PERGAMON

Computers & Education 36 (2001) 183–204

COMPUTERS & EDUCATION

www.elsevier.com/locate/compedu

Computer simulations in physics teaching and learning: a case study on students' understanding of trajectory motion

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Received 24 April 2000; accepted 15 November 2000

Abstract

A major research domain in physics education is focused on the study of the effects of various types of teaching interventions aimed to help students' alternative conceptions transformation. Computer simulations are applications of special interest in physics teaching because they can support powerful modeling environments involving physics concepts and processes. In this study two groups (control and experimental) of 15–16 years old students were studied to determine the role of computer simulations in the development of functional understanding of the concepts of velocity and acceleration in projectile motions. Both groups received traditional classroom instruction on these topics; the experimental group used computer simulations also. The results presented here show that students working with simulations exhibited significantly higher scores in the research tasks. Our findings strongly support that computer simulations may be used as an alternative instructional tool, in order to help students confront their cognitive constraints and develop functional understanding of physics. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Simulations; Interactive learning environments

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1. Introduction

Learning physics is often considered by teachers and students to be a difficult pursuit. Over the last two decades a great deal of educational research has been directed towards the exploration of students' ideas and difficulties on physical concepts and processes (Driver, Guesne & Tiberghien, 1985; Duit, Goldberg & Nidderer, 1991). Research on physics and science education has often focused on the study of alternative conceptions and mental representations that students employ

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PII: S0360-1315(00)00059-2

before and after instruction. Related to the above is research focused on the study of the consequences of special teaching interventions aiming to transform students' alternative conceptions.

A common research assumption is that students possess a system of beliefs and intuitions about physical phenomena mainly derived from their everyday experience. Such systems of beliefs and intuitions are usually incompatible with scientific theories and knowledge; they have been referred to as misconceptions or alternative conceptions. For example, research studies (Halloun & Hestenes, 1985; Whitaker, 1983) have suggested that students' beliefs about motion in the earth's gravitational field are usually based in Aristotelian ideas derived from limited first-hand experience of real-life phenomena. Research has further shown that high school (and sometimes university) students' knowledge consists of a small number of facts and equations that are not effective for the interpretation of simple, real-world physical phenomena. Defective procedural knowledge is often evident in the problem solving approaches employed by most of the students (Halloun & Hestenes, 1985).

Research findings also suggest that conventional instruction is ineffective in dealing with misconceptions. Students' alternative conceptions of velocity and acceleration, for example, are considered to be as not easily affected by traditional instructional methods. Students often connect velocity with the position of the moving objects (Hewson, 1985; Trowbridge & McDermott, 1980), confuse velocity and acceleration or create analogies between them (Trowbridge & McDermott, 1981; Whitaker, 1983), and face major difficulties when using graphical or stroboscopic representations of motions (Beichner, 1994; McDermott, Rosenquist & van Zee, 1987).

Transforming ideas and correcting defects of students' knowledge in physics is beyond the reach of the traditional teaching approaches because they tend to ignore the possibility that the perception of students is possibly different than that of the teacher (McDermott, 1993). The main aim of an alternative constructivist teaching approach should then be the development of such conditions that would facilitate students' active engagement in learning and functional understanding of physics. Furthermore, such an approach should enable students to effectively apply physical concepts and principles in novel situations. Further research on these issues could be proved very helpful for improving instructional patterns, and designing and developing new learning environments.

Among the important issues concerning the employment of constructivist approaches to learning is the study of the effects of computer tools aimed to facilitate students' active engagement in physics teaching and learning. This study presents the findings of an alternative teaching intervention, based on computer simulations through *Interactive Physics*. Students' cognitive constraints and alternative conceptions about velocity and acceleration in simple projectile motions in the earth's gravitational field were investigated. The analysis of the data obtained shows that simulations assist students to overcome the cognitive constraints originating from various misconceptions.

2. Computer simulations in physics teaching

Schools' widespread access to Information and Communications Technologies (ICT) pose tremendous challenges to physics teaching and learning. Physics is one of the first areas where the possibilities that computers may offer for the employment of new teaching methods have been and are still explored. A variety of computer applications have been developed and used in teaching Physics, such as spreadsheets (Dory, 1988), computer-based laboratories (Thornton & Sokoloff, 1990), multimedia (Crosby & Iding, 1997; Wilson & Redish, 1992), simulations (Andaloro, Bellomonte & Sperandeo-Mineo, 1997), exploratory environments (Teodoro, 1993) and intelligent tutors (Schulze, Shelby, Treacy & Wintersgill, 2000). Furthermore, research has often been employed to direct educational software design and development, as well as educational software evaluation.

Today numerous ICT applications are available, aiming to stimulate students' active engagement and offering the opportunity to work under conditions that are extremely difficult, costly or time-consuming to be created in the classroom or even the physics lab. The use of such ICT applications has developed a new research field in physics education, since it radically changed the framework under which physics teaching is being understood and implemented.

Among the various ICT applications, computer simulations are of special importance in Physics teaching and learning. Simulations offer new educational environments, which aim to enhance teachers' instructional potentialities and to facilitate students' active engagement. Computer simulations offer a great variety of opportunities for modeling concepts and processes. Simulations provide a bridge between students' prior knowledge and the learning of new physical concepts, helping students develop scientific understanding through an active reformulation of their misconceptions. Specifically, they are open learning environments that provide students with the opportunity to:

1. develop their understanding about phenomena and physical laws through a process of hypothesis-making, and ideas testing;
2. isolate and manipulate parameters and therefore helping them to develop an understanding of the relationships between physical concepts, variables and phenomena;
3. employ a variety of representations (pictures, animation, graphs, vectors and numerical data displays) which are helpful in understanding the underlying concepts, relations and processes;
4. express their representations and mental models about the physical world; and
5. investigate phenomena which are difficult to experience in a classroom or lab setting because it is extremely complex, technically difficult or dangerous, money-consuming or time-consuming, or happen too fast.

The constructivist perspective in physics teaching argues that knowledge is not discovered but it is rather achieved by constructing models of physical phenomena. According to Hestenes (1992) we can define two types of models:

1. *mental models*, which are representations of the physical phenomena constructed in the minds of students and contain a set of information about what students know (either correct or incorrect); and
2. *conceptual models*, which originate from mental models and are created by the cooperative activities of scientists. They are objective representations in the sense that they are independent of any particular individual. Students' active engagement with them is essential to overcome their conceptual obstacles and reach the scientific conceptual models.

We can distinguish between two types of computer models in physics (Bliss, 1996):

1. *exploratory models*, which are constructed by experts to represent domain knowledge. Usually they are micro-worlds that simulate physical processes and laws. Such micro-worlds encourage students explore and interact with them, handle parameters and observe their results; and
2. *expressive models*, which allow students express their own ideas on a domain. They provide learners with tools to define relationships between concepts, explore the consequences of those student-defined relationships and learn through an active process of representing their own models.

Today a wide variety of educational software is available for teachers and students helping them to present and model physical phenomena and processes (see *Interactive Physics,* 2000; *Modellus,* 2000), or solve physics problems (see *Andes* at Schulze et al., 2000). Computer simulations have been successfully applied from high school (Andaloro et al., 1997; Tao, 1997) to university physics teaching (Schroeder & Moore, 1993). They have been used to diagnose and remedy alternative conceptions of velocity (Hewson, 1985), and confront alternative students' conceptions in mechanics (Tao, 1997). A recent study showed that simulations were equally effective to micro-computer based labs in facilitating the comprehension of concepts involving the free fall of objects (Peña & Alessi, 1999). Other studies focus on the effects of the use of computer simulations on students' conceptual understanding (Andaloro et al., 1997; Jimoyiannis, Mikropoulos & Ravanis, 2000; Tao, 1997). An interesting finding is that, even after computer-supported Physics instruction, students conserve most difficulties and vacillate between alternative and scientific conceptions from one context to another (Tao & Gunstone, 1999).

3. Simulating Newtonian mechanics through Interactive Physics

Interactive Physics is a two-dimensional virtual physics laboratory that simulates fundamental principles of Newtonian mechanics. The simulation engine needs no programming. Simulations produced by the system are based on two numerical analysis methods, a fast (Euler) and an accurate one (Kutta-Merson) and present a realistic movie of the objects' evolution on the screen. A series of physical quantities (velocity, acceleration, momentum, angular momentum, kinetic energy, etc.) can be measured in vector, digital, graphical or bar form, while the simulation is executed.

Interactive Physics offers a friendly user interface though a series of interaction objects such as:

1. buttons, that enable students add commands directly to the working space without the need to invoke dialog boxes;
2. controls, that allow students adjust simulation parameters before and during a simulation's execution; and
3. meters, that allow measurement of the relevant physical quantities in digital, graphical or bar form. Data from any meter can be exported to other applications, such as spreadsheets or graphics packages.

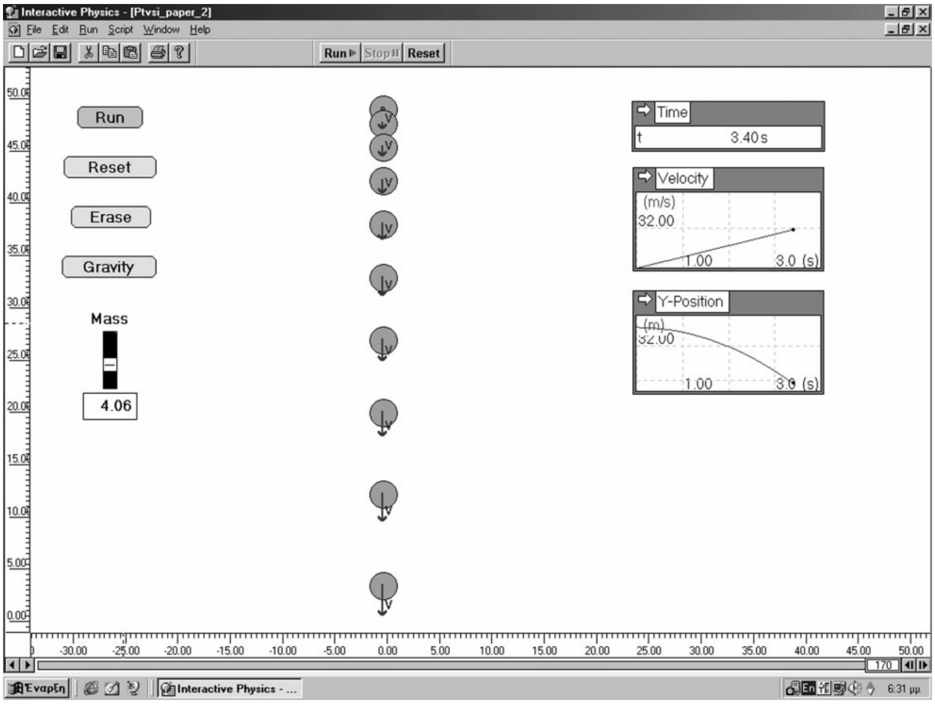
Fig. 1 shows the Interactive Physics III screen that simulates a ball falling freely from a given height in the earth's gravitational field. The various frames that project successive positions of the ball are also presented.

The software also provides the user with a *player mode* where the various functions are hidden from the user. Furthermore, users are offered access to a friendly interface with controls such as RUN/STOP, RESET, ERASE (delete traces) and GRAVITY (change the value of the gravity constant) by clicking the relevant buttons.

Interactive Physics can be used in Physics teaching and learning as:

1. a virtual Physics laboratory for modeling and presenting phenomena and processes; and
2. an expressive environment where students can demonstrate their ideas and mental models, make predictions, derive physical laws and solve problems.

Experimenting on trajectory motion in school physics labs is difficult since it demands from students adequate experimental skills, as well as skills on using stroboscopes. The simulation through Interactive Physics is an alternative approach offering distinct teaching and pedagogical advantages. The stroboscopic representation of a kinematical phenomenon and the simultaneous display of the position and velocity offer an open environment where students may experiment, study the physical laws, make assumptions or predictions and derive conclusions. They can repeat their experiments as many times as they need to understand the relevant laws and principles of motion. Students can easily modify either the mass of the sphere or the gravity constant and



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Mass 4.06

Fig. 1. Interactive Physics III screen showing the simulation of the free fall.

immediately observe the results on the computer screen. They can get information from the attached meters giving the graphical representation of the position y and the velocity V_y of the moving body. Finally, they can export their data to a spreadsheet for further analysis, in order to derive the physical laws.

Overall, simulating physical concepts and phenomena through Interactive Physics may be effective in teaching high school students because:

1. its powerful environment supports stroboscopic studies of physical phenomena;
2. it has a friendly and flexible user interface; and
3. it is an easily accessed and maintained computer environment.

4. Method

4.1. Research aims and questions

The research presented and discussed in this paper aims to investigate the effects of computer simulations to high school students' understanding of basic kinematical concepts concerning simple motions in earth's gravitational field. More specifically, the research questions are:

1. What are the major difficulties faced by high school students when applying the concepts of velocity and acceleration in simple motions in the gravitational field?
2. What are the effects of the use of simulations on students' alternative conceptions?
3. Does the use of simulations help students develop scientific models?

4.2. The sample

A total of 90 students attending the first year of Lyceum[1] (15–16 years old) participated in the research. These students were attending courses in three typical public high schools in the city of Ioannina, Greece and represented a wide range of achievement levels. The students in the sample were coming from a variety of social-economic backgrounds. Most of them (66.6%) had computer experience. The students were grouped in the control and experimental group. The control group consisted of 60 students who were attending courses in two different high schools (Lyceum1 and Lyceum2). The experimental group consisted of 30 students who were attending courses in another high school (Lyceum3).

Our research was carried out during the academic year 1998–1999 and took place about 5 months after students had received school teaching on basic kinematical concepts. Kinematics is the first teaching topic described in the Greek Lyceum Physics Curriculum. It includes the concepts of velocity and acceleration, the laws of linear motions, and the study of simple trajectory motions such as the free fall, the vertical and horizontal throw in the gravitational field of earth. Prior to their participation in the research all students had received traditional instruction on these topics in the classroom. No

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[1] Lyceums are schools providing upper secondary education in Greece (three grades in total).

experimental activities took place in the Physics lab. Students' school activities (in the classroom and homework), prior to their participation in the research, were restricted to conventional methods based on problem solving of mathematical equations and deriving quantitative results.

4.3. The educational intervention

Our educational intervention took place approximately two weeks after students in the experimental group had received traditional classroom teaching on the relevant topics. All students from the experimental group were offered two 1-h lessons in the computer lab. During the first lesson the teacher, with the collaboration of a researcher, used *Interactive Physics* to display simple kinematical phenomena and analyze the free fall laws. Furthermore, all students had a short period of practice in order to familiarize with the simulation environment. Two students at a time worked on a computer.

During the second lesson students were engaged in tasks demanding the use of *Interactive Physics* stroboscopic representations. Students' engagement in simulation tasks was restricted to the study of the free fall. Subjects were encouraged to change the mass of the bodies or the gravity constant, make assumptions or predictions, give explanations and observe the results of their decisions on the computer screen. They also used the meters provided by the simulation software to represent various physical quantities in graphical form, understand the relationships between physical concepts and, finally, to develop an in-depth understanding of the physical laws. Students in the experimental group did not use simulations to experiment with other types of trajectory motion.

4.4. The procedure

The research tool was a questionnaire based on open-ended questions. This questionnaire was administered to all students. Students were asked to answer questions based on descriptions of the tasks and provide the necessary justifications to their responses. In particular, the students were asked to evaluate *qualitatively* the experimental processes of the tasks and justify their responses without using mathematical expressions. The questionnaire (Appendix) included three tasks concerning the concepts of velocity (v) and acceleration (a) of two similar objects (balls) moving in the gravitational field. The questions focused on three parameters: the mass of the two objects, the height of the free fall's starting point and the type of the motion. The first task concerned two freely falling balls with different masses. The second task concerned two freely falling balls starting from different heights. The third task concerned a freely falling ball and a ball with a constant horizontal velocity component.

5. Analysis

The analysis of the research data included two distinct phases or levels of statistical analysis. The first phase is based on the statistical description of the data. The second one involves the use of a Multiple Correspondence Analysis (Benzécri, 1992) with the statistical software package SPAD (2000).

5.1. Descriptive analysis

Our initial analysis of the data produced a set of mental models by identifying the relationships between the students' reasoning procedures. A procedure is a statement schematizing ideas and explanations that are not random or isolated but are common to several students. The related reasoning procedures used by the students in this study have been classified in the following categories:

1. Effectual answers (E), were characterized those answers that gave a correct response to the tasks and were based on the relevant scientific models.
2. Various difficulties (D), characterizing students' responses which exhibited misconceptions not common to several students or responses which correspond to correct answers, but are based on incomplete or no reasoning.
3. Context dependent misconceptions (M), in which key elements in students' reasoning were contextual features, scientifically irrelevant to the subject of the task, such as the mass of the balls, the height of the starting point and the type of their motion.
4. Inefficient responses (I), which were students' responses that gave no answer at all or gave answers totally irrelevant to the subject of the questions.

5.1.1. Task T1

As shown in Table 1 (students' answers in task T1a), 21.7% of the control group students gave inefficient answers while only 6.6% of the experimental group did so. In fact, most of the students' responses falling in this category were no answers at all. However, there were cases where students did provide an answer that was considered as inefficient; examples of such answers are presented below:

> The two balls have the same velocity because they fall simultaneously
>
> The two balls have the same velocity because the air resistance is negligible
>
> The two balls have the same velocity because they are not subjected to any force

Table 1

Descriptive statistics of students' responses to task T1a (comparison of the velocity of two freely falling balls starting simultaneously from the same height)

Item[a]	Procedure	Control group % ($n=60$)	Experiment group % ($n=30$)
I	Inefficient	21.7	6.6
M	Ball B has larger (or doubled) velocity than ball A	50.0	26.7
D	The two balls have the same velocity (no justification)	8.3	3.3
E	The two balls have the same velocity (efficient justification)	20.0	63.3

[a] I, inefficient responses; M, context dependent misconceptions; D, various difficulties; E, effectual answers.

The most frequent misconception revealed by the analysis of students' answers is based on Aristotelian ideas about the free fall. Fifty percent of the control group students seemed to believe that the speed of the ball is proportional or correlated to its weight. On the other hand, 26.7% of the experimental group students hold the same beliefs. This misconception has also been detected in other studies concerning college students (Halloun & Hestenes, 1985; Whitaker, 1983).

Only 20.0% of the control group students gave scientifically correct responses, arguing that

> The two balls have the same velocity, because free fall depends only on the gravity constant

In the experimental group more than 6 out of 10 students gave correct responses with sufficient justification.

Table 2 below classifies students' responses to task T1b concerned the concept of acceleration. Among the control group students 16.6% gave inefficient responses, while only one student in the experimental group did the same. Most of the control group students did not answer at all. Some of them however gave the following answers that were also considered as inefficient:

> The two balls have the same acceleration because they start falling simultaneously

> The two balls have the same acceleration because they fall from the same height

The most frequent students' misconception identified seems to be based on the belief that acceleration is related to the ball's weight. Since students seem to have employed the same belief about velocity (see task T1a), we assume that students tend to confuse the concepts of velocity and acceleration. Forty percent of the control group students displayed this belief. On the other hand, 26.7% of the experimental group students seem to also hold this alternative conception.

Among the control group students, only 26.7% gave correct responses such as:

> The two balls have the same acceleration, which equals to the gravity constant

In the experimental group 60.0% of the students gave a scientifically correct answer.

Table 2

Descriptive statistics of students' responses to task T1b (comparison of the acceleration of two freely falling balls starting simultaneously from the same height)

Item[a]	Procedure	Control group % ($n=60$)	Experiment group % ($n=30$)
I	Inefficient	16.6	3.3
M1	Ball A has larger (or doubled) acceleration than ball B, since ball B has a doubled mass	6.6	0
M2	Ball B has larger (or doubled) acceleration than ball A, since its mass is doubled	40.1	26.7
D	The two balls have the same acceleration (no justification)	10.0	10.0
E	The two balls have the same acceleration, which equals the gravity constant	26.7	60.0

[a] I, inefficient responses; M, context dependent misconceptions; D, various difficulties; E, effectual answers.

Table 3
Descriptive statistics of students' responses to task T2a (comparison of the velocity of two freely falling balls starting simultaneously from a different height)

Item[a]	Procedure	Control group % ($n=60$)	Experiment group % ($n=30$)
I	Inefficient	33.4	13.3
M1	Ball A has larger velocity than ball B, because it moves for longer time	3.3	13.3
M2	Ball A has larger velocity than ball B, because it falls from a higher height	20.0	30.0
D1	Ball A has larger velocity than ball B, because it has larger acceleration	5.0	3.3
D2	Ball A has larger velocity than ball B (no justification)	18.4	0
E	Ball A has larger velocity than ball B, because it moves with zero initial velocity and the same acceleration for longer time	16.6	40.1
E	Ball A has larger velocity than ball B according to the energy conservation theorem	3.3	0

[a] I, inefficient responses; M, context dependent misconceptions; D, various difficulties; E, effectual answers.

5.1.2. Task T2

In Table 3, results concerning students' responses to task T2a (which compares the motions of two similar objects falling freely from a different height) are presented. One out of three control group students gave inefficient responses. Among the experimental group students (13.3%) provided us with inefficient answers. Some of the responses were no answers at all. Examples of students' answers that were also classified as inefficient are shown below:

> The two balls have the same velocity because they fall simultaneously with the same acceleration

> The two balls have the same velocity because they have the same acceleration, but ball B will reach the ground sooner

> The two balls have the same velocity because they fall freely

As shown in Table 3, although students in the experimental group exhibited most of the inefficient types of answers that were also given by control group students, we observe a gradual shift to responses that were close to the scientifically correct ones. This is the case of the following answer:

> Ball A has larger velocity than ball B, because it falls from a higher height

This seems not to be a strong misconception but rather an incomplete answer, since the students did not focus their justification on the key element of the task, i.e. that the balls are uniformly accelerated by the earth's gravitational field with zero initial velocity. Four out of 10

Table 4
Descriptive statistics of students' responses to task T2b (comparison of the acceleration of two freely falling balls starting simultaneously from a different height)

Item[a]	Procedure	Control group % ($n=60$)	Experiment group % ($n=30$)
I	Inefficient	25.0	3.3
M	Ball A has larger acceleration than ball B, because it falls from a larger height	25.0	10.0
D	The two balls have the same acceleration (inefficient justification)	20.0	10.0
E	The two balls have the same acceleration (efficient justification)	30.0	76.7

[a] I, inefficient responses; M, context dependent misconceptions; D, various difficulties; E, effectual answers.

experimental group students gave scientifically correct answers. On the other hand, only 20.0% of the control group students gave correct answers.

In Table 4 we classify our results concerning student's responses to task T2b. In this task 25.0% of the control group students gave inefficient responses, while in the experimental group only one student (3.3%) did the same. Most of the students in the control group gave no answer at all, while two of them gave the following answer:

> Ball B has larger acceleration because it is always in front of ball A

In this task 25.0% of the students in the control group exhibited difficulties in understanding the concept of acceleration. These difficulties were related to contextual characteristics like the height of the free fall. Among the control group students (30.0%) provided us with efficient justifications, while 76.7% of the experimental group students did the same.

5.2. Task T3

This task demands from students employ their ideas on trajectory motion and their understanding of the independence of the horizontal and vertical components of velocity. Table 5 shows students' responses to task T3a concerning the comparison of speed in two different projectile motions.

From a qualitative point of view these answers are similar, indicating alternative conceptions of the same type. In this task 36.7% in the control group gave inefficient answers (most of them gave no answer at all), while only 10.0% of the experimental group students did the same.

Among the control group students (25.0%) answered that the two balls have the same speed. The corresponding percentage of the experimental group students is 36.7%. Characteristic justifications were the following:

> The two balls have the same speed because they have the same acceleration

> The two balls have the same speed because they start falling from the same height

> The two balls have the same speed because they have the same acceleration and the only force they are subjected to is their weight.

Table 5
Descriptive statistics of students' responses to task T3a (comparison of the speed of a freely falling ball and a horizontally thrown ball from the same height)

Item[a]	Procedure	Control group % ($n=60$)	Experiment group % ($n=30$)
I	Inefficient	36.7	10.0
M1	Ball A has larger speed than ball B, because it falls vertically	21.7	13.3
M2	The two balls have the same speed	25.0	36.7
D1	Ball B has larger speed than ball A (inefficient justification)	8.3	33.4
D2	The two balls have different speed (Vb is the superposition of the Vx and Vy components)	6.6	3.3
E	Ball B has larger speed than ball A, because it is the superposition of the Vx and Vy component (Vy is the same for both balls)	1.7	3.3

[a] I, inefficient responses; M, context dependent misconceptions; D, various difficulties; E, effectual answers.

It is also interesting that 21.7% of the control group students argued that

Ball A that moves vertically has higher speed than ball B.

On the other hand, 33.4% of students in the experimental group argued that ball B has higher speed. A significant number of students in the experimental group had also drawn the trajectory of the motion. Although they had the picture of this motion, they failed to apply effectively the independence of the horizontal and vertical components of the velocity. Most of these responses could be considered to be closer to the investigated physical situation, although students argued that

Ball B has larger speed than ball A, because it covers a larger distance

Ball B has larger speed than ball A, because it falls for a longer time

It is evident from our results that students in both groups face serious understanding and comprehension problems concerning the principle of the independence of the horizontal and vertical components of the velocity. Similar problems have also been identified in a study concerning college students (Whitaker, 1983). All students from both groups had been taught the topic of the independence of the horizontal and vertical components of the velocity through conventional instruction. The experimental group students had not used relevant simulations during our intervention. We believe that the issue of the superposition of the horizontal and vertical components of velocity is quite suitable to evaluate the effects of the use of simulations to students' mental models.

Table 6 shows the students' responses to task T3b. In this task 41.7% of the control group students gave inefficient responses while in the experiment group only three students (10.0%) provided us with similar answers. Most of inefficient responses were no answers at all. Examples of other inefficient responses are shown below:

Table 6
Descriptive statistics of students' responses to task T3b (comparison of the acceleration of a freely falling ball and a horizontally thrown ball from the same height)

Item[a]	Procedure	Control group % ($n=60$)	Experiment group % ($n=30$)
I	Inefficient	41.7	10.0
M1	Ball A has larger acceleration than ball B, because it falls vertically	18.4	13.3
M2	Ball B has larger acceleration than ball A, because it falls horizontally	13.3	13.3
D	The two balls have the same acceleration (no justification)	10.0	0
E	The two balls have the same acceleration, that equals the gravity acceleration g (efficient justification)	16.6	63.4

[a] I, inefficient responses; M, context dependent misconceptions; D, various difficulties; E, effectual answers.

> The acceleration of the two balls is proportional to their velocity

> The two balls have different acceleration because ball B has an initial velocity and it is not subjected only to the weight force

> The two balls have the same acceleration because they fall freely with the same initial velocity.

A considerable percentage of students in both groups gave justifications where the key element of reasoning was the type of motion and not the relevant kinematical characteristics concerning the concept of acceleration. These students seem not to have realized that acceleration due to gravity acts independently of motion. On the other hand, 63.4% of the experimental group students answered correctly. This indicates that they had understood the concept of acceleration in projectile motion in the earth's gravitational field.

The results of the descriptive statistics indicate that there are significant differences between the two groups. Fig. 2 shows the comparison diagram of students' correct answers for both groups. Overall, it appears that educational environments based on simulations assist students in overcoming their cognitive constraints and misconceptions about the trajectory motion.

5.3. Multiple correspondence analysis

The structure of students' alternative conceptions and knowledge cannot be revealed through conventional statistical methods. Moreover a descriptive analysis of the students' responses reveals only their different approaches to the various tasks. To overcome these limitations we employed a multiple correspondence analysis (Benzécri, 1992). We chose this type of factorial analysis because it reveals various correlations, thus allowing us to study thoroughly the students' knowledge and misconceptions. Using this analysis we had the opportunity to obtain a more global view of the students' answers and the relevant parameters.

The subjects under study are usually described by a large number of parameters. With the help of a variance method we are able to derive not only the students' alternative conceptions and knowledge but also their correlations. Furthermore, we can construct a topographic map of those parameters, thus making clearer categorizations of students on the basis of their cognitive approach to the different tasks. We believe that this analysis provides us with a wider perspective concerning students':

1. knowledge and misconceptions; and
2. classification, on the basis of their attitudes in conjunction with their age, sex, social-economic background, computer experience and other characteristics.

In particular, the employment of the multiple correspondence analysis is aimed to help us:

1. derive student's knowledge and alternative conceptions;
2. understand the structure and the organization of students' knowledge and misconceptions and also how they group or correlate; and
3. reveal similarities and differences between control and experimental group students.

More specifically, we have performed three analyses. The first concerns the control group, the second the experimental group and the third intertwines all data from both groups.

5.3.1. The control group

In order to derive factorial analysis of the data concerning the control group, we have used as dependent variables the students' responses in the six tasks. Students' age, sex, school and computer experience, have been used as independent variables.

The multiple correspondence analysis reveals the first axis (factor) with eigenvalue $\lambda_1 = 0.6632$ and coefficient of inertia $\tau_1 = 17.30\%$. This axis is characterized as the efficiency–inefficiency axis.

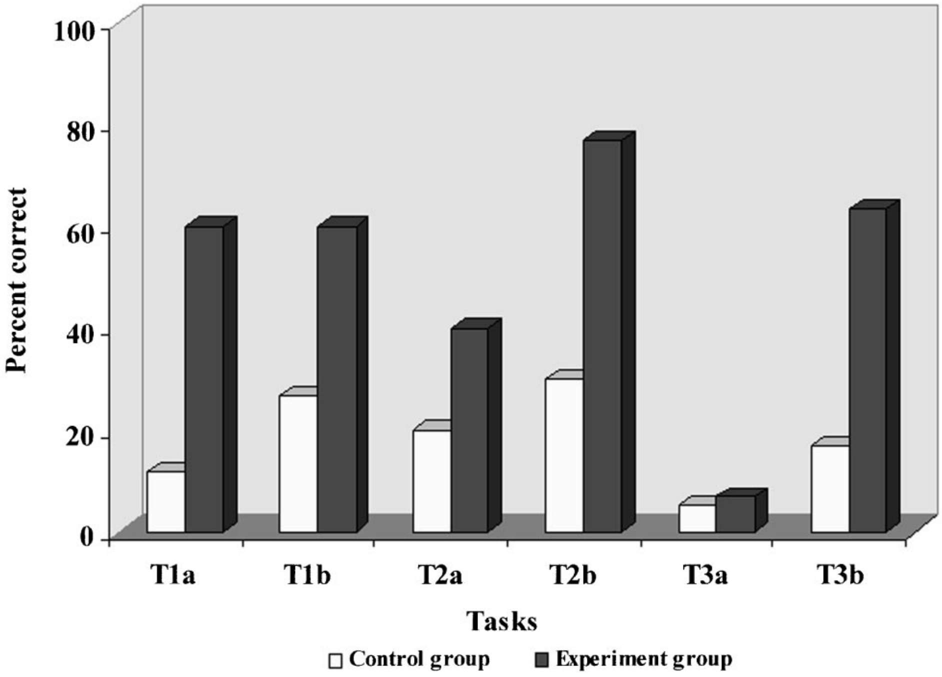


Fig. 2. Students' effectual answers for the control and the experimental group.

It is a very important factor in our analysis, since it shows the contradiction between the students' effectual responses on the one hand and the inefficient answers and alternative conceptions on the other. It is evident that the students' answers are explicitly grouped around two poles. The first pole is defined by the students' well-structured knowledge and the second one corresponds to those students for whom the relevant physical concepts are totally unstructured.

The second axis, with eigenvalue $\lambda_2 = 0.4299$ and coefficient of inertia $\tau_2 = 11.22\%$, can be characterized as the inefficiency–misconceptions axis. This factor opposes students' inefficient responses with the alternative conceptions of the various tasks that are context dependent. It is evident that there exists a group of students with unstructured knowledge contradicting the group of the constituted misconceptions.

Fig. 3 shows the graphical representation of our results in the variance system defined by the first two axes (factors). Students' responses are represented in the graph in the form Task number-Procedure code. The values of the variables, when projected on the variance plane, define three clouds. This situation has been described as the *Gouttman effect* and indicates a strong correlation between the values of the variables under analysis (Lebart, Morineau & Pitron, 1998).

The first cloud N1 is defined by the values that correspond to the effectual responses of the six tasks and the value that corresponds to the misconception T3a-M2, which concerns students who argued that

> The two balls have the same velocity.

This misconception group consists of a small number of students, since the corresponding values are far from the origin of the two axes. The existence of the value T3a-M2 inside the cloud N1 implies that, although some students have responded efficiently to the other tasks (in other

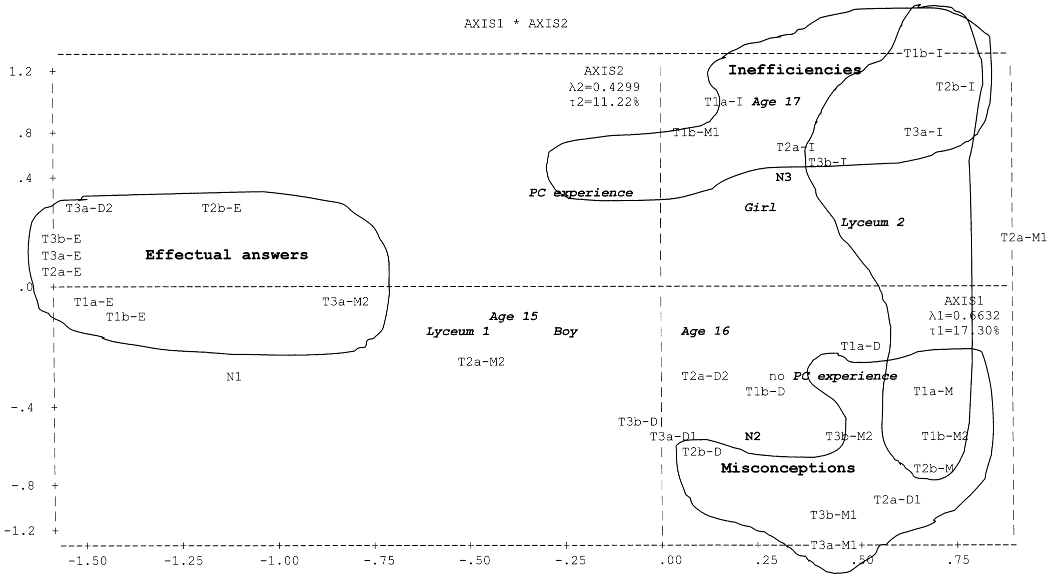


Fig. 3. Variance graph of the control group in the system defined by the two axes. It represents the opposition between three groups of students: effectual responses, inefficient responses, and various misconceptions.

words they have effectively understood and employed the concepts of velocity and acceleration), they hold this alternative conception.

From the graph and the position of the values corresponding to the independent variables we can derive that the older students, the girls, the students having computer experience and those coming from Lyceum 2 are classified, at a larger percentage, near the cloud N3 of the inefficient answers. The younger students, the boys and the students coming from Lyceum 1 are classified, at a larger percentage, near the cloud N1 of the efficient answers. The students with no experience with computers are placed near to the cloud of misconceptions N2.

5.3.2. The experimental group

In the analysis of the data concerning the students in the experimental group we have used as dependent variables their responses to the six tasks. Students' age, sex and experience with computers constituted the independent variables.

The analysis reveals the first axis with eigenvalue $\lambda_1 = 0.6693$ and coefficient of inertia $\tau_1 = 19.12\%$. This axis is characterized as the efficiency–inefficiency and misconceptions axis. The effectual responses to the six tasks together with the misconception T3a-M2 are located to the left side of this axis. With the exception of the task T3a, the efficient responses in the experimental group are more frequent. In the right side there are the students' inefficient responses for tasks T3a and T3b (T3a-I, T3b-I) and the context dependent misconceptions about the six tasks of the research.

The second axis with eigenvalue $\lambda_2 = 0.4851$ and coefficient of inertia $\tau_2 = 13.86\%$ is the inefficiency–misconceptions axis. It reveals the contradiction between students' inefficient responses to tasks T2b, T3b, T3a, T2a on the one hand, and the alternative conceptions based on various contextual features of the motions and the responses without justification for task T1a on the other.

In Fig. 4 the variance graph describing the experiment group is presented. There are three clouds, indicating a strong correlation between the values of the relevant variables (Gouttman

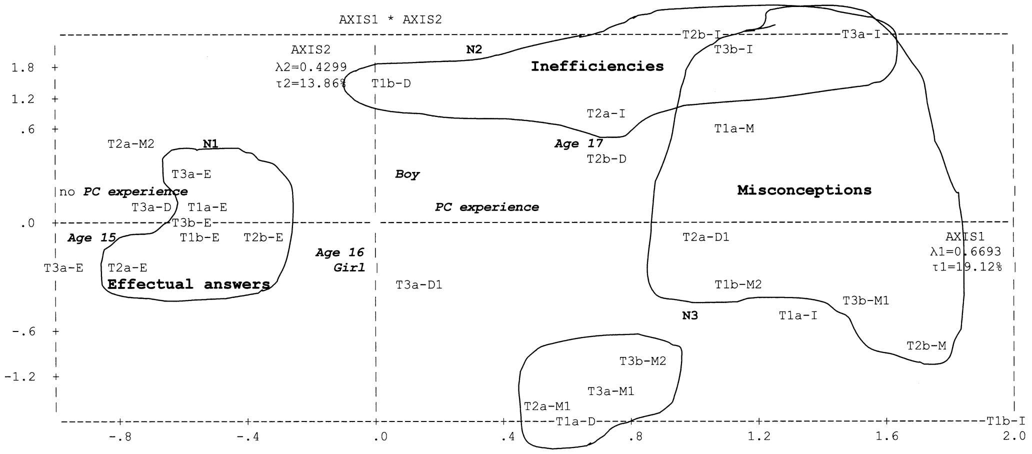


Fig. 4. Variance graph of the experimental group in the system defined by the two axes. It represents the opposition between three groups of students: effectual responses, inefficient responses, and various misconceptions.

effect). There is an explicit similarity with the students in the control group, as we can observe in Fig. 3. The cloud N1 consists of the values corresponding to the effectual responses to tasks T1a, T2a, T1b, T2b and T3b and to the misconception T3a-M2. As shown in Fig. 4 the value that concerns the effectual answer to the task T3a is placed near the cloud N1, although its distance from the origin of the two variance axes is large, showing that only a small number of students have approached the task efficiently.

Cloud N2 consists of the values corresponding to the ineffectual responses to the tasks and the difficulty T1b-D, which concerns correct answers with no or inefficient justification. Cloud N3 gathers various misconceptions concerning the concepts of velocity and acceleration. The position of the independent variables in the variance graph indicates that the younger students and the girls are grouped near the cloud N1 (efficient responses). On the other hand, the boys and the older students are found near the cloud N2 (inefficient responses).

5.3.3. *Total data analysis*

The third analysis was based on the data concerning both groups. This analysis allowed us to study similarities and differences between students in the control and the experiment group concerning their knowledge development and alternative conceptions about velocity and acceleration. We used as dependent variables the responses of the students (six variables). The independent variables were students' age, sex, school, group type (control and experimental) and their computer experience.

The first axis has eigenvalue $\lambda_1 = 0.6693$ and coefficient of inertia $\tau_1 = 17.48\%$. This factor defines the efficiency–inefficiency and misconceptions axis. The effectual responses to the five tasks T1a, T1b, T2a, T2b, T3b and the misconception T3a-M2 are gathered to its right side. In the left side there are students' inefficient approaches to tasks T2b, T3a, T3b and the context dependent misconceptions of the tasks T2b, T1b and T1a.

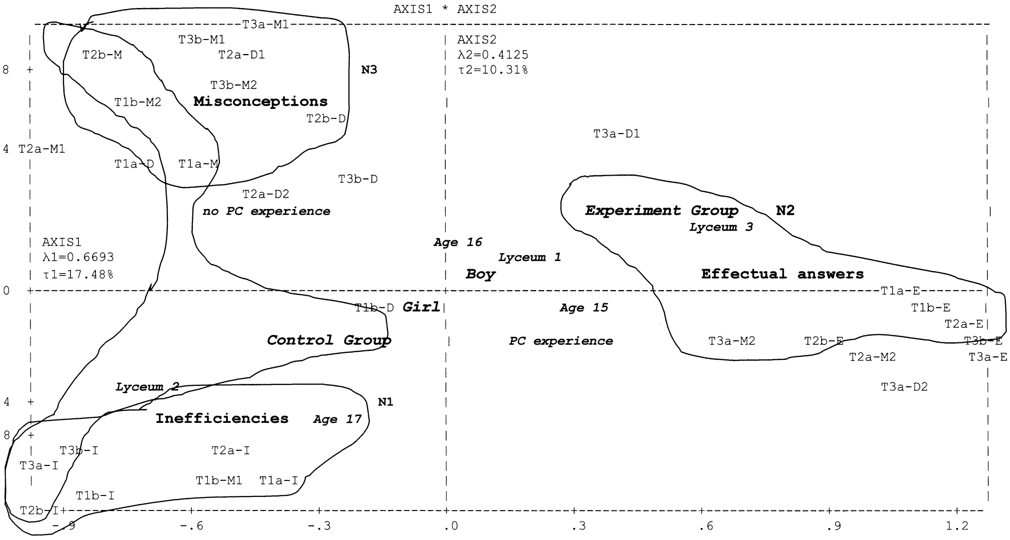


Fig. 5. Variance graph of the experiment and control groups in the system defined by the two axes. It represents the opposition between three groups of students: effectual responses, inefficient responses, and various misconceptions.

The second axis with eigenvalue $\lambda_2 = 0.4125$ and coefficient of inertia $\tau_2 = 10.31\%$ is the inefficiency–misconceptions axis. It shows the contradiction between students' inefficient responses to the six tasks and misconception T1b-M1 in one side, with the various alternative conceptions of the students in the other.

In the variance graph of Fig. 5 we can see three clouds. N1 is the cloud of the inefficient approaches, since it includes the totally irrelevant responses and misconception T1b-M1. N2 is the cloud of the effectual responses including also misconception T3a-M2. Finally, N3 is the cloud of the alternative conceptions.

Our results indicate that there is a strong correlation between the values of the three clouds (Gouttman effect). The position of the independent variables in the variance graph shows that the students in the experiment group, the younger children, the boys and the students who have computer experience gave efficient responses at a larger percentage. On the other hand, the students in the control group, the girls, the older students and Lyceum 2 gave inefficient responses at a larger percentage.

6. Conclusions

This study provided us with supportive evidence regarding the use of computer simulations in physics teaching and learning. Our analysis indicates that there are significant differences in students' achievement concerning the concepts of velocity and acceleration, depending on whether they have been engaged in tasks demanding the use of *Interactive Physics* stroboscopic representations or not.

From a qualitative point of view, the range of the students' types of responses is similar for both groups indicating alternative conceptions of the same type, but are different as far as their frequencies are concerned. Students in the experimental group exhibited significantly improved achievement rates. It seems that working with computer simulations helps students overcome their cognitive constraints and effectively apply the concept of instantaneous velocity and acceleration.

Furthermore, we have identified common students' misconceptions found in related studies (Halloun & Hestenes, 1985; Whitaker, 1983). Most of the students' inefficiencies are due to reasoning procedures focused on the contextual features of the physical processes, such as the mass of the moving objects, the height of their starting point or the type of motion. Furthermore, the confusion about the concepts of velocity and acceleration seems to play a central role in students' responses.

Our hypothesis about the role of computer simulations in physics teaching is strongly confirmed. It seems that educational environments based on simulations assist students to overcome their cognitive constraints and refine their alternative conceptions about the trajectory motion up to a significant point.

More specifically, we have found significant improvement of students' achievement for the tasks concerning the concept of acceleration. About 7 out of 10 students in the experiment group seem to have understood that the acceleration in trajectory motion is equal to the gravity constant and does not depend on the special contextual characteristics of each motion.

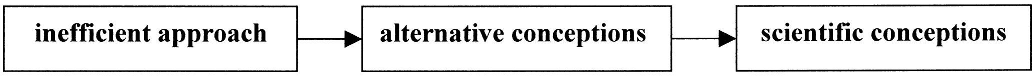


Fig. 6. Students' conceptual change using simulations.

The progress of the students in the experiment group is significantly improved in the two free fall tasks concerning the concept of velocity (tasks T1a and T2a). According to our teaching experience we believe that task T3a, which deals with two different projectile motions, is a difficult one. The students had to compare the speed of two objects with different kinematical characteristics. It seems that the participating students even after receiving instruction still hold their ideas and preconceptions. They face serious difficulties centered at the independence of the horizontal and vertical components of the velocity in the gravitational field.

Because the students from both groups received only traditional instruction on the topics related to task T3, we found no differences in students' achievement between them. This, albeit indirectly, confirms the argument that simulations can help students achieve conceptual change and meaningful understanding in physics.

What mainly differentiates the two groups is the explicit shift of the experimental group students from inefficient approaches and alternative conceptions to meaningful understanding of the concepts under discussion. The effects of learning using simulations were significant for the experimental group. The results of the multiple correspondence analysis indicate that the use of simulations reinforces students' conceptual change in a gradual process as shown in Fig. 6.

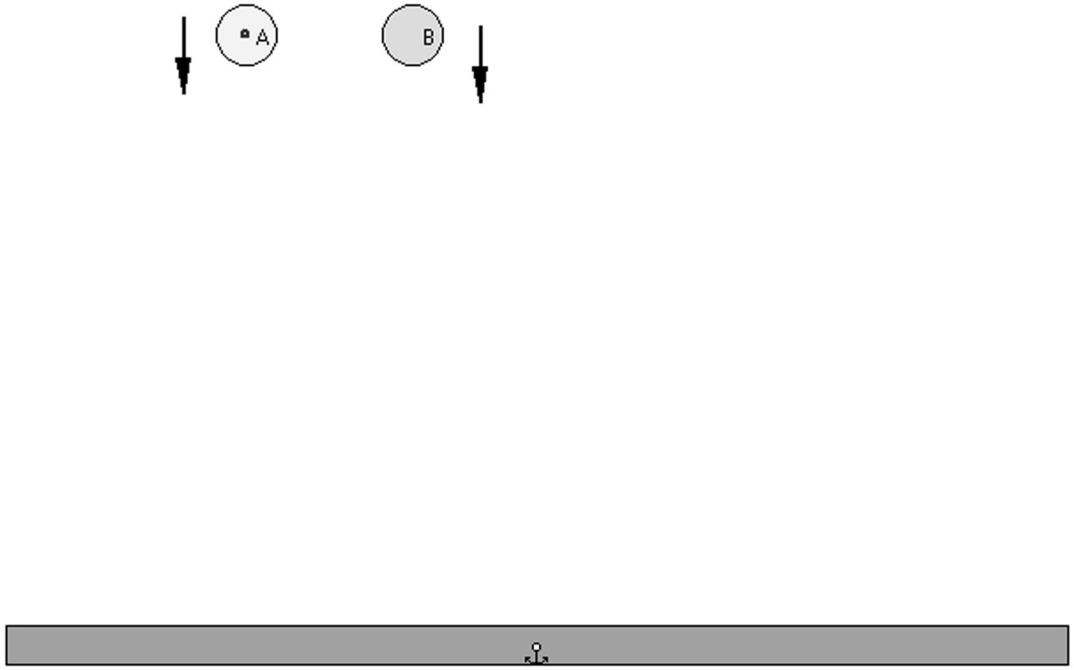
The use of simulations in physics teaching and learning opens up important research issues. The results presented here show that computer simulations could be used complementary or alternative to other instructional tools in order to facilitate students' understanding of velocity and acceleration.

Acknowledgements

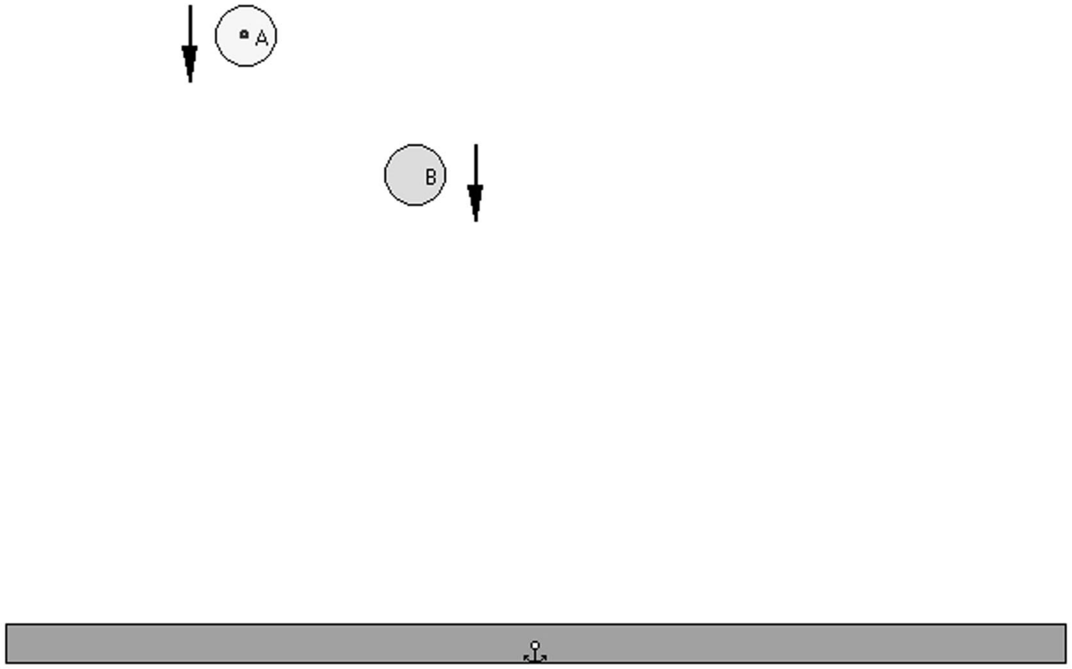
The authors are grateful to Dr. Andreas Kollias and Mr. Yiannis Goumenakis for their critical reading of the manuscript, and to the Physics teachers and the students who participated in the research.

Appendix. The questionnaire

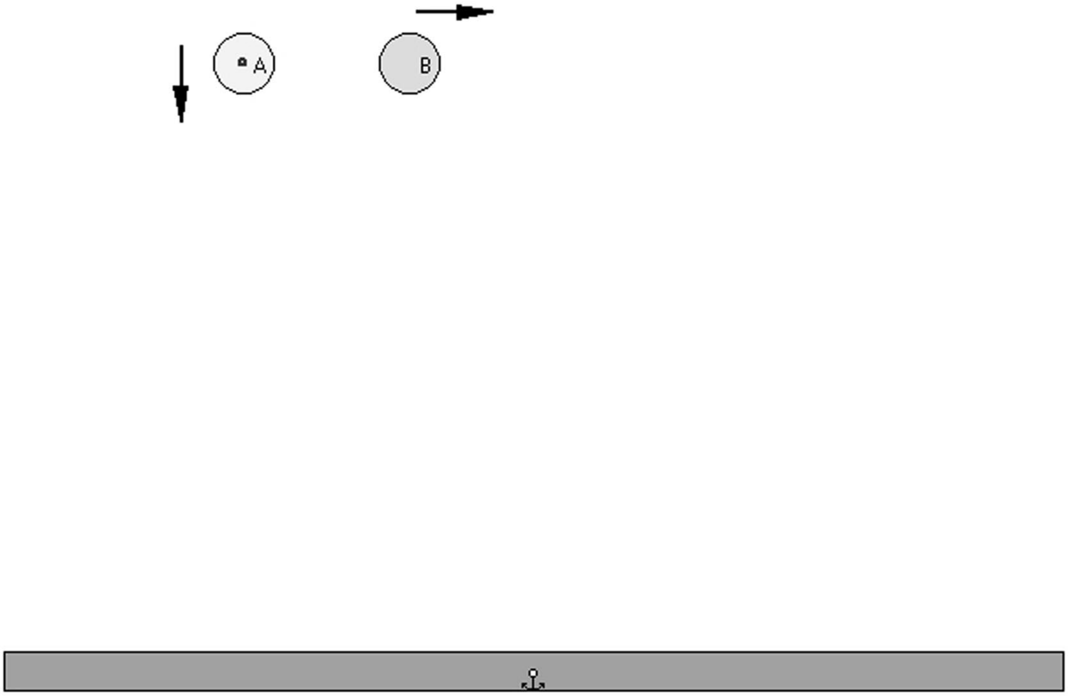
Task 1. Two balls, A and B, fall freely, starting simultaneously from the same height, as shown in the adjacent figure. Ball B has a mass which is twice the mass of ball A. (a) Compare the velocity of the two balls when they reach level E. (b) Compare the acceleration of the two balls. Justify your answers.



Task 2. Two balls A and B fall freely, starting simultaneously from a different height, as shown in the adjacent figure. (a) Compare the velocity of the two balls when they reach the ground. (b) Compare the acceleration of the two balls. Justify your answers.



Task 3. Ball A falls freely from a specific height. Simultaneously, ball B is thrown horizontally from the same height, as shown in the adjacent figure. (a) Compare the speed of the two balls when they reach the ground. (b) Compare the acceleration of the two balls. Justify your answers.



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