The problem of Timekeeping with the Help of the Simple Pendulum: An Empirical Study of 14-15-year-old Greek School Students

SOTIRIS DOSSIS and DIMITRIS KOLIOPOULOS
Postgraduate Student, Dept. of Early Childhood Education, University of Patras
(E-mail : sdossis@upatras.gr)
Assistant Professor, Dept. of Early Childhood Education, University of Patras
(E-mail : dkoliop@upatras.gr)

1. Timekeeping and the Pendulum: The Framework of the Research

The study of the simple pendulum in Greece occurs within the framework of the traditional perception of the curriculum of natural sciences. The use of different conceptual frameworks, the empirical methodological approach and the downgraded or non-existent cultural component of scientific knowledge are some of the features of this approach. The need to replace this framework with one which is more valid epistemologically has been pointed out in numerous studies (see, e.g., Hodson, 1988; Matthews, 2000). In an earlier study (Koliopoulos and Constantinou, 2005), we proposed a curriculum for teaching about the pendulum in secondary school in the context of the so-called innovative perception of the analytical curriculum of natural sciences. The main features of this curriculum are the following:

A broad unit is formed whereby timekeeping constitutes the leading theme, that is to say the (cultural) framework within which the desired conceptual and methodological features of the pendulum study acquire meaning. This unity is structured on the basis of certain problems, such as the problem of the isochronal motion of the pendulum clock which the students will have to study with the help of a teacher.

There is an in-depth analysis of a conceptual framework which, in this case, relates to showing a qualitative / semi-quantitative relation between the period of the simple pendulum, the string length of the pendulum and its gravitational acceleration. The mathematical approach to this relation does not need to be taught in this grade. At the same time, the study relating to other conceptual frameworks, such as the Newtonian analysis, the energetic analysis and the measure of gravitational acceleration are omitted.

A hypothetico-deductive approach of the relation between the period of the simple pendulum, its string length and its gravitational acceleration is attempted in contrast to the empirical methodological approach in which the dependence of the period on the length of the string of the simple pendulum and the acceleration of gravity does not appear as a conceptual problem but as a technical problem solved through a series of commands for the “successful” performance of an experimental activity.

The cultural dimension is designated as an essential element of the educational procedure. The cultural dimension (in this case the timekeeping problem) not only a) acts as a means of approaching the everyday/technological reality and of familiarizing oneself with the scientific/technological tradition (e.g. familiarization with the sundial, the hourglass and the pendulum clock) and b) constitutes a guiding principle for the broad unit, but also c) acquires an organic relation to the conceptual and methodological dimension, thus attributing meaning to the study of these two dimensions. Hence, the function of the clock is not viewed merely as a component of the pendulum study. Conversely, the study of the technological and natural phenomenon of the clock’s operation leads to its conversion into a physical phenomenon (study of the modelled simple pendulum) (Baltas, 1990). The choice of timekeeping as the appropriate cultural framework within which it is possible for stu-

dents to study the conceptual and methodological dimension of scientific knowledge concerning the pendulum has already emerged in isolated curricula (Matthews, 2000, p. 311) or in national curricula such as the French analytical curriculum currently in use (BO, 2001). However, we are not aware of any studies related to the efficacy of such curricula.

Nevertheless, according to the constructivist approach to the teaching of the natural sciences, the final form of the content of the proposed curriculum can be achieved as long as the students' pre-instructional conceptions concerning the concepts, the methodology and the cultural features of the scientific knowledge involved in the specific curriculum are taken into account (Astolfi & Develay, 1989). These conceptions can function either as "seeds" for the potential construction of certain concepts or as obstacles in the way of conceptual construction. As a result, the incorporation in various ways of these conceptions in the curriculum content (e.g. in the form of appropriate teaching activities which will lead to the students' surmounting conceptual obstacles) can improve the efficacy of the curriculum which is thus rendered not only scientifically more valid but also educationally more compatible with the cognitive make-up and evolution of students of this age[1]. Therefore, the broadening of the conceptions of Greek secondary school students in relation to the concepts, the methodology and the cultural features of the pendulum, constitutes an organic part of the broader research program which aims at planning and assessing the proposed curriculum for teaching about the pendulum.

Thus, the present study refers to a section of an empirical research study on how 13-14-year-old Greek students understand whether, why and how it is possible to measure time with the help of a simple pendulum. Specifically, we will be presenting data related to whether and in what ways children of this age a) conceive the pendulum as a mechanism for precise timekeeping, and b) conceive why it is possible to measure time with the help of a simple pendulum. The first question is related to the cultural dimension of scientific knowledge, i.e., to whether one knows what a pendulum clock is and how historically it has replaced all other forms of clocks, while the second question is related to the conceptual and methodological dimension of scientific knowledge and, mainly, to whether one perceives isochronous pendulum motion as well as the way in which we control its existence. Next, having referred to the historical forming of the problem of measuring time with the help of a pendulum as well as to the existing bibliography regarding students' pre-instructional conceptions of the pendulum[2], we will present the results of the research effort as they emerge out of both the analysis of a questionnaire which was given to the students before the teaching took place and the analysis of conversations between the researchers and the students which were held in the context of activities/ problems posed to the students. Finally, we will discuss the effect our study's results may have on the planning of an innovative curriculum.

2. Timekeeping and the Pendulum: Galileo's Ideas and Children's Conceptions

A. GALILEO'S IDEAS

In the Greek tradition there are two types of clocks that predate the pendulum clock: the sundial and the water clock or clepsydra. The Horologium built by astronomer Andronicus of Cyrrhus dates back to the mid-1st century A.D. and is a typical monument that functioned as a kind of weather station. It was an octagonal tower with a bronze weathervane and a system of sundials on the outside and a water clock on the inside. There is no evidence in the Greek tradition of the mechanical clock that appeared in Central Europe during the Middle Ages and is considered the precursor of the pendulum clock. The obvious inability of sundials and water clocks to precisely measure spaces of time (a typical example is the measuring of the so-called temporary or temporal hours – Matthews, 2000, p. 54) was compensated by the mechanical clocks which emerged in the 14th century and marked the passage from church time and unequal hours to secular time and equal hours. However, the great weakness of the escapement mechanism of the mechanical clock was that it had no natural frequency of oscillation. "It was the pendulum's natural frequency, ascertained by Galileo, that was to make it the core of accurate timekeeping. In the ideal situation, all pendulums of the same length vibrated with the same frequency independently of mass or amplitude of swing" (Matthews, 2000, p.63). Finally, Galileo, while working on the longitude problem, constructed a mechanical clock in which the old escapement mechanism was replaced by the pendulum.

According to Matthews (2000, p. 95) "the new technology of timekeeping resulted from a new scientific analysis of pendulum motion, which in turn was possible because of a new philosophical theory of knowledge." In other words, the pendulum clock emerged as the solution to a cultural/technological problem on the one hand, and, on the other, as the product of the scientific analysis of pendulum motion as it is found in the work of Galileo. The main elements of this analysis are related as much to the conceptual dimension as to the methodological dimension of scientific knowledge. On a conceptual level, the concept of isochronous pendulum motion is rendered fundamental. This concept derives as much from the law of length as from the law of amplitude. "To claim that pendulum motion is isochronous is to claim that every swing takes the same time. That is, that all subsequent oscillations take the same time as the first oscillation. This does not follow from the law of amplitude. It almost follows from the law of length: if period depends only upon length, then ideally, each swing will take the same time as any other swing. But friction at the fulcrum, the air's resistance to the bob, and the dampening effects of the weight of the string or wire will all contribute to a slowing of the pendulum" (Matthews, 2000, p. 113).

On the other hand, on a methodological level, Galileo's work shows that the mathematical explanation precedes any experimental proof of isochronous pendulum motion. "If experiment does not confirm the proof, then there is always the 'accidents' and 'imperfections' of matter to consider (Matthews, 2000, p. 112). The concept of isochronous pendulum motion, therefore, appears at the same time as a new methodological approach to natural phenomena which is based on the transformation of natural objects into physical objects (Baltas, 1990). As Matthews writes: "The history of the pendulum begins when real objects become theoretical objects. That is, when people begin to describe, conceptualize, explain, and ultimately theorize about pendulums" (Matthews, 2000, p. 79).

The above analysis leads us to the conclusion that when scientific knowledge concerning the pendulum becomes the object of traditional teaching in Greek secondary school, it undergoes a drastic recontextualization. The pendulum is taught in the absence of a specific cultural framework since it is not related to a cultural framework (precise timekeeping and/or the technological problems of constructing clocks), while the experimental approach to the laws of the pendulum is marked by clearly empiricist features, in which the conceptual framework of isochronous motion has been reduced to a purely technical matter. The passage, therefore, from the traditional to the innovative conception vis-à-vis teaching about the pendulum requires that the preceding scientific analysis be taken into account. This will lead to the legitimization of the nature and the features of the proposed curriculum described in the first part, as well as of the framework within which it is possible to broaden the students' conceptions, which, after all, is the object of this study. Specifically, based on the previous analysis, we can be justified in studying the students' conceptions concerning a) how the pendulum is related to timekeeping, b) the isochronous pendulum motion, and c) the methodological relation between the experiment and the theoretical reasoning leading up to it. In this paper we will address the first two issues.

B. CHILDREN'S CONCEPTIONS

Surprisingly, the bibliography related to the broadening of students' conceptions of the pendulum is relatively meager; for example, in his thorough bibliographical study, Gauld (2002) cites one single reference to "student conceptions of the pendulum." Almost all the bibliographical references we found referred to or were related to the methodological dimension of scientific knowledge of the pendulum. Several studies have been carried out in the context of the Piagetian paradigm, exploring the strategies used by children to control the variables involved in pendulum motion (Inhelder & Piaget, 1958; Stafford, 2002). An interesting result of this research is that children of the age group with which our study is concerned are capable, in principle, of using the hypothetico-deductive reasoning directly related to scientific methodology. With regard to the separation of variables strategy and the exclusion of inoperant links, Inhelder mentions that "towards 14-15 years, *but not earlier*, adolescents correctly test all the possible hypotheses [concerning the 'Genevan' pendulum experiment] by combining them methodically. In varying the length, they take care to maintain the weight, the amplitude and momentum constant. In varying the weight, they hold constant the length of the string, as well as all the other factors, etc. The famous method, familiarly called 'method of all other things equal,' then always has recourse to combinational operations on the one hand and neutralization or compensation of factors on the other" (Bond, 2002, v. I, p. 123).

However, studies concerning the conceptual dimension of scientific knowledge of the pendulum refer mainly to the conceptual framework of the dynamic analysis of pendulum motion (see, e.g., Cwudkova & Musilova, 2000 or Galili & Sela, 2002), while one can only find indirect references to the problem of isochronous pendulum motion. Il-Ho Yang et al. (2002) mention that students' prior knowledge of the pendulum has a significant impact on formulating, testing and revising hypotheses. According to their study, quite a few seventh grade students (about 40% of the sample) believe that the frequency of a pendulum increases or decreases when the pendulum is dropped from a higher or lower point in relation to a certain point. Personal experience ("in the past, when I dropped an object from a higher building it would drop faster") or not recognizing the relation between distance and time ("The further back I pull the bob, the faster it will swing because the dropping force may increase", v.I, p. 167) are two reasons that explain the students' conceptions. The fact that the students spontaneously do not recognize isochronous pendulum motion is also evident in conversations they had with a teacher during an innovative method of teaching about the pendulum to Greek ninth grade students (… the students have already measured the time for ten oscillations. "*T*: If this time we measure twenty oscillations, how much time do you think it'll take? *S1*: Less. *S2*: More. *T*: Why less? *S1*: Because now it's covering less distance, *S2*: Yes, but at a lower speed" – Koumaras, 2002, v.II, p. 213).

Finally, in none of the bibliographical references located were we able to find studies related to the cultural dimension of scientific knowledge of the pendulum (i.e. concerning the broadening of students' conceptions of the relation between the simple pendulum and the pendulum clock). As we mentioned earlier, our own research aims at exploring the pre-instructional conceptions of 14-15-year-old Greek school students, mainly of the cultural and conceptual dimension of scientific knowledge of the pendulum in view of an innovative curriculum. From the previous bibliographical analysis it arises that we are fully justified in carrying out this research, on the one hand in order to fill the gap that exists in relation to the cultural dimension of scientific knowledge of the pendulum, and, on the other, to reaffirm that the problem of isochronous pendulum motion is a serious conceptual problem faced by students of this age.

3. Timekeeping and the Pendulum: An Empirical Research Study

A. PLANNING THE RESEARCH

Two complementary methods were used in order to trace the students' conceptions: the *review*, with the help of a pertinent questionnaire, and the *case study*. The questionnaire is made up of three parts, one for each component of scientific knowledge of the pendulum (cultural, conceptual, and methodological). Each part includes three to five, mainly closed, questions. There are a total of twelve questions. In this paper we will be presenting the results of two of the questions that concern the cultural dimension of scientific knowledge (questions 1A, 1B and 1C of the questionnaire) and two of the questions that concern the conceptual dimension of scientific knowledge (questions 3A, 4 and 7 of the questionnaire). *Appendix 1* contains the phrasing of the questions.

Through the cultural-type questions we wish to discern whether the students are aware that the mechanism of the pendulum clock can measure time more precisely than that of the sundial or the hourglass. Through the conceptual-type questions we wish to discern whether the students recognize isochronous pendulum motion (a constant period for a different starting angle), as well as the way in which we can control it (control of variables). The research was based on 169 ninth grade boys and girls, from four different schools, who had never been systematically taught about the pendulum. However, during the last two years of their education in the natural sciences, they had all been taught aspects of Newton's Mechanics, since in Greece the teaching of mechanical phenomena is one of the most popular chapters of Physics (the teaching of Mechanics begins in fifth grade!). The analysis of the results was carried out with the help of the SPSS statistics package.

The case study consists of the observation of two nine-member groups of students who are to participate in a discussion initiated by the researcher through certain "activities/problems" posed to the students (Ravanis, 1998). The criteria for the students' selection is being good at the natural sciences and having good communication skills. During the discussion, the students must produce a written text for each activity/problem. Ten such activities/problems, divided into four sections, were posed. Each section lasted 45-50 minutes. In two of these, the students held a discussion based on texts related to the history of the natural sciences (Koliopoulos et al., 2005). The students discussed among themselves, either split up into subgroups of three (making up a total of 6 subgroups), or as a single group with the researchers monitoring the discussion. In this paper we will be presenting the results that are related to only three of the ten activities. *Appendix 2* contains the descriptions of these three activities as they were given to the students.

Activity 1 concerns the cultural dimension, while activities 2 and 3 concern the conceptual dimension of scientific knowledge of the pendulum. The students that participated in the case study did not reply to the answers posed in the questionnaire. The analysis of the results was carried out by the Nvivo qualitative data analysis package.

B. INITIAL RESULTS OF THE RESEARCH

The analysis of the results of both methods is still at a preliminary stage. Nevertheless, we believe that the results presented here will lead to a first series of conclusions and hypotheses concerning the nature and the characteristics of the students' conceptions.

b1. The cultural dimension of scientific knowledge

All the students recognize the three different types of clocks mentioned in *question 1A*. *Table 1* indicates the absolute and relative frequencies of the students' answers to *question 1B*. The results show that the majority of the students (72.2 %) believes that the most probable sequence in which humankind used the three mechanisms is: sundial – hourglass – pendulum clock. ($x^2(3) = 210.2$, $p<.05$).

Table 1 about here

However, the percentage of students that give the wrong chronological order cannot be considered small. That means that for 27.8% of the students there exists a serious problem concerning the cultural knowledge of timekeeping mechanisms. *Table II* indicates the absolute and relative frequencies of the students' answers to *question 1C* ($x^2(3) = 197.2$, $p<0.05$), while *Table III* indicates the absolute and relative frequencies given by the students as to which mechanism they think keeps time with greater precision ($x^2(6) = 22.6$, $p<0.05$). It appears that the majority of the students recognizes that the pendulum clock is the most precise timekeeping mechanism and at least half of the students offer a justification for why it is so. A significant difference was noted between the observed and the anticipated frequencies of the 7 answers given by the students in order to justify a mechanism's precision ($x^2(6)=22.59$, $p<0.05$). The students most likely link the pendulum clock's precision to the fact that it is still used to this day and that it measures in seconds, just like modern-day clocks.

Tables 2 and 3 about here

It is at this point that the problems begin, since only 16.6% of the students offers a justification that refers to the functioning principle of the mechanism. All the other justifications refer more to cultural criteria that are foreign to scientific thought. Nevertheless, the issue of precision in timekeeping is posed to almost all the student subgroups in the context of *activity/problem 1*. Of course, that does not mean that all students attribute the same meaning to the concept of precise timekeeping. The following discussion between the students of one subgroup is typical:

> *G2-S1:* So then the hourglass measures in reverse, counting down.
> *G2-S2:* And it can't keep time; that is, it can't measure seconds
> *G2-S1:* Right. It measures, but not with precision and for a space of time that is known from the beginning.
> *G2-S2:* I wouldn't say not with precision, because we know that it'll take 2 hours. We can't measure the seconds that have passed, 1 second, 2 seconds, that we can't do, but we do know that in two hours it will have run out. You can't say that [so many seconds] have passed.
> *G2-S1:* Yes, but there's no precision in that. You have to wait for the sand to run out.
> *G2-S2:* When it runs out you can be sure 2 hours have passed, for example.
> *G2-S1:* Well, yes. It's the same thing with the others.

From the aforementioned we can safely conclude that most of the students of our sample understand that the pendulum clock is a sophisticated mechanism for precise timekeeping. That which might appear strange is the fact that not all the students have acquired the cultural knowledge that the pendulum clock is a sophisticated mechanism for precise timekeeping. This matter needs to be explored further. However, many fewer students clearly justified why it is that the pendulum clock measures time more precisely than the other two mechanisms. Precision timekeeping through the use of the pendulum appears, therefore, to be not only a conceptual but also a cultural problem for a significant percentage of the students.

b2. The conceptual and methodological dimension of scientific knowledge

Table 4 indicates the absolute and relative frequencies of the students' answers to *question 3A*. The majority of the students answers correctly, i.e. that two half-periods of motion are equal ($x^2(3) = 224.0$ $p<0.05$). Of course, the percentage of students that does not accept the invariability of the period (and therefore isochronous pendulum motion) is not insignificant. This percentage, as shown by the answers to *question 4* (*Table 5*) increases to 78.4 % ($x^2(3) = 141.0$ $p<0.05$). It seems more likely to the students that the time needed for a swing would decrease. That the majority of the students do not recognize isochronous pendulum motion is to be expected and refers directly to the historical analogue.

Tables 4 and 5 about here

On the other hand, from the discussions between the researcher and the students and/or the students among themselves carried out in the context of a*ctivity/problem 2*, we observe that the students spontaneously express their surprise at isochrony. The following dialogue between the researcher and the students is typical:

> *R*: What does it say? Let's see what it says.
> *G3-S*: That from the perpendicular position it goes to the 1^o mark.
> *R*: That's right. 1^o.
> *G3-S*: And then from the perpendicular position it has to go to 90^o mark.
> *R*: Yes.
> *G2-S2*: And that'll take the same amount of time?
> *R*: That's it! That's what he claims…
> *G2-S2*: Well, what this guy's saying is very unlikely…

…………………………………………………………………..
R: Let us understand what the question is. We will give an answer, but have you understood the question?
G1-S2: That's irrational.

The students' difficulty at accepting isochronous pendulum motion is evident in the discussions within each group. Nevertheless, they begin using rational sounding arguments in order to prove the hypothesis of isochrony. One could describe the kind of proof given as a mix of Aristotelian and modern scholarly views which the students have been taught so far. The following dialogue is typical:

G1-S2: When it starts off at the 90^o mark it's moving at high speed.
G1-S3: It has momentum…
G1-S1: Yes, it has momentum and hence greater speed, while when it goes to the 1^o mark from the perpendicular position it's moving at low speed.
G1-S3: In the same amount of time there's much more damping [?].
G1-S1: There is? Yes, because it's moving faster, whereas then it'll move less and less, so that when it reaches the 1^o mark it'll be going like this.
G1-M2: But even then it doesn't need the same amount of time. The distance may be shorter, but it's moving… but if that's also shorter…no.

We should note, however, that the discussion among the students is lengthy and shows that the above process is quite laborious since, in effect, the students are being "forced" to come up with some proof.

Finally, *question 7* of the questionnaire, which is indirectly linked to the issue of isochrony, checks whether the students are using hypothetico-productive reasoning in the experimental verification of the swing angle. As can be seen in *Table 6*, less than half the students choose the correct answer ($x^2(4) = 60.9$ $p<0.05$). In Piagetian terms, that could mean that the students have yet to reach the final stage of development, that of formal operations. However, with regard to the conceptual problem of isochronous pendulum motion, that means that quite a few students face an added difficulty in its understanding.

Table 6 about here

This difficulty appears to be related not only to the nature of the hypothetico-productive reasoning, but also to the content to which this reasoning is applied. Thus, if we examine the written responses of the students' subgroups (who had previously discussed at great length the problem of isochrony) to *activity/problem* 3, we can see that five out of six groups propose an experimental activity which, on the whole, observes the "method of all other things equal." Here are two of the students' written responses:

G2: "Materials: 2 identical pendulums and two planks of wood. We set up the two pendulums. The first will swing to the 2^o mark and the other to the 180^o mark. We place one plank at the 1^o mark and the other at the 90^o mark. We release both pendulums at the same time and if they hit the planks at different times, that means they need a different amount of time, while if they hit simultaneously, it means that they need the same amount of time."
G4: "We take a piece of string which we hang at a perpendicular angle to the ground, hanging a weight on the end of the string closest to the ground. We move the string so that it is parallel to the ground (at a 90^o angle) the first time, and the next time at a one-degree angle from its resting position, measuring the angles with a protractor. We use a stopwatch to measure how long the motions last and whether they are equal."

4. Timekeeping and the Pendulum: The Effect of the Research on Teaching

In discussing the results of our analysis set out in this unity, we can draw certain preliminary conclusions and point out the resultant effects on teaching about the pendulum.

First of all, with regard to the cultural dimension of scientific knowledge of the pendulum, we conclude that, even though a large part of the student sample recognizes that the pendulum is a precise timekeeping mechanism in relation to older mechanisms, nevertheless it does not seem to be able to express a clear perception of why this is so. That means that timekeeping can constitute an interesting context in which the simple pendulum can be studied by the students not only because it may be linked to interesting cultural elements for them (e.g. references to ancient Greek timekeeping mechanisms), but also because for the majority of the students it constitutes a familiar context (as opposed, say, to a more "technological" context, in which the students would have to recognize the pendulum as an improving mechanism in the mechanical clock). We believe that the familiarity of the students with the cultural context and the concepts it contains constitutes a determining factor in both the planning and the efficacy of the teaching. For example, the concept of precise timekeeping (together with the concept of periodicity, which was not addressed by the present paper), which, in the case of the pendulum, is a feature common to both cultural and conceptual knowledge, appears to be a concept which is familiar to the students while at the same time being favorable for further broadening.

In relation to the conceptual context, it seems that the majority of the students does not recognize isochronous pendulum motion, as was to be expected. At the same time, however, it emerges as an interesting topic which can provoke constructive discussions, as was shown by the dialogue with and among the students. The students seem to be determined to find proof of the phenomenological paradox of isochrony which is "theoretical" rather than "experimental." Not emphasizing the problem of isochronous pendulum motion in traditional teaching means that an opportunity is lost for the creation of areas of conceptual interest for students (compared to other, more "mathematicalized" and, therefore, less interesting conceptual frameworks such as the dynamic and energetic analysis of pendulum motion). What's more, it appears that isochrony constitutes a serious conceptual problem for the students which must be taken into account when formulating suitable teaching goals. The planning of teaching based on the formulation of aims-obstacles can lead to more effective teaching (Ravanis et al., 2004). Finally, the data indicates that underscoring isochrony as a basic conceptual problem can facilitate the understanding of experimental procedure through which it is possible to highlight the laws of the pendulum. In the same time, underscoring the hypothetico-productive method as a basic methodological choice seems to take on, besides epistemological validity (in relation to the empiricist approach of traditional education), educational validity as well. However, a full analysis of our data as a whole is required in order for us to adequately substantiate this view.

In conclusion, we would like to point out that the careful and systematical analysis of students' learning demands that can be operationalized as content goals in an innovative curriculum vis-à-vis the pendulum, is a first step in the forming of a pedagogically and scientifically valid teaching content. Besides, that is the final goal of the broader research effort in which this paper is registered. For us, the International Pendulum Project constitutes a constructive international research environment for the planning, the dissemination and the assessment of our work.

Notes

[1] In this text, the term "constructivist approach" is used in the context of a French research tradition according to which the planning of curricula results from a) the epistemological analysis of the content of the thematic unity to be taught, b) the cognitive pre-instructional traits of the students which the curriculum is targeting, and c) the features of the educational system within which the curriculum is being implemented (see, e.g., Artigues, 1988; Tiberghien et al., 1995; Koliopoulos & Ravanis, 2000).

[2] The information concerning the historical and epistemological analysis as well as the students' pre-instructional conceptions are based, by and large, on Matthews, 2000 and Matthews, 2002.

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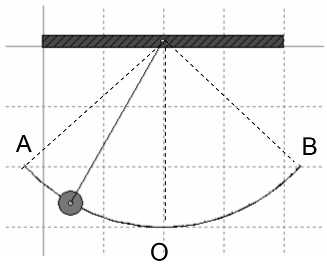
Appendix 1 (The questionnaire)

1. The sundial, the pendulum clock and the hourglass[iii] are three types of clocks that humankind has used in the past for keeping time.
1A) Fill in the name of each type of clock under the respective photograph.

1B) Circle the answer you believe to be correct.
In what chronological order do you think humankind used them?
(i) First the pendulum clock, then the hourglass, and then the sundial.
(ii) First the sundial, then the pendulum clock, and then the hourglass.
(iii) First the sundial, then the hourglass, and then the pendulum clock.
(iv) First the hourglass, then the pendulum clock, and then the sundial.
(v) I don't know.

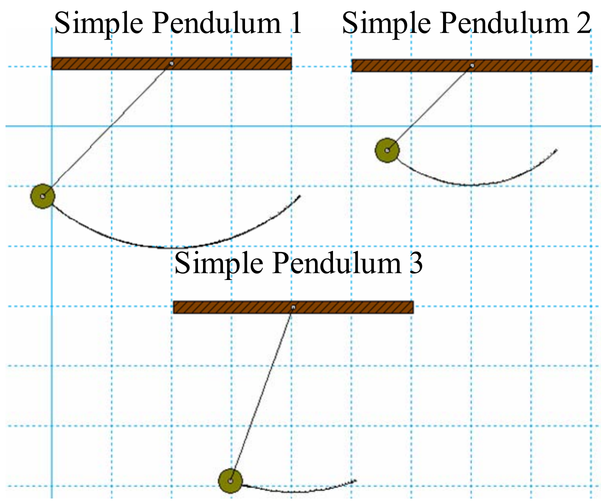
1C) Circle the answer you believe to be correct.
Which of the following keeps time with greater precision?
(i) The sundial.
(ii) The pendulum clock.
(iii) The hourglass.
(iv) I don't know.
Justify your answer.

3A) Circle the answer you believe to be correct.
The time needed for the simple pendulum shown in the figure below to swing from position A to position B is:
(i) More than the time needed for it to return from position B to position A.
(ii) Equal to the time needed for it to return from position B to position A.
(iii) Less than the time needed for it to return from position B to position A.
(iv) I don't know.



4. Circle the answer you believe to be correct.
The simple pendulum shown in the figure to the right (same figure as in question 3A) is allowed to swing freely from position A. Little by little, its swing becomes smaller. The time needed for it to become a simple swing:
(i) Increases while the phenomenon lasts.
(ii) Decreases while the phenomenon lasts.
(iii) Does not change while the phenomenon lasts.
(iv) I don't know.

7. **Circle the answer you believe to be correct.** The figure below depicts three simple pendulums that differ in pairs, either in terms of the point from which we drop them (either higher or lower), or in terms of the length of the string. If you wanted to check how the position from which we drop the pendulum affects the time needed for it to complete a simple swing, which of the pendulums would you use?
(i) Pendulums 1 and 2
(ii) Pendulums 1 and 3
(iii) Pendulums 2 and 3
(iv) All three pendulums.
(v) I don't know.



Appendix 2 (Activities/Problems)

Activity/Problem 1
What do you think is the greatest advantage in keeping time with a pendulum clock, as opposed to the other types of clocks?

Activity/Problem 2
How do you think Salviati (i.e. the character that expresses Galileo's ideas) would go about giving a convincing answer to Sagredo's claims?
(This activity refers to a text which has been given to the students and which can be found in *Appendix* 3).

Activity/Problem 3
What specific technique would you use in order to verify Sagredo's claim?

Appendix 3 (The text used for Activity/Problem 2)

Galileo and Timekeeping

The year 1638 was a historic one for science. *Galileo* published his work *Dialogues Concerning Two New Sciences*, one of the first written records of the birth of modern Physics. Galileo wrote *Dialogue*s in the form of a play and discusses his ideas through its three main characters: *Salviati*, a brilliant scientist, who expresses Galileo's beliefs, Sagredo, a clever amateur disguised as a neutral participant and *Simplicio*, the well-meaning defender of the ideas of the time.
The following excerpt from Galileo's *Dialogues Concerning Two New Sciences* deals with pendulum motion, i.e. it is related to today's lesson.
Sagredo: "… I have observed, thousands of times, the swinging of chandeliers, especially in churches, or lamps hanging from the ceiling and moving to and fro. But the only thing I have established from these observations is that it is most unlikely that the opinion of those people who claim that all these oscillations are maintained by the environment is correct. For, if that were the case, then the wind would have to act with great insight and have nothing else to do than to give this suspended weight a perfectly regular to-and-fro motion. It is impossible for me to imagine that the same body, suspended from a string of approximately 50 meters, and moved away by 90 degrees (90^o) from its perpendicular position and then one degree (1^o) from the perpendicular position could, in both cases, take the same time to cover a very large arc and then next a very small one. That seems to me very unlikely."

Appendix 4 (Tables)

	Question 1B
(i)	8 (4.7 %)
(ii)	7 (4.1 %)
iii)	122 (72.2 %)
(iv)	32 (18.9 %)
(v)	0
Total	169 (100%)

Table 1

	Question 1C
(i)	29 (17.2 %)
(ii)	120 (71.0 %)
(iii)	6 (3.6 %)
(iv)	14 (8.3 %)
Total	169 (100%)

Table 2

Justification	Question 1C
The pendulum clock because it is used to this day	31 (18.3 %)
The pendulum clock because it measures seconds	28 (16.6 %)
The pendulum clock through “the process of elimination”	17 (10.1 %)
The pendulum clock because its mechanism is more sophisticated	9 (5.3 %)
The sundial because it is based on the steady motion of the sun	15 (8.9 %)
Other answers	34 (20.1 %)
I don’t know	22 (13.0 %)
No answer given	13 (7.7 %)
Total	169 (100%)

Table 3

	Question 3A
(i)	14 (8.3 %)
(ii)	126 (74.6 %)
(iii)	22 (13.0 %)
(iv)	7 (4.1 %)
Total	169 (100%)

Table 4

	Question 4
(i)	25 (14.8 %)
(ii)	108 (63.9 %)
(iii)	27 (16.0 %)
(iv)	9 (5.3 %)
Total	169 (100%)

Table 5

	Question 7
(i)	28 (16.6 %)
(ii)	74 (43.8 %)
(iii)	20 (11.8 %)
(iv)	25 (14.8 %)
(v)	22 (13.0 %)
Total	169 (100%)

Table 6

[iii] For the purposes of the questionnaire we have used the modern version of the clepsydra that contains sand, since we considered it to be the form of hourglass most familiar to the students, as opposed to the water clock.