA (n = 10), and that the conceptions of 13 students out of 21 improved (below the diagonal).
38 The most frequent change (n = 8) was the shift from conception EA (only the earth attracts) to
39 conception CBA (there is attraction on earth and on the moon). However, the improvement
40 was never great enough to attain the correct conception, GA (bodies are attracted to all
41 celestial bodies around them, at all points in space). At the end of the first session, the most
42 common conception was CBA (n = 10). The middle panel (N2) indicates that the students'
43 conceptions evolved little during the second session: 19 students out of 21 were still on the
44 diagonal. Only two students progressed to conception CBA. For the Newton approach as a
45 whole (lower panel, N3), the conceptions of 16 students had improved, but almost entirely due
46 to the effect of the joint session. At the end of the whole sequence, half of the class (12
47 students) had conception CBA. Only those students who had the most comprehensive
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3 conception (GA) before the lesson still had it afterwards, with no other students managing to
4 reach this level. Moreover, we can see that the students' responses no longer involved several
5 explanatory systems (AE&Atmos and Arist&Atmos).
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10 11 12 *Results of Classes Taught Using the New Einstein Approach*

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14 Table 2 presents the evolution of the conceptions of students taught using the Einstein
15 approach. In the table, E1 shows how the conceptions evolved during the joint session
16 (students from both approaches), E2 how they evolved during the second session (Einstein),
17 and E3 how they evolved for the entire Einstein sequence.
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36 We can see in the upper panel (E1) that the most common conception before the lesson was
37 EA (n = 10). The conceptions of 62 students improved (below the diagonal). The most
38 frequent progress (n = 33) was the shift from conception EA to conception CBA. Five
39 students attained the most comprehensive conception (GA). The most common conception at
40 the end of the first session was CBA (n = 41). The middle panel (E2) indicates that the
41 conceptions of 59 students improved. The most frequent progression (n = 30) was the shift
42 from conception CBA to conception GA, generalized attraction: bodies located at all points in
43 space fall toward surrounding celestial bodies. For the Einstein approach as a whole (lower
44 panel, E3), the conceptions of 85 students improved. The two most common conceptions were
45 GA (39 students, although this conception had not been found for any of the students before
46 the lesson) and CBA (37 students). Note that the majority of the students who, before the
47 lesson, had the most incorrect conceptions (derived from an Aristotelian and/or atmosphere-
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3 based explanatory system) did not achieve the most general conception and remained "stuck"
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5 on a conception of attraction near the earth only, or near the earth and the moon.
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10 *Comparing the Results of the Newton and Einstein Groups*

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12 Given that the aim of this study was to evaluate the effectiveness of the new educational
13 perspective, the changes in the conceptions of students taught with this new approach were
14 compared to those of students in a control group taught using the more-traditional Newton
15 approach. Let us first analyze the evolution of students' conceptions about falling bodies,
16 before we look at the students' understanding of the concept of local gravitational acceleration
17 after the lesson.
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29 *Evolution of Conceptions*

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31 As indicated in the rightmost column of panels N1 and E1 (Tables 1 and 2), the frequencies of
32 the various conceptions before the lesson were comparable for the two groups (conception EA
33 was the most prevalent). Figure 3 presents the evolution of each conception during the two
34 teaching sessions in each approach (Newton and Einstein). A positive change means that the
35 prevalence of the corresponding conception increased; a negative change, that it decreased.
36 We can see that the two groups evolved in a comparable way during the first session (joint),
37 with a substantial increase in conception CBA to the detriment of conception EA, which
38 became less prevalent. By contrast, during the second session (Newton or Einstein), the
39 evolution was different. Almost no progress was noted for the Newton group, whereas for the
40 Einstein group, the prevalence of conception GA rose considerably (+38%) to the detriment of
41 conception CBA.
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Insert Figure 3 here

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Understanding of Local Gravitational Acceleration After Teaching with the Newton and Einstein Approaches

17 Before the lesson, the students knew nothing about the concept of local gravitational
18 acceleration. Let us compare the two groups' grasp of g after the lesson. Table 3 describes how
19 the concept of local gravitational acceleration and its variations were understood by students
20 taught using each of the two approaches. We can see that fewer students taught by the new
21 Einstein approach confused the g of gram and the g of local gravitational acceleration. On the
22 other hand, more of them explained variations of g in terms of a celestial body or altitude.
23 Also, more than 22% of these students explicitly used the theory of space-time deformation to
24 answer the questions (Figure 4).
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Insert Table 3 here

Insert Figure 4 here

Discussion

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3 The purpose of the present study was to describe students' initial conceptions about the
4 phenomenon of falling bodies, and to compare how these conceptions evolved during a lesson
5 taught using two different teaching methods. Let us first analyze the students' initial
6 conceptions and then discuss the relative effectiveness of the new educational perspective.
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8 Next, we will examine the way these conceptions evolved and discuss the reasons why the
9 Einstein approach promoted conceptual change.
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20 *Initial Conceptions*

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22 The most common conception before the lesson was EA (bodies fall because they are attracted
23 but the attraction occurs only on earth). As in the history of the sciences, the students
24 separated the earth from the rest of space, granting it a special place in the universe. In this
25 view, physical phenomena are not the same on earth as elsewhere in space. It is possible that
26 the centrality of the earth's position in the students' minds is a reflection of a form of
27 egocentrism on their part. Like Galili and Bar (1997), who noted that students defined the
28 weight of an object in terms of their own sensations, our students defined gravity with respect
29 to themselves and to their own experience. This location-specific separation of phenomena led
30 to mixed conceptions combining several explanatory systems. On this point, our results are in
31 line with previous research (Baldy & Aubert, 2005; Palmer, 2001; Graham & Berry, 1997;
32 Bar, Zinn, & Rubin, 1997; Watts, 1982).
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50 *Comparative Effectiveness of the Two Approaches*

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52 For the control-class students taught by the Newton approach, most of the conceptions
53 remained "stuck" on the idea that bodies fall due to attraction but only in the vicinity of a
54 celestial body. This conception is correct but its field of applicability is limited. During the
55 joint session, the videotape study of bodies falling on earth and on the moon enabled these
56 students to see that bodies fall due to the existence of an attraction toward the earth or the
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3 moon, but it did not allow them to generalize this explanation to all of space. During the
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5 second session, the study of the theory of bodies interacting at a distance did not lead to
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7 conceptual change. As Table 1 shows, the Newton session did not allow students who had not
8
9 yet reached the CBA conception to move up to it; nor did it allow those who had attained that
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11 level to go beyond it. Thus, from the standpoint of changes in the students' conceptions about
12
13 the physical phenomenon of falling bodies, this session was highly ineffective. This
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15 observation provides an experimental confirmation of the failure reported regularly by
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17 teachers in the classroom. Because students do not understand the physical nature of
18
19 attraction, they are unable to see gravity as a universal phenomenon. It seems that only a
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21 rational, meaningful explanation can trigger the generalization of the existing explanatory
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23 system, until then confined to phenomena occurring in the vicinity of a celestial body.
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31 For the students taught by the Einstein approach, the initial conceptions and their evolution
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33 during the joint session were comparable to those of the Newton group. On the other hand,
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35 after the Einstein session, 38% of these students had moved up to conception GA, wherein
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37 attraction by surrounding celestial bodies applies to all points in space. Our working
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39 hypothesis was that conception CBA (attraction in the vicinity of a celestial body) would be a
40
41 prerequisite to understanding the space-time deformation theory introduced in the next
42
43 session. Indeed, 30 of the 39 students who shifted to GA already had conception CBA before
44
45 the session. The Einstein approach helped a much greater number of students to generalize the
46
47 attraction-based explanation of falling bodies to the entire universe. With respect to this goal,
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49 then, the Einstein approach was more effective than the Newton approach. It also led to better
50
51 knowledge of local gravitational acceleration, its symbol g , and its variations (Table 3). The
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53 Einstein approach met both educational objectives set here, conceptual change and an
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55 understanding of g .
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How the Students' Conceptions Evolved

Our study pointed out two kinds of non-mutually-exclusive conceptual change. The first was "positive substitution" or the change from an incorrect explanatory system (e.g., bodies fall due to the atmosphere) to a correct system, but possibly with a limited domain of validity. According to Kang et al. (2004), this first kind of conceptual change is brought about by a cognitive conflict following a discrepant event. The second kind of conceptual change (already noted by several authors: Strike & Posner, 1992; Vosdianou, 1994; Givry & Tiberghin, 2005) was "generalization", which consisted of expanding the domain of validity of a correct explanatory system (e.g., the phenomenon of bodies falling due to attraction is no longer confined to the earth but becomes valid for all celestial bodies or throughout the universe). Triggering the first type of change was the goal of the joint session. The upper panels of Tables 1 and 2 (N1 and E1) show that the most frequent conceptual change during this first session was in fact the shift to conception CBA. The Aristotelian or atmosphere-based explanatory systems were much less frequent after this session than before it. Most of the students arrived at an attraction-based understanding of falling bodies for phenomena occurring on celestial bodies. Triggering the second type of evolution was the goal of the second session. As shown above in the analysis of the effectiveness of the two approaches, this goal was not attained with the Newton approach: the students' conceptions were about the same before and after the second session. By contrast, with the Einstein approach, the goal was at least partially attained: the most frequent conceptual change during this session was the shift from CBA to GA (E2 in Table 2). These students generalized their attraction-based conception to all points in the universe.

The mixed conceptions detected initially (e.g., AE&Atmos), which had several active facets (Minstrell, 1992; Palmer, 2001), were necessarily based on at least one erroneous explanatory system. The first session triggered a positive-substitution type of change that (temporarily or

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3 definitively?) eliminated the erroneous explanatory system, or at least decreased its
4 prevalence. This led to greater conceptual uniformity among the students. The next step was
5 to prompt the expansion of this locally-correct explanatory system. At the end of the second
6 session in the Einstein approach, the correct explanatory system "bodies fall due to attraction"
7 had in fact been changed to "attraction exists at all points in space", via an extension of its
8 domain of validity.
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20 This conceptual change took place in three stages. At first, attraction pertained solely to the
21 earth, which was a special case. Then it was generalized to the moon, and finally, to all points
22 in the universe. It is important to note that the change involved more than simply extending
23 the explanatory system's domain of validity. The generalization of attraction was accompanied
24 by a restructuring of more general "*presuppositions*" (Vosdianou, 1994) or "*p-prims*" (diSessa,
25 1988) underlying the conception of falling bodies. In the case of conception EA (attraction
26 phenomena occur only on earth) attraction is usually attributed to a force coming from the
27 earth's core, whereas in conception GA (bodies are attracted at all points in space due to the
28 presence of surrounding celestial bodies) attraction is no longer "directly" provoked by the
29 celestial body but is due to the deformation that celestial bodies cause in space, which in turn
30 causes other bodies to move toward them. In their answers to the question *Why do planets*
31 *attract bodies?*, the deep meaning of the term "attraction" underlying the falling-body concept
32 evolved to the point where certain students became aware of its unsuitability. Indeed, we can
33 see that half of the students who had the most general conception (Table 3) relied on the idea
34 of space-time deformation in explaining falling bodies in space, either in their verbal
35 description or in their drawings.
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Why Was the New Educational Perspective More Effective?

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3 Several reasons for the greater effectiveness of the Einstein approach can be given with
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5 respect to the two points tackled here -- generalization of attraction, and knowledge of g -- and
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7 they validate our hypotheses. It was hypothesized that the mysteriousness surrounding the
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9 notion described in Newton's theory -- that there is a force of interaction between bodies at a
10
11 distance -- is what prevents students from understanding that bodies made of "normal" matter,
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13 i.e., neither magnetic nor "magical", are attracted to each other. Einstein's theory and its
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15 presentation by way of a spatial analogy provided an explanation of the source of the falling
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17 without calling upon any intrinsic force of matter. Bodies fall due to the space-time
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19 deformation produced by the great mass of celestial bodies. When steel balls of different sizes
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21 and masses that caused cavities in the pillow were used to represent celestial bodies, the
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23 students were led to consider all celestial bodies from the same angle. Because a ball that
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25 created a dip in the pillow could represent the earth as well as the moon, there was no reason
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27 to distinguish the earth from other celestial bodies. This analogy also showed that a ball
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29 placed on the pillow produced a deformation covering a large distance that extended beyond
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31 the area close to the ball. The elements "perceived" on the pillow model enabled students to
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33 extend the effect of attraction to points located far away from a celestial body. Thus, two
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35 aspects of this new approach played an important role in its effectiveness: the presentation of
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37 the pillow analogy, and the specific point of view adopted in Einstein's theory. In Newton's
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39 theory, the attraction of bodies is caused by a "mysterious" property of matter (an apple is
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41 attracted by the earth), and all analogies we could present could only emphasize this causality,
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43 which, sooner or later, had to be discarded in order to address the concept the weight (g) and
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45 its variations. The approach via Einstein's theory clarifies the phenomenon of falling bodies by
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47 enabling the teacher to relate the magnitude of g to the deformation of space by matter. The
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49 presentation of the pillow analogy accentuated this link and thus promoted an initial
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51 understanding of the phenomenon. Indeed, the spatial analogy also provided a "visual
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53 rendition" of local gravitational acceleration, and its variations and their causes. There is a
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3 relationship between the slope of the cavity and the mass of the ball representing the celestial
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5 body. When g is said to be this slope, students can make the connection between the value of
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7 g and the mass of the ball. In this approach, the concept of local gravitational acceleration is
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9 not introduced, *a posteriori*, as the coefficient of proportionality between the weight and the
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11 mass, as it is in the Newton approach. The concept is presented relative to a physical
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13 phenomenon; it has a physical dimension (each point in space has a characteristic local
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15 gravitational acceleration), a source (the deformation caused by the mass of the celestial
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17 body), and an impact (the greater it is, the more the body will tend to fall toward the celestial
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19 body). Of course, these remarks are not intended to mean that the students built a
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21 representation of the universe that conformed to Einstein's theory on all points, nor that they
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23 understood the theory. Our results simply suggest that they began to assimilate one aspect of it
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25 (matter deforms space and this changes the trajectories of bodies) in a global and intuitive way
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27 that enabled them to assign an understanding of the physical phenomenon to the formula
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29 $W = mg$. These acquisitions, like all others, were probably unstable and will need to be
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31 solidified in future lessons. A longitudinal study could provide information on this point.
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43 Conclusion

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45 The results of this study confirm the relative ineffectiveness of teaching the concept of falling
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47 bodies using Newton's theory. At the same time, they point out the merits of a new
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49 educational perspective based on Einstein's theory. The success of the new approach can be
50
51 regarded as a double validation: it validates the teaching method (the new approach enabled
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53 students to make more progress than the old one) and it validates the psychological model of
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55 students' conceptions and their evolution in terms of the generalization of a correct initial
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57 explanatory system (Strike & Posner, 1992; Palmer, 2001; Givry & Tiberghien, 2005). The
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59 effectiveness of the Einstein approach can be seen as a testimony to a correspondence between
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3 the logic underlying this teaching method and the psychological process of learning:
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5 substituting a correct conception for an incorrect one, if necessary, and then extending it to a
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7 broader domain.
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12 The originality of this study lies in its in-depth approach to analyzing conceptual change.
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14 Firstly, our analysis distinguished two non-mutually-exclusive phases. **These two phases**
15 **correspond to the two views of conceptual change presented above (discrepant event and**
16 **cognitive conflict vs. generalization), and can be used in the classroom to reach two**
17 **complementary goals: substitute a correct conception for an incorrect one ("positive**
18 **substitution") followed by "generalization". In addition,** our analysis showed that the
19
20 generalization process can induce a deeper level of conceptual change, i.e., the level that
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22 affects what Vosdianou (1994) called "*presuppositions*" and what diSessa (1988) called "*p-*
23 *prims*". In our study, the new teaching approach led some students to attribute a new meaning
24
25 to the concept of attraction: attraction became an effect of a property of space, not a property
26
27 of bodies. In turn, this new meaning initiated a revised view of space and phenomena
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29 occurring in it (falling bodies, movement of celestial bodies, etc.). Understanding that the
30
31 mass of celestial bodies deforms space-time, and this aspect alone, can be regarded as
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33 constituting an entry into the "zone of proximal development" (Vygotsky, 1986) characteristic
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35 of the cognition of 15-year-old students. The students could assimilate the spatial and
36
37 conceptual relations found in the space-time deformation theory, and this assimilation process
38
39 induced a restructuring of their knowledge to achieve a better fit with the knowledge of
40
41 science. The use of Einstein's theory of the deformation of space-time by matter enabled some
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43 students (nearly 40%) to gain an overall understanding of why bodies fall, and to grasp the
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45 phenomenon of gravity in general and the meaning of *g*. These students became capable of
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47 (qualitatively) solving more complex problems. Above all, they began to understand how our
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49 universe works, and why, for example, the moon rotates around the earth without ever falling
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3 down. However, not all of the students tested here were able to make this progress. At the end
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5 of the lesson, 36% of them still confined the phenomenon of attraction to the vicinity of a
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7 celestial body, and another 20% thought it only occurred on earth. It is evident that, like any
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9 other physical concept, this particular theory could not be fully understood by every student
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11 after a mere two sessions. But this new perspective seems to take a first step toward
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13 accomplishing this lengthy learning process.
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20 The new meaning of the term "attraction" generated a vocabulary problem here. This term
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22 from classical physics continued to be used, even though it no longer meant the same thing.
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24 The students' drawings of the deformation of space-time in their answers to the test exercises
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26 (Figure 4) showed that they no longer attributed the movement of bodies to a magical force
27
28 possessed by matter. A body is not really attracted "by" the earth, but moves "toward" it
29
30 because of the space-time deformation the earth provokes. **The drawings made by the students**
31
32 **to depict the deformation of space-time, and the questions brought up by the use of the term**
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34 **"attraction", indicate that the students had begun to grasp the significance of Einstein's theory**
35
36 **for the problem at hand: the falling of an apple and the rotation of the moon are not caused**
37
38 **solely by the earth, but are also due to the fact that they deform space.** Despite this, both the
39
40 teacher and the students often employed the term "attraction" to refer to the movement of
41
42 bodies. It would seem that it is even more difficult to change people's usage of vocabulary
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44 words than it is to change their conceptions. Don't we all still say that the sun rises and sets,
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46 even though it has been known for more than five centuries that the earth turns, not the sun?
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55 Certain students in this study asked why a body moves in space. In the case of our analogy, if
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57 the marble falls into the dip in the pillow formed by the ball, it is especially because of the
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59 "earth's attraction", which we cannot escape. In the case of real space, couldn't a body on a
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slope remain stationary? The teaching process carried out here required answering a series of

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3 *Why's: Why do bodies fall?* (because they are attracted to each other), *Why are they attracted*
4 *to each other?* (because they deform space), *Why ...?* and so on. This last question can only be
5 answered by referring to the principle of inertia, which ninth graders have not yet learned.
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10 Inertia is not introduced in France until tenth grade, when it is presented in the classical
11 manner: a body subjected to no forces is at rest or follows a rectilinear trajectory at a constant
12 speed. This statement is invalid in a modern conception of mechanics, where the notions of
13 force and rectilinear trajectory no longer exist. The principle of inertia should be stated
14 differently: a body traveling on its own follows the geodesic on which it is located. Or more
15 simply, it continues along its "path"; if that path turns, it turns too. These observations suggest
16 that an understanding of Einstein's theory of space-time deformation should be accompanied
17 by a general overhaul of the methods used to teach mechanics, as also proposed by Galili
18 (2001).
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34 This analysis does not imply that there is no room for Newton's model "in the school science
35 curriculum". However, the goal in ninth grade is not only to have students memorize a
36 formula and some definitions, but also to enable them to grasp the phenomenon of falling
37 bodies (Why do bodies fall on earth? Do they fall on the moon? If so, why? Why don't they
38 fall in the same way?). An understanding of the impact of a planet's mass on the magnitude of
39 g , and the resulting understanding of how g varies according to what planet is being
40 considered, must be the outcome of a representation of the universe based on the deformation
41 of space-time by masses, as defined in Einstein's theory. In higher grades, students will have
42 to calculate forces and trajectories by manipulating equations, for example. At that point,
43 Newton's theory will provide a more operational framework. Generally speaking, these two
44 pedagogical approaches are not incompatible but complementary. Regarding potential
45 implications for teaching in the future, it would be desirable -- regardless of the school grade,
46 the goal of the lesson, and the teaching context --- for teachers to lead students to switch back
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3 and forth between thinking in terms of Einstein's theory and thinking in terms of Newtonian
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5 mechanics. In such a framework, students will know that "it is as if bodies were subjected to
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7 forces proportional to their mass and inversely proportional to the square of the distance
8
9 between them". Just as every theory has its specific domains of validity in physics, the use of a
10
11 given theory has its specific domains of effectiveness in physics teaching. Moreover, the shift
12
13 from one theory to another in class could provide epistemological food for thought about the
14
15 development and impact of theories in the history of science. According to Coll, France and
16
17 Taylor (2005), this kind of thinking -- developing awareness of several theories -- should play
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19 an important role in both the acquisition of scientific knowledge and understanding the nature
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21 of science by students.
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For Peer Review Only

		after joint session							
before joint session		GA	CBA	EA	A&atmos	atmos	arist&atmos	arist	No. of students
	GA	2	0	0	0	0	0	0	2
	CBA	0	1	0	0	0	0	0	1
	EA	0	8	2	0	0	0	0	10
	A&atmos	0	0	0	1	1	0	0	2
	atmos	0	0	2	0	1	0	0	3
	arist&atmos	0	1	2	0	0	0	0	3
	arist	0	0	0	0	0	0	0	0
	No. of students	2	10	6	1	2	0	0	21

Table N1

		after Newton session							
before Newton session		GA	CBA	EA	A&atmos	atmos	arist&atmos	arist	No. of students
	GA	2	0	0	0	0	0	0	2
	CBA	0	10	0	0	0	0	0	10
	EA	0	0	6	0	0	0	0	6
	A&atmos	0	1	0	0	0	0	0	1
	atmos	0	1	0	0	1	0	0	2
	arist&atmos	0	0	0	0	0	0	0	0
	arist	0	0	0	0	0	0	0	0
	No. of students	2	12	6	0	1	0	0	21

Table N2

		after both session							
before either session		GA	CBA	EA	A&atmos	atmos	arist&atmos	arist	No. of students
	GA	2	0	0	0	0	0	0	2
	CBA	0	1	0	0	0	0	0	1
	EA	0	8	2	0	0	0	0	10
	A&atmos	0	1	0	0	1	0	0	2
	atmos	0	1	2	0	0	0	0	3
	arist&atmos	0	1	2	0	0	0	0	3
	arist	0	0	0	0	0	0	0	0
	No. of students	2	12	6	0	1	0	0	21

Table N3

Table 1. Evolution of students' conceptions in the Newton approach (n = 21).

		after joint session							
before joint session		GA	CBA	EA	A&atmos	atmos	arist&atmos	arist	No. of students
	GA	0	0	0	0	0	0	0	0
	CBA	1	14	0	0	0	0	0	15
	EA	3	33	9	4	11	0	0	60
	A&atmos	0	4	0	0	0	0	0	4
	atmos	0	2	0	2	2	0	0	6
	arist&atmos	0	4	0	0	2	0	0	6
	arist	1	4	1	1	4	0	0	11
	<i>No. of students</i>	5	61	10	7	19	0	0	102

Table E1

		after Einstein session							
before Einstein session		GA	CBA	EA	A&atmos	atmos	arist&atmos	arist	No. of students
	GA	1	3	1	0	0	0	0	5
	CBA	30	18	11	0	2	0	0	61
	EA	1	5	3	0	1	0	0	10
	A&atmos	0	4	2	0	1	0	0	7
	atmos	7	7	3	0	2	0	0	19
	arist&atmos	0	0	0	0	0	0	0	0
	arist	0	0	0	0	0	0	0	0
<i>No. of students</i>	39	37	20	0	6	0	0	102	

Table E2

		after both session							
before either session		GA	CBA	EA	A&atmos	atmos	arist&atmos	arist	No. of students
	GA	0	0	0	0	0	0	0	0
	CBA	13	2	0	0	0	0	0	15
	EA	23	24	11	0	2	0	0	60
	A&atmos	1	2	1	0	0	0	0	4
	atmos	0	2	2	0	2	0	0	6
	arist&atmos	1	3	2	0	0	0	0	6
	arist	1	4	4	0	2	0	0	11
<i>No. of students</i>	39	37	20	0	6	0	0	102	

Table E3

Table 2. Evolution of students' conceptions in the Einstein approach (n = 102).

Answers	Newton Approach	Einstein Approach
g = gram, or other entity (answer to the question "What does the symbol g stand for in the formula $W = mg$?")	25%	1.6%
g = local gravitational acceleration (answer to the question "What does the symbol g stand for in the formula $W = mg$?")	62%	86.6%
Local gravitational acceleration differs for different celestial bodies	21%	85%
Local gravitational acceleration changes with altitude	4%	43%
Explicit use of the space-time deformation theory	-	22%

Table 3. Comparison of the understanding of local gravitational acceleration at the end of the lesson based on the Newton ($n = 21$) or Einstein ($n = 102$) approach.

Newton Approach	Einstein Approach
Initial Test	
Joint Session	
<p>- <u>Initial test</u>: (1) What happens if a man drops a stone on earth? (2) On the moon? Why?</p> <p>- <u>Teacher-student discussion</u> of various hypotheses.</p> <p>- <u>Experiment</u>: A piece of chalk is dropped into a vacuum bell jar.</p> <p>- <u>Teacher-student discussion</u> of the phenomenon of falling bodies on the moon.</p> <p>- <u>Viewing of a video</u> showing men walking on the moon.</p> <p>- <u>Viewing of a video</u> showing "weightless" men in a spaceship.</p>	
Intermediate Test	
Newton Session	Einstein Session
<p>- <u>Presentation of the theory</u> of interacting bodies: bodies with a mass are attracted to each other. The force of attraction depends on the mass of the bodies and on the distance between them.</p> <p>- <u>Definition of weight</u> as a special case of FP/B, where B is a body and P is a planet. Force is measured in newtons.</p> <p>- <u>Introduction of the equation</u> $W = mg$, which relates weight to mass: g is the coefficient of proportionality between the weight and the mass; it is called local gravitational acceleration.</p>	<p>- <u>Test</u>: Why are bodies attracted to the earth and to the moon?</p> <p>- <u>Teacher-student discussion</u> of various hypotheses.</p> <p>- <u>Presentation of Einstein's theory using the pillow analogy</u>: matter deforms space-time. Conduct experiments (falling bodies, movement of the moon, black holes).</p> <p>- <u>Definition of g</u> as the local gravitational acceleration or tendency to "cause to fall" and study its qualitative variations: the greater the slope of the cavity, the more bodies tend to fall and the greater the value of g.</p> <p>- <u>Definition of weight</u> as equal to the force (in newtons) applied to the object in the cavity, which: -> depends on the slope of the cavity, g. -> depends on its own mass, m.</p>
Final Test	

Figure 1. Description of the Newton and Einstein teaching sequences proposed to ninth graders.

Explanatory Systems			
Initial Test	Attraction	Aristotle	Atmosphere
A man drops a stone on earth: What happens? Why?	The stone falls because of the earth's attraction	The stone falls because nothing holds it back	The stone falls because of the atmospheric pressure
A cosmonaut drops a stone on the moon: What happens? Why?	The stone falls because of the moon's attraction		The stone floats in the vacuum
	The stone and the cosmonaut float because there is no attraction		
Intermediate Test			
With a drawing showing the earth and the moon, the student is asked what happens for a body:			
- near the moon	The body is attracted by the moon		The body floats in the vacuum of the moon
- near the earth	The body is attracted by the moon		
- in space	The body is subjected to the attraction of the earth and moon		The body is no longer attracted because it has moved out of the atmosphere
- in a vacuum bell jar on earth	The body falls to the ground		The body floats in the vacuum
Final Test			
What happens if a cosmonaut takes off his boots on the moon?	The attraction is weaker on the moon than on earth		Since there is no atmosphere, so without gear, the cosmonaut floats
What does the g mean in the formula $W = mg$?	g represents the local gravitational acceleration		
A drawing of a rocket between the earth and the moon is shown. The rocket's reactor breaks down; it remains at the place shown in the drawing. Why is this possible only at this particular place?	The two forces of attraction, the earth's and the moon's, oppose each other and a state of equilibrium is reached		The rocket isn't attracted any more because it's outside the earth's atmosphere
	The rocket is in a state of equilibrium on the bump located between the two cavities formed by the earth and the moon		The rocket floats in the vacuum of space
	The rocket floats since it is too far from the earth and moon to feel their attraction		

Figure 2. Typical answers given to the characteristic questions on the three tests, listed by explanatory system used.

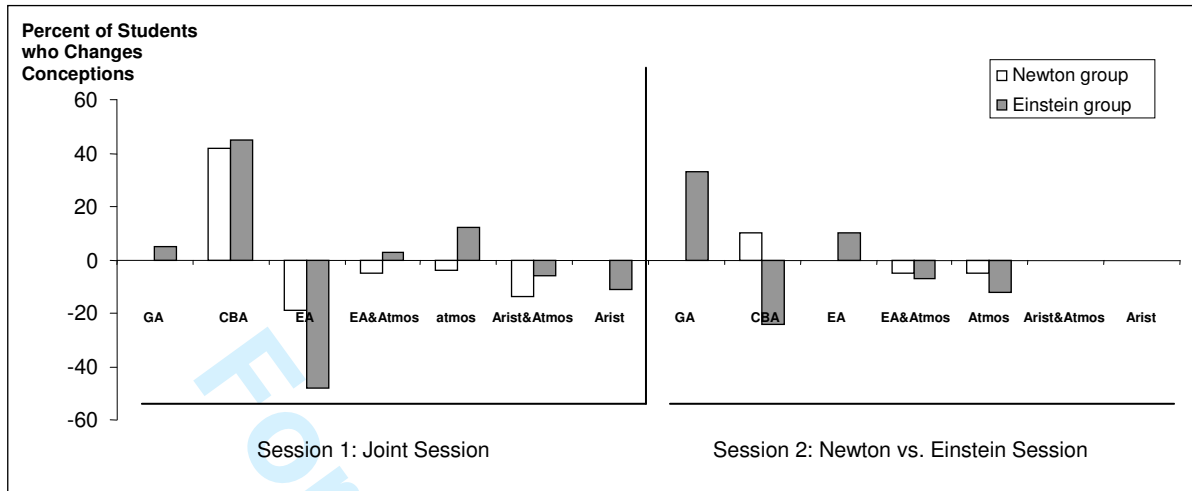


Figure 3. Comparison of the effects of the Newton and Einstein approaches, by session.

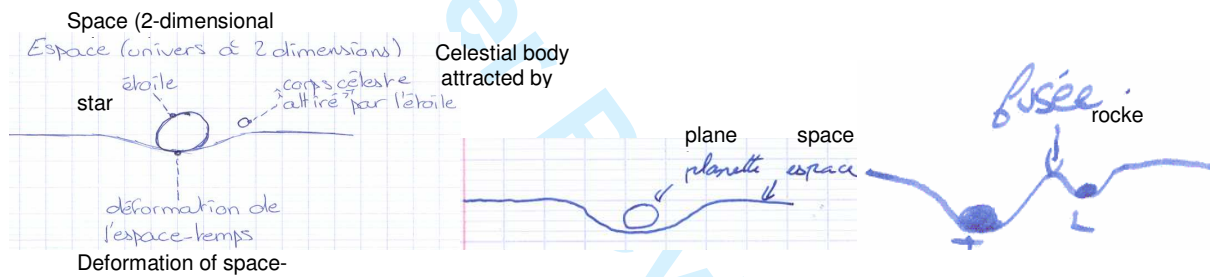


Figure 4. Examples of student drawings showing answers based on the deformation of space.

A New Educational Perspective for Teaching Gravity

Introduction

Research on teaching the phenomenon of falling bodies has generally revolved around students' conceptions before they are taught this lesson in school. These naive understandings are often shown to be erroneous. Bar, Zinn, and Rubin (1997) found that, for Israeli students ages 9 to 17 years, the source of the earth's attraction is often a magnetic force that requires a medium -- air -- to be propagated from the earth to the object. Watts (1982) showed that, for 12-year-old English students, gravity is "selective" in that it does not apply to bodies at rest or bodies thrown up into the air. Palmer (2001) found that 11- to 16-year-old Australian students think attraction is a phenomenon that only occurs on earth. On other celestial bodies, such as the moon, bodies do not to fall but float because they are in a vacuum, and the fact that bodies fall is often ascribed to the presence of the atmosphere. This author also noted that students' conceptions are highly resistant, changing little with age when conventional teaching methods are used.

The present article looks at how these initial conceptions evolve in French ninth graders (age 15) as they learn about this phenomenon in school. After a description of what is already known about such conceptions and about conceptual change in general, a few specific hypotheses will be set forth regarding ninth graders' conceptions of falling bodies and the potential evolution of those conceptions. Next, the current teaching approach and the problems it poses will be analyzed. Then a "new educational perspective" which takes students' initial conceptions and their evolution into account will be proposed. Finally, the effectiveness of two teaching approaches, one based on the current method and the other based on the new perspective will be compared.

The Research Literature: Conceptions and Conceptual Change

The notion of a "conception" has been in use for about thirty years in research on science teaching, and its definition changes as new studies are conducted. Conceptions are students' conceptual bases prior to teaching, or as Givry and Tiberghien (2005) called them, their "ideas". They serve as a frame of reference for understanding the world and acting within it. Watts (1982) contended that conceptions about a given knowledge domain are not isolated pieces of knowledge, but are combined into an overall structure with its own logic. Vosdianou (1994) added that conceptions are emergent parts of broader and more complex cognitive constructions, which she called "*presuppositions*" (p. 46) and diSessa (1988) called "*phenomenological primitives*" or "*p-prims*" (p. 4). According to Minstrell (1992) and Palmer (2001), conceptions have several facets that one might call "explanatory systems". Depending on the situation, one or another of the explanatory systems underlying a given conception is activated. Vosdianou (*ibid*) suggested that conceptions have a certain amount of "plasticity", which makes them virtually impossible to destroy but easier to change. Although, following Bachelard (1938), conceptions were long regarded as obstacles that had to be eliminated, they are seen today as modifiable. According to Vosdianou (*ibid*), conceptual change does not occur by way of a sudden shift from one theory to another, but through a continuous process that takes place gradually as already-constructed knowledge is reinterpreted. When a conceptual change occurs, one conception is not necessarily replaced by another; it can be the result of the greater use of a scientifically correct conception that makes sense to the student. Thus, along with Palmer (2001), Givry and Tiberghien (2005), and also Strike and Posner (1992), instead of directly attacking an erroneous explanatory system, one could attempt to reduce its use by increasing the domain of validity of a correct explanatory system already

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3 possessed. Givry and Tiberghien (*ibid*) suggested that extending the domain of validity of a
4 correct explanatory system is the most frequent road to conceptual change. Several studies
5 (e.g., Akerson, Flick, & Lederman, 2000; Justi, Souza, & Ferreira, 2005) have demonstrated
6 the effectiveness of using analogies to trigger this type of change. The analogy approach
7 implies pointing out the similarities between a situation that students understand and know
8 how to explain, and a new situation that resembles it. Students can then transfer what they
9 know to the new situation.
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22 In sum (1) conceptions are composed of several explanatory systems or facets, (2)
23 conceptions about a knowledge domain are linked into an overall system that has its own
24 logic, (3) conceptions are backed by deeper cognitive structures, (4) they exhibit a certain
25 degree of plasticity that promotes their evolution, and (5) conceptual change usually involves
26 the generalization of a valid explanatory system.
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36 The next section looks more specifically at students' conceptions about the physical
37 phenomenon of falling bodies.
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46 **Initial Conceptions of Falling Bodies**

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48 Past research on conceptions about falling bodies among 15-year-old students (Baldy &
49 Aubert, 2005) has shown that students at this age rely on several explanatory systems to
50 account for the phenomenon, depending on the place where it occurs. The explanation that
51 bodies fall due to attraction is reserved for events occurring on earth. On the moon or in
52 space, where there is no atmosphere, bodies float because they are in a vacuum. For students,
53 then, the phenomenon of falling, i.e., gravity, is not universal, and the earth is treated as a
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3 special case: it seems to occupy a privileged place that is not part of space. As soon as the
4 event no longer happens on earth, students have incorrect conceptions regarding both the facts
5 (bodies float or bodies fall) and the explanations given of them (attraction, atmosphere, etc.).
6
7 Vosdianou (1994) showed that until the end of elementary school, Greek pupils do not see the
8 earth as a planet, but as a physical body that obeys laws of its own, and Baldy and Aubert
9 (*ibid.*) found that such a distinction still exists in 15-year-old students. This "*presupposition*"
10 -- in Vosdianou's (*ibid.*) sense of the term -- is comparable to an idea that was shared by many
11 scholars up through the Middle Ages, namely, that the earth is separate from "the heavens". In
12 fact, it was Galileo who first considered terrestrial and celestial phenomena in the same way.
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27 These observations suggest that one way to enable students' conceptions about falling bodies
28 to evolve would be to try to eliminate the distinction between phenomena on earth and
29 phenomena at other locations in the universe. In other words, students should be led to
30 generalize the physical event "bodies fall", and the correct explanatory system "bodies fall
31 because of attraction", to all places in the universe. Gravity must become a universal
32 phenomenon.
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45 46 **The Current Educational Approach to Teaching Gravity**

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48 Knowledge taught in school is never an exact copy of scholarly knowledge as it is elaborated
49 by the scientific community. Due to its complexity, the latter type of knowledge is usually
50 inaccessible to students. To become teachable it must be transformed, and this requires
51 making choices. In 1993, the school curricula in France (and in most other countries)
52 recommended using Newton's theory of the interaction of bodies at a distance to teach
53 students the connection between the earth's attraction and weight. In this theory, all bodies
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3 that have a mass are attracted to each other, and the attraction between bodies is proportional
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5 to their mass and inversely proportional to the square of the distance between them. This
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7 theory is based on the concept of force, defined as an action exerted on an object. It is
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9 introduced in ninth grade, right before students are taught the concept of weight.
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15 In practice, this approach has proven unsatisfactory. It raises a large number of questions
16
17 about the nature of the force exerted by the earth on falling bodies. Student do not understand
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19 this force -- is it magnetic, is it magic, ...? Why do we say that bodies are attracted to each
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21 other when everyday experience shows that they do not spontaneously start moving toward
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23 each other? Newton himself was unable to explain what he called the "force of the earth's
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25 attraction" and gave it a divine origin.
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32 Note that in the course of history, theories have not been adopted by the sheer strength of their
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34 arguments. The same holds true of learning in class; students do not adhere to a theory simply
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36 because they are told to do so. According to Posner, Strike, Hewson, and Gertzog (1982), a
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38 new theory must meet several conditions to be accepted by students: it must be
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40 understandable, plausible, and effective for solving problems. The theory of bodies interacting
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42 at a distance does not fulfill these conditions: students do not understand the nature of matter's
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44 mysterious force of attraction, and they have trouble believing the theory because their
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46 everyday experience seems to contradict it (bodies do not move toward each other).
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53 Newton's theory was taken out of the French curriculum in 1998, but the new teaching
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55 approach omits the physical side of the phenomenon and considers only its mathematical side.
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57 The concept of weight is not explained but is simply defined as a force due to the attraction of
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59 the earth (or the moon). The lessons focus solely on the mathematical calculation of this force,
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3 using the formula $W = mg$ (where W stands for weight, m for mass, and g for local
4 gravitational acceleration). Once teachers have introduced this formula, they tend to assume
5 that their students are capable of manipulating it correctly, and of understanding the physical
6 phenomenon it represents. Unfortunately, this is far from being the case. Presented as such,
7 the formula is not connected to the conceptual field of the physical phenomenon of bodies
8 falling, nor to the mathematical knowledge needed to use it. Students do not relate this new
9 knowledge ($W = mg$) to the old knowledge they already possess (correct, incorrect, or perhaps
10 even contradictory). Some students are capable of learning the formula, remembering it, and
11 reciting it, but without understanding the concepts or physical phenomenon it models.
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27 Neither of these approaches takes students' prior knowledge into account, nor the results of
28 research on how student conceptions change. They propose a teaching method derived from a
29 theory that is four centuries old and is clearly outdated. Both our scholarly knowledge of
30 physical phenomena, and our understanding of the cognitive functioning of students, have
31 evolved. Hence, teaching methods should do likewise, not only for this subject but for all
32 disciplines taught in school. In biology, for example, the fast pace of recent discoveries in
33 genetics calls for regular updating of teaching programs. What about new perspectives for
34 teaching physics?
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51 **A New Educational Perspective for Teaching Gravity**

52 The new approach to teaching gravity proposed here attempts to update both the knowledge
53 taught and the method of teaching it. Regarding the knowledge itself, an "analogical" version
54 of Einstein's theory is presented, with explanations of the phenomenon of falling bodies based
55 on the time-space topology that follows from the general theory of relativity. Recall that
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3 Newton devised this theory in the 17th century, i.e., about three centuries before Einstein.
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5 Today, Einstein's more recent theory is acknowledged by the scientific community as a good
6
7 approach for explaining the phenomenon of gravity. France's popular science magazines for
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9 youth have presented it several times and consider it to be accessible to adolescents (*Sciences*
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11 & *Vie Junior*, No. 140 May 2001, No. 171 December 2003, and Special Issue No. 59 January
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13 2005). Yet current teaching curricula do not include an introduction of Einstein's theory -- not
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15 even a simplified one -- to explain the concept of gravity and weight, probably because
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17 experts deem it to be too complex. Yet, as Galili (2005) suggested, the "too-complex" view of
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19 modern physics deprives us of a good opportunity for helping students obtain a clearer
20
21 understanding of the concepts of gravity and weight. According to this author, the failures
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23 noted with current methods of teaching gravity should prompt teachers to change strategies
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25 *"though based on ideas of modern physics, the material is far from being too formally*
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27 *complex for the average student"* (p. 1081).
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35 Einstein's theory offers some answers to the didactic issues and contradictions that the
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37 interacting-bodies theory does not resolve. For example, it gets rid of the problem of force at a
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39 distance, which according to Vosdianou (1994) and Bar, Zinn, and Rubin (1997), ninth
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41 graders do not understand. Einstein's theory gives a geometric explanation of falling bodies
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43 without relying on the force of attraction. Hopefully, students will be able to see that bodies
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45 do not possess some mysterious property of attraction but "simply" have the effect of
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47 "deforming" the space-time that surrounds them, and that this deformation changes their
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49 trajectory as they pass near each other. While it appears as though bodies are mutually
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51 attracted to each other, they in fact merely continue along their path in a deformed space-time,
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53 under the effect of inertia.
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3 In the new approach used in this study, Einstein's theory is introduced to students via the so-
4 called "pillow" model: the pillow represents space, and steel balls of different sizes and
5 masses are used to represent celestial bodies. When a marble representing a body is placed
6 next to a ball, it falls into the dip in the pillow created by the ball. And if the marble is rolled
7 fast enough, it deviates from its normal trajectory in the vicinity of the ball. Whenever two
8 balls on the pillow are close enough to each other, the area between them is deformed by each
9 one. Clearly, the deformation of space-time is not confined to a deformation of space. But this
10 analogy was chosen for introducing the theory here because this is how Einstein himself
11 described his theory when addressing an audience of non-specialists. This is also the way it is
12 found in all physics textbooks and scientific and lay journals, including the ones mentioned
13 above. Furthermore, studies by Brown (1992), Akerson, Flick, and Lederman (2000), Duit
14 and Treagust (2003), and Justi, Souza, and Ferreira (2005) have all shown that conceptual
15 change in students takes place more readily when the teaching method is based on an analogy.
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36 In our earlier work (Baldy & Aubert, 2005), we noted that students often confused the g of
37 local gravitational acceleration with the g of gram. In traditional curricula, the concept of
38 local gravitational acceleration (along with its symbol " g ") is introduced and defined as the
39 coefficient of proportionality between weight and mass. Local gravitational acceleration has
40 no physical existence in this case. In the transposition of Einstein's theory proposed here, the
41 relation between the weight of a body, its mass, and local gravitational acceleration in a given
42 location, along with the corresponding physical phenomenon, are simultaneously addressed
43 and explained via the pillow analogy. This model gives a concrete and intuitive dimension to
44 gravitational acceleration. The weight of a body is said to depend on its mass and on the slope
45 of the cavity where the body is located. The notion of local gravitational acceleration is
46 characterized in terms of the slope. Near the ball, where the slope is the steepest, the
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3 gravitational acceleration is greater than farther away from the center of the cavity. With this
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5 image-based presentation, local gravitational acceleration "g" has a physical definition that is
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7 easier for students to understand.
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12 We know that some students separate those phenomena that take place on earth from those
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14 that occur in space, as if the earth were a special body that isn't really part of space. In fact,
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16 students' initial conceptions about what happens on earth are often correct -- bodies fall
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18 because of the earth's attraction -- while being incorrect for the rest of the universe. In the
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20 analogy used here, all bodies are represented by balls of variable size and mass that create
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22 cavities in the pillow. The falling of a body is due to the slope of the cavity, and all bodies
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24 make slopes that extend far beyond their centers. The fact of having every ball act in the same
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26 manner, no matter where it is located on the pillow, should help students generalize the
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28 phenomenon of gravity to all points in space (whether near to or far from a celestial body).
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30 Generalization of this phenomenon should lead to less diversity in the explanatory systems
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32 and thereby enable students to see gravity as a universal phenomenon.
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41 The aims of the present study were to test the effectiveness of this "new educational
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43 perspective" with respect to (1) how students' conceptions evolve and (2) how well students
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45 understand *g*. Einstein's theory answers the question of why bodies are attracted to each other.
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47 It must therefore be introduced after students are taught the notion that bodies fall because
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49 they are attracted by a celestial body. For students who think that bodies float in a vacuum,
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51 this theory shows that the only determining factor in whether a body will fall is the presence
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53 or absence of mass.
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Effectiveness of the New Perspective

Method and Sample

The effectiveness of our new approach based on Einstein's theory of space-time deformation was tested on 102 ninth graders who were compared to a control class of 21 ninth graders being taught via Newton's theory (bodies interacting at a distance). In both approaches, the lessons were always given in the classroom by the same teacher, with the experimenter present. The participating students were selected from the same junior high school so as to reduce potential effects of the teacher or social class. Any performance differences across approaches could thus be ascribed to differences in the effectiveness of the teaching approaches. Given their age (15), the students who participated in this experiment had already acquired the concept of weight and its conservation (Piaget, 1972; Galili & Bar, 1997).

The first session in both approaches (described in Figure 1) was a joint session aimed at helping students see that bodies fall on earth and on the moon because of the attraction of celestial bodies and not the atmosphere. Our working hypothesis here was that grasping this notion is a prerequisite to understanding each of the two theories proposed in the next session. For the second session of the Newton approach, Newton's theory of the interaction between bodies was presented; for the second session of the Einstein approach, the theory of space-time deformation was presented.

Insert Figure 1 here

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3 The evolution of each individual student's conceptions about falling bodies was assessed three
4 times during the sequence, via three tests: initial test, intermediate test (between the two
5 sessions), and final test. After the entire sequence, their understanding of the concept of local
6 gravitational acceleration and its variations (final test) was analyzed. Each test consisted of
7 five or six short-answer questions, sometimes accompanied by drawings (planets, a rocket,
8 etc.). In illustration, the first column of Figure 2 presents the most characteristic questions.
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Insert Figure 2 here

34 **Results**

35 *Coding the Responses*

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37 The students' conceptions were inferred from their answers on the three tests (initial,
38 intermediate, and final). The questions asked covered three areas: interplanetary space, the
39 moon, and the earth. Figure 2 above lists the most typical answers given to the characteristic
40 questions, for each type of explanatory system.
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51 A complete analysis of the students' responses showed that they considered two events:
52 bodies floating and bodies falling. They relied on three explanatory systems to account for
53 why bodies fall: the presence of an atmosphere, the presence of an attraction, and the fact that
54 they return to their place of origin (Aristotelian explanation). The following seven
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3 conceptions were inferred from the students' test answers, in decreasing order of correctness
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6 (from the most complete and most correct, to the most incorrect).
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8 1. Generalized attraction (GA): there is attraction on earth and on the moon,
9 and more generally at any point in space.
10

11 2. Celestial body attraction (CBA): objects fall down on earth and on the moon
12 because they are attracted by the celestial body.
13

14 3. Earth's attraction only (EA): attraction is a phenomenon that takes place only
15 on earth.
16

17 4. Attraction on the earth and atmosphere on the moon (EA&Atmos): two
18 explanatory systems are used, one for the earth and one for the moon. On earth,
19 falling is due to the earth's attraction, whereas on the moon, objects float
20 because there is no air.
21

22 5. Atmosphere (Atmos): falling is due to the atmosphere.
23

24 6. Aristotelian explanation on earth and atmosphere on the moon
25 (Arist&Atmos): two explanatory systems are used, one for the earth and one
26 for the moon. On earth, objects fall to return to the ground, their original place.
27 On the moon, objects float because there is no atmosphere.
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29 7. Aristotle (Arist): the Aristotelian conception of falling applies on both the
30 earth and the moon.
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51 The first three conceptions are correct from the standpoint of the reason why bodies fall
52 (attraction), but for CBA, the students think that the attraction of a celestial body is present
53 only near its surface, and for EA they think the earth is the only celestial body that attracts.
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58 The fourth conception, AE&Atmos, is correct for the earth but incorrect for the moon. The
59
60 last three conceptions are based on incorrect explanatory systems regarding why bodies fall.

Note that GA, CBA, EA, Atmos and Arist are homogeneous, i.e., students use the same explanatory system no matter what place is at stake. AE&Atmos and Arist&Atmos are mixed conceptions, in that students rely on different explanatory systems for different places.

Results of the Control Classes Taught Using the Newton Approach

Table 1 presents the evolution of the conceptions of students taught using the Newton approach. The upper panel of the table (N1) shows how the conceptions evolved during the first session (joint session for both teaching approaches); the middle panel (N2) shows how they evolved during the second session (Newton); and the lower panel (N3), how they evolved for the entire Newton sequence.

Insert Table 1 here

We can see in the upper panel (N1) that the most common conception before the lesson was EA (n = 10), and that the conceptions of 13 students out of 21 improved (below the diagonal). The most frequent change (n = 8) was the shift from conception EA (only the earth attracts) to conception CBA (there is attraction on earth and on the moon). However, the improvement was never great enough to attain the correct conception, GA (bodies are attracted to all celestial bodies around them, at all points in space). At the end of the first session, the most common conception was CBA (n = 10). The middle panel (N2) indicates that the students' conceptions evolved little during the second session: 19 students out of 21 were still on the diagonal. Only two students progressed to conception CBA. For the Newton approach as a whole (lower panel, N3), the conceptions of 16 students had improved, but almost entirely

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3 due to the effect of the joint session. At the end of the whole sequence, half of the class (12
4
5 students) had conception CBA. Only those students who had the most comprehensive
6
7 conception (GA) before the lesson still had it afterwards, with no other students managing to
8
9 reach this level. Moreover, we can see that the students' responses no longer involved several
10
11 explanatory systems (AE&Atmos and Arist&Atmos).
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15 16 17 *Results of Classes Taught Using the New Einstein Approach*

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19 Table 2 presents the evolution of the conceptions of students taught using the Einstein
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21 approach. In the table, E1 shows how the conceptions evolved during the joint session
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23 (students from both approaches), E2 how they evolved during the second session, and E3 how
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25 they evolved for the entire Einstein sequence.
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34 Insert Table 2 here
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41 We can see in the upper panel (E1) that the most common conception before the lesson was
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43 EA (n = 10). The conceptions of 62 students improved (below the diagonal). The most
44
45 frequent progress (n = 33) was the shift from conception EA to conception CBA. Five
46
47 students attained the most comprehensive conception (GA). The most common conception at
48
49 the end of the first session was CBA (n = 41). The middle panel (E2) indicates that the
50
51 conceptions of 59 students improved. The most frequent progression (n = 30) was the shift
52
53 from conception CBA to conception GA, generalized attraction: bodies located at all points in
54
55 space fall toward surrounding celestial bodies. For the Einstein approach as a whole (lower
56
57 panel, E3), the conceptions of 85 students improved. The two most common conceptions were
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3 GA (39 students, although this conception had not been found for any of the students before
4 the lesson) and CBA (37 students). Note that the majority of the students who, before the
5 lesson, had the most incorrect conceptions (derived from an Aristotelian and/or atmosphere-
6 based explanatory system) did not achieve the most general conception and remained "stuck"
7 on a conception of attraction near the earth only, or near the earth and the moon.
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17 *Comparing the Results of the Newton and Einstein Groups*

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19 Given that the aim of this study was to evaluate the effectiveness of the new educational
20 perspective, the changes in the conceptions of students taught with this new approach were
21 compared to those of students in a control group taught using the more-traditional Newton
22 approach. Let us first analyze the evolution of students' conceptions about falling bodies,
23 before we look at the students' understanding of the concept of local gravitational acceleration
24 after the lesson.
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36 *Evolution of Conceptions*

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38 As indicated in the rightmost column of panels N1 and E1 (Tables 1 and 2), the frequencies of
39 the various conceptions before the lesson were comparable for the two groups (conception EA
40 was the most prevalent). Figure 3 presents the evolution of each conception during the two
41 teaching sessions in each approach (Newton and Einstein). A positive change means that the
42 prevalence of the corresponding conception increased; a negative change, that it decreased.
43
44 We can see that the two groups evolved in a comparable way during the first session (joint),
45 with a substantial increase in conception CBA to the detriment of conception EA, which
46 became less prevalent. By contrast, during the second session (Newton or Einstein), the
47 evolution was different. Almost no progress was noted for the Newton group, whereas for the
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3 Einstein group, the prevalence of conception GA rose considerably (+38%) to the detriment
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5 of conception CBA.
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12 Insert Figure 3 here
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20 *Understanding of Local Gravitational Acceleration After Teaching with the Newton and*
21 *Einstein Approaches*
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24 Before the lesson, the students knew nothing about the concept of local gravitational
25 acceleration. Let us compare the two groups' grasp of g after the lesson. Table 3 describes the
26 understanding of the concept of local gravitational acceleration and its variations for students
27 taught using each of the two approaches. We can see that fewer students taught by the new
28 Einstein approach confused the g of gram and the g of local gravitational acceleration. On the
29 other hand, more of them explained variations of g in terms of a celestial body or the altitude.
30 Also, more than 22% of these students explicitly used the theory of space-time deformation to
31 answer the questions (Figure 4).
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Insert Table 3 here

Insert Figure 4 here

Discussion

The purpose of the present study was to describe students' initial conceptions about the phenomenon of falling bodies, and to compare how these conceptions evolved during a lesson taught using two different teaching methods. Let us first analyze the students' initial conceptions and then discuss the relative effectiveness of the new educational perspective. Next, we will examine the way these conceptions evolved and discuss the reasons why the Einstein approach promoted conceptual change.

Initial Conceptions

The most common conception before the lesson was EA (bodies fall because they are attracted but the attraction occurs only on earth). As in the history of the sciences, the students separated the earth from the rest of space, granting it a special place in the universe. In this view, physical phenomena are not the same on earth as elsewhere in space. It is possible that the centrality of the earth's position in the students' minds is a reflection of a form of egocentrism on their part. Like Galili and Bar (1997), who noted that students defined the weight of an object in terms of their own sensations, our students defined gravity with respect

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3 to themselves and to their own experience. This location-specific separation of phenomena led
4
5 to mixed conceptions combining several explanatory systems. On this point, our results are in
6
7 line with previous research (Baldy & Aubert, 2005; Palmer, 2001; Graham & Berry, 1997;
8
9 Bar, Zinn, & Rubin, 1997; Watts, 1982).
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12 13 14 15 *Comparative Effectiveness of the Two Approaches*

16
17 For the control-class students taught by the Newton approach, most of the conceptions
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19 remained "stuck" on the idea that bodies fall due to attraction but only in the vicinity of a
20
21 celestial body. This conception is correct but its field of applicability is limited. During the
22
23 joint session, the videotape study of bodies falling on earth and on the moon enabled these
24
25 students to see that bodies fall due to the existence of an attraction toward the earth or the
26
27 moon, but it did not allow them to generalize this explanation to all of space. During the
28
29 second session, the study of the theory of bodies interacting at a distance did not lead to
30
31 conceptual change. As Table 1 shows, the Newton session did not allow students who had not
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33 yet reached the CBA conception to move up to it; nor did it allow those who had attained that
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35 level to go beyond it. Thus, from the standpoint of changes in the students' conceptions about
36
37 the physical phenomenon of falling bodies, this session was highly ineffective. This
38
39 observation provides an experimental confirmation of the failure reported regularly by
40
41 teachers in the classroom. Because students do not understand the physical nature of
42
43 attraction, they are unable to see gravity as a universal phenomenon. It seems that only a
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45 rational, meaningful explanation can trigger the generalization of the existing explanatory
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47 system, until then confined to phenomena occurring in the vicinity of a celestial body.
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57 For the students taught by the Einstein approach, the initial conceptions and their evolution
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59 during the joint session were comparable to those of the Newton group. On the other hand,
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3 after the Einstein session, 38% of these students had moved up to conception GA, wherein
4 attraction by surrounding celestial bodies applies to all points in space. Our working
5 hypothesis was that conception CBA (attraction in the vicinity of a celestial body) would be a
6 prerequisite to understanding the space-time deformation theory introduced in the next
7 session. Indeed, 30 of the 39 students who shifted to GA already had conception CBA before
8 the session. The Einstein approach helped a much greater number of students to generalize the
9 attraction-based explanation of falling bodies to the entire universe. With respect to this goal,
10 then, the Einstein approach was more effective than the Newton approach. It also led to better
11 knowledge of local gravitational acceleration, its symbol g , and its variations (Table 3). The
12 Einstein approach met the two educational objectives set here, conceptual change and an
13 understanding of g .

31 *How the Students' Conceptions Evolved*

32
33 Our study pointed out two kinds of non-mutually-exclusive conceptual change. The first was
34 "positive substitution" or the change from an incorrect explanatory system (e.g., bodies fall
35 due to the atmosphere) to a correct system, but possibly with a limited domain of validity; the
36 second (already noted by several authors: Strike & Posner, 1992; Givry & Tiberghien, 2005)
37 was "generalization", which consisted of expanding the domain of validity of a correct
38 explanatory system (e.g., the phenomenon of bodies falling due to attraction is no longer
39 confined to the earth but becomes valid for all celestial bodies or throughout the universe).
40 Triggering the first type of change was the goal of the joint session. The upper panels of
41 Tables 1 and 2 (N1 and E1) show that the most frequent conceptual change during this first
42 session was in fact the shift to conception CBA. The Aristotelian or atmosphere-based
43 explanatory systems were much less frequent after this session than before it. Most of the
44 students arrived at an attraction-based understanding of falling bodies for phenomena

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3 occurring on celestial bodies. Triggering the second type of evolution was the goal of the
4
5 second session. As shown above in the analysis of the effectiveness of the two approaches,
6
7 this goal was not attained with the Newton approach: the students' conceptions were about the
8
9 same before and after the second session. By contrast, with the Einstein approach, the goal
10
11 was at least partially attained: the most frequent conceptual change during this session was the
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13 shift from CBA to GA (E2 in Table 2). These students generalized their attraction-based
14
15 conception to all points in the universe.
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22 The mixed conceptions detected initially (e.g., AE&Atmos), which had several active facets
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24 (Minstrell, 1992; Palmer, 2001), were necessarily based on at least one erroneous explanatory
25
26 system. The first session triggered a positive-substitution type of change that (temporarily or
27
28 definitively?) eliminated the erroneous explanatory system, or at least decreased its
29
30 prevalence. This led to greater conceptual uniformity among the students. The next step was
31
32 to prompt the expansion of this locally-correct explanatory system. At the end of the second
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34 session in the Einstein approach, the correct explanatory system "bodies fall due to attraction"
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36 had in fact been changed to "attraction exists at all points in space", via an extension of its
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38 domain of validity.
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45 We can see in Figure 5 that this conceptual change took place in three stages. At first,
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47 attraction pertained solely to the earth, which was a special case. Then it was generalized to
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49 the moon, and finally, to all points in the universe.
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Insert Figure 5 here

It is important to note that this conceptual change involved more than simply extending the explanatory system's domain of validity. The generalization of attraction was accompanied by a restructuring of more general "presuppositions" (Vosdianou, 1994) or "p-prims" (diSessa, 1988) underlying the conception of falling bodies. In the case of conception EA -- attraction phenomena occur only on earth -- attraction was usually attributed to a force coming from the earth's core, whereas in conception GA -- bodies are attracted at all points in space due to the presence of surrounding celestial bodies -- attraction was no longer "directly" provoked by the celestial body but was due to the deformation that celestial bodies cause in space, which in turn causes other bodies to move toward them. In their answers to the question *Why do planets attract bodies?*, the deep meaning of the term "attraction" underlying the falling-body concept evolved to the point where certain students became aware of its unsuitability. Indeed, we can see that half of the students who had the most general conception (Table 3) relied on the idea of space-time deformation in explaining falling bodies in space, either in their verbal description or in their drawings.

Why Was the New Educational Perspective More Effective?

Several reasons for the greater effectiveness of the Einstein approach can be given with respect to the two points tackled here -- generalization of attraction, and knowledge of g -- and they validate our hypotheses. It was hypothesized that the mysteriousness surrounding the notion described in Newton's theory -- that there is a force of interaction between bodies at a

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3 distance -- is what prevents students from understanding that bodies made of "normal" matter,
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5 i.e., neither magnetic nor "magical", are attracted to each other. Einstein's theory and its
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7 presentation by way of a spatial analogy provided an explanation of the source of the falling
8
9 without calling upon any intrinsic force of matter. Bodies fall due to the space-time
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11 deformation produced by the great mass of celestial bodies. When steel balls of different sizes
12
13 and masses that caused cavities in the pillow were used to represent celestial bodies, the
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15 students were led to consider all celestial bodies from the same angle. Because a ball that
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17 created a dip in the pillow could represent the earth as well as the moon, there was no reason
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19 to distinguish the earth from other celestial bodies. This analogy also showed that a ball
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21 placed on the pillow produced a deformation covering a large distance that extended beyond
22
23 the area close to the ball. The elements "perceived" on the pillow model enabled students to
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25 extend the effect of attraction to points located far away from a celestial body.
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34 The spatial analogy also provided a "visual rendition" of local gravitational acceleration, and
35
36 its variations and their causes. There is a relationship between the slope of the cavity and the
37
38 mass of the ball representing the celestial body. When g is said to be this slope, students can
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40 make the connection between the value of g and the mass of the ball. In this approach, the
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42 concept of local gravitational acceleration is not introduced, *a posteriori*, as the coefficient of
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44 proportionality between the weight and the mass, as it is in the Newton approach. The concept
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46 is presented relative to a physical phenomenon; it has a physical dimension (each point in
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48 space has a characteristic local gravitational acceleration), a source (the deformation caused
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50 by the mass of the celestial body), and an impact (the greater it is, the more the body will tend
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52 to fall toward the celestial body).
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Conclusion

The results of this study confirm the relative ineffectiveness of teaching the concept of falling bodies using Newton's theory. At the same time, they point out the merits of the new educational perspective based on Einstein's theory. The success of the new perspective can be regarded as a double validation: it validates the teaching approach (the new perspective enabled students to make more progress than the old one) and it validates the psychological model of students' conceptions and their evolution in terms of the generalization of a correct initial explanatory system (Strike & Posner, 1992; Palmer, 2001; Givry & Tiberghien, 2005). The effectiveness of the Einstein approach can be seen as a testimony to a correspondence between the logic underlying this teaching approach and the psychological process of learning: substituting a correct conception for an incorrect one, if necessary, and then extending it to a broader domain.

The originality of this study lies in its in-depth approach to analyzing conceptual change. Firstly, our analysis distinguished two non-mutually-exclusive phases called "positive substitution" and "generalization", and secondly, it showed that the generalization process can induce a deeper level of conceptual change, i.e., the level that affects what Vosdianou (1994) called "*presuppositions*" and what diSessa (1988) called "*p-prims*". In our case, the new teaching approach led some students to attribute a new meaning to the concept of attraction: attraction became an effect of a property of space, not a property of bodies. In turn, this new meaning initiated a revised view of space and phenomena occurring in it (falling bodies, movement of celestial bodies, etc.). Understanding that the mass of celestial bodies deforms space-time can be regarded as constituting an entry into the "proximal zone of development"

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3 (Vygotsky, 1986) characteristic of the cognition of 15-year-old students. The students could
4
5 assimilate the spatial and conceptual relations found in the space-time deformation theory,
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8 and this assimilation process induced a restructuring of their knowledge to achieve a better fit
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10 with the knowledge of science. The use of Einstein's theory of the deformation of space-time
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12 by matter enabled some students (nearly 40%) to gain an overall understanding of why bodies
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14 fall, and to grasp the phenomenon of gravity in general and the meaning of g . These students
15
16 became capable of (qualitatively) solving more complex problems. Above all, they began to
17
18 understand how our universe works, and why, for example, the moon rotates around the earth
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20 without ever falling down. However, not all of the students tested here were able to make this
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22 progress. At the end of the lesson, 36% of them still confined the phenomenon of attraction to
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24 the vicinity of a celestial body, and another 20% thought it only occurred on earth. It is
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26 evident that, like any other physical concept, this particular theory could not be fully
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28 understood by every student after a mere two sessions, but this new perspective seems to take
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30 a first step toward accomplishing this lengthy learning process.
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39 The new meaning of the term "attraction" generated a vocabulary problem here. This term
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41 from classical physics continued to be used, even though it no longer meant the same thing.
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43 The students' drawings of the deformation of space-time in their answers to the test exercises
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45 (Figure 4) showed that they no longer attributed the movement of bodies to a magical force
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47 possessed by matter. A body is not really attracted "by" the earth, but moves "toward" it
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49 because of the space-time deformation the earth provokes. Despite this fact, both the teacher
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51 and the students often employed the term "attraction" to refer to the movement of bodies. It
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53 would seem that it is even more difficult to change people's usage of vocabulary words than it
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55 is to change their conceptions. Don't we all still say that the sun rises and sets, even though it
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57 has been known for more than five centuries that the earth turns, not the sun?
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3 Certain students in this study asked why a body moves in space. In the case of our analogy, if
4 the marble falls into the dip in the pillow formed by the ball, it is especially because of the
5 "earth's attraction", which we cannot escape. In the case of real space, couldn't a body on a
6 slope remain stationary? The teaching process carried out here required answering a series of
7 *Why's: Why do bodies fall?* (because they are attracted to each other), *Why are they attracted*
8 *to each other?* (because they deform space), *Why ...?* and so on. This last question can only be
9 answered by referring to the principle of inertia, which ninth graders have not yet learned.
10 Inertia is not introduced in France until tenth grade, when it is presented in the classical
11 manner: a body subjected to no forces is at rest or follows a rectilinear trajectory at a constant
12 speed. This statement is invalid in a modern conception of mechanics, where the notions of
13 force and rectilinear trajectory no longer exist. The principle of inertia should be stated
14 differently: a body traveling on its own follows the geodesic on which it is located. Or more
15 simply, it continues along its "path"; if that path turns, it turns too. These observations suggest
16 that an understanding of Einstein's theory of space-time deformation should be accompanied
17 by a general overhaul of the methods used to teach mechanics, as also proposed by Galili
18 (2001).

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Newton Approach	Einstein Approach
Initial Test	
Joint Session	
<p>- <u>Initial test</u>: (1) What happens if a man drops a stone on earth? (2) On the moon? Why?</p> <p>- <u>Teacher-student discussion</u> of various hypotheses.</p> <p>- <u>Experiment</u>: A piece of chalk is dropped into a vacuum bell jar.</p> <p>- <u>Teacher-student discussion</u> of the phenomenon of falling bodies on the moon.</p> <p>- <u>Viewing of a video</u> showing men walking on the moon.</p> <p>- <u>Viewing of a video</u> showing "weightless" men in a spaceship.</p>	
Intermediate Test	
<p style="text-align: center;">Newton Session</p> <p>- <u>Presentation of the theory</u> of interacting bodies: bodies with a mass are attracted to each other. The force of attraction depends on the mass of the bodies and on the distance between them.</p> <p>- <u>Definition of weight</u> as a special case of FP/B, where B is a body and P is a planet. Force is measured in newtons.</p> <p>- <u>Introduction of the equation</u> $W = mg$, which relates weight to mass: g is the coefficient of proportionality between the weight and the mass; it is called local gravitational acceleration.</p>	<p style="text-align: center;">Einstein Session</p> <p>- <u>Test</u>: Why are bodies attracted to the earth and to the moon?</p> <p>- <u>Teacher-student discussion</u> of various hypotheses.</p> <p>- <u>Presentation of Einstein's theory using the pillow analogy</u>: matter deforms space-time. Conduct experiments (falling bodies, movement of the moon, black holes).</p> <p>- <u>Definition of g</u> as the local gravitational acceleration or tendency to "cause to fall" and study its qualitative variations: the greater the slope of the cavity, the more bodies tend to fall and the greater the value of g.</p> <p>- <u>Definition of weight</u> as equal to the force (in newtons) applied to the object in the cavity, which: -> depends on the slope of the cavity, g. -> depends on its own mass, m.</p>
Final Test	

Figure 1. Description of the Newton and Einstein teaching sequences proposed to ninth graders.

Explanatory Systems			
Initial Test	Attraction	Aristotle	Atmosphere
A man drops a stone on earth: What happens? Why?	The stone falls because of the earth's attraction	The stone falls because nothing holds it back	The stone falls because of the atmospheric pressure
A cosmonaut drops a stone on the moon: What happens? Why?	The stone falls because of the moon's attraction		
	The stone and the cosmonaut float because there is no attraction		The stone floats in the vacuum
Intermediate Test			
With a drawing showing the earth and the moon, the student is asked what happens for a body:			
- near the moon	The body is attracted by the moon		The body floats in the vacuum of the moon
- near the earth	The body is attracted by the moon		
- in space	The body is subjected to the attraction of the earth and moon		The body is no longer attracted because it has moved out of the atmosphere
- in a vacuum bell jar on earth	The body falls to the ground		The body floats in the vacuum
Final Test			
What happens if a cosmonaut takes off his boots on the moon?	The attraction is weaker on the moon than on earth		Since there is no atmosphere, so without gear, the cosmonaut floats
What does the g mean in the formula $W = mg$?	g represents the local gravitational acceleration		
A drawing of a rocket between the earth and the moon is shown. The rocket's reactor breaks down; it remains at the place shown in the drawing. Why is this possible only at this particular place?	The two forces of attraction, the earth's and the moon's, oppose each other and a state of equilibrium is reached		The rocket isn't attracted any more because it's outside the earth's atmosphere
	The rocket is in a state of equilibrium on the bump located between the two cavities formed by the earth and the moon		The rocket floats in the vacuum of space
	The rocket floats since it is too far from the earth and moon to feel their attraction		

Figure 2. Typical answers given to the characteristic questions on the three tests, listed by explanatory system used.

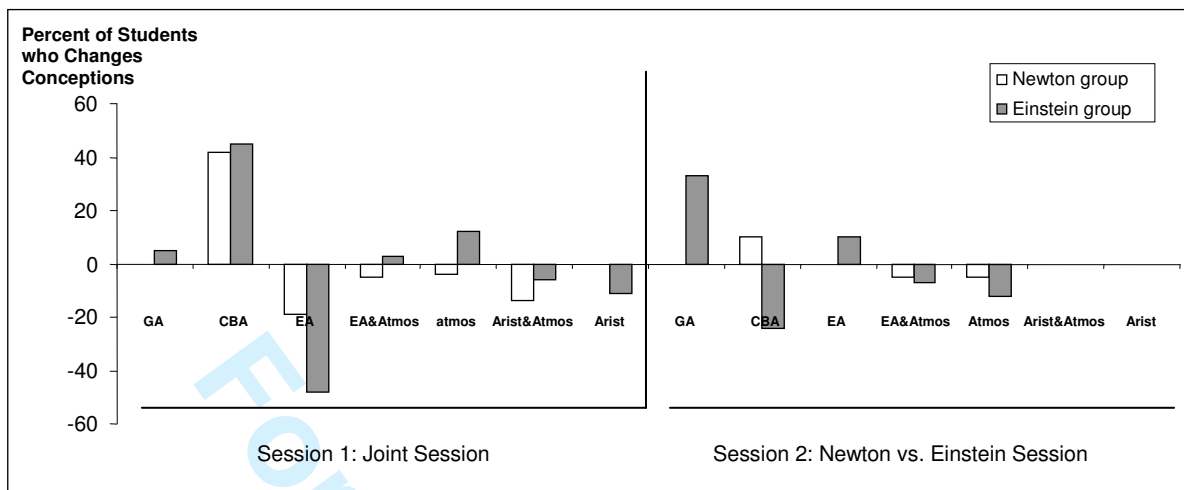


Figure 3. Comparison of the effects of the Newton and Einstein approaches, by session.

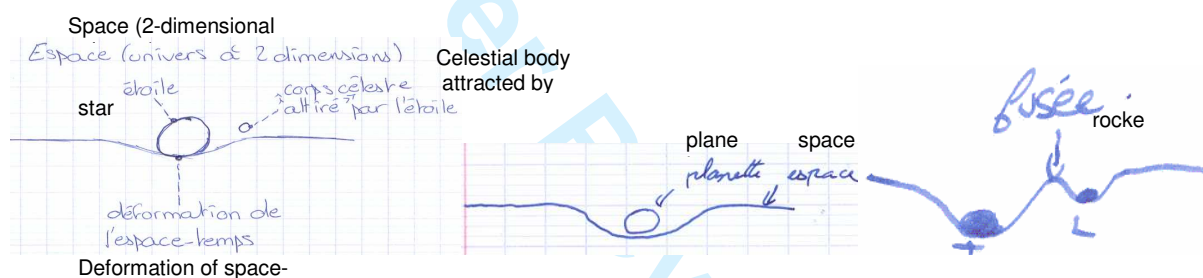


Figure 4. Examples of student drawings showing answers based on the deformation of space.

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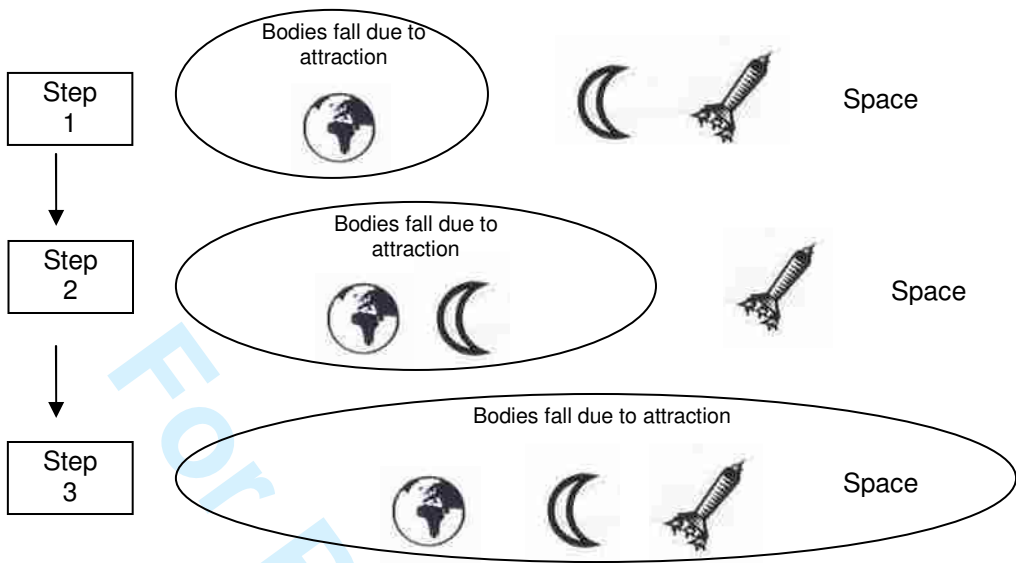


Figure 5. Structural evolution of the systems used to explain conceptions about falling bodies.