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To cite this article: T Radnai *et al* 2019 *J. Phys.: Conf. Ser.* **1223** 012006

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Educational experiments with motion simulation programs: can gamification be effective in teaching mechanics?

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Abstract. Students in secondary schools are all members of the so-called Z-generation. They grew up using their smartphones, tablets and the Internet. It is an obvious consequence that science teaching should also exploit this spontaneous interest in IT. A possible way to utilize this trend in teaching physics is to use motion simulation programs. These software are designed to simulate real-life physics experiments using realistic two-dimensional visualization, while motion-related data can be read from graphs that are displayed during the motion. The use of such programs can strengthen the previously acquainted knowledge in the topic of kinematics and dynamics, support problem solving skills, or just raise interest in the subject. The most well-known physics simulation software are Algodoo and Physion. A Hungarian company (Intellisense) has also been developing a similar software, FIZIKA with the contribution of our research group that can be used for free in schools and can be easily fit in physics education. In recent years, there has been an increasing amount of literature about the use of physics simulation programs, however no quantitative study has been conducted on how these programs effect student performance. Our research group completed an educational experiment on teaching kinematics involving about 500 students in the autumn of 2016. Half of the students used the simulation software in physics classes and at home, while the other half was the control group. After a few months, their development in the subject was measured with a test and the results showed significant difference between the two groups.

1. Introduction

In the past decades the number of physics lessons was dramatically decreased in Hungary, so present students in secondary school have only 2 lessons per week for 3 years. Physics teachers have much less opportunity to deepen their students' knowledge that leads to the sad fact that most students can solve only the easiest well-defined problems that contains only basic math. That is why teachers must boost the self-motivation of their students in every possible way.

Real experiments can be extremely motivating, but they have their downsides: preparation and demonstration may take too much time and sometimes experiment tools simply do not work the way they should. An alternative way to increase the motivation can be the application of simulation software. The most important advantage of simulations is that students can run them by themselves without the help of a teacher or parent. Simulation programs are extremely useful tools, since they work by the same rules that students learn in physics lessons and have a user interface that is highly intuitive for them.

PhET (http://phet.colorado.edu) is the most commonly used website in physics education, that provides a huge database of ready-made simulations. This website is growing since its foundation in 2002 and nowadays has over 360 million simulations. After the first few years, the simulations covered almost the whole physics curriculum [1]. Perkins at al. [2] analyzed a large-scale self-report survey from about 1500 educators who were using PhET. They found, that PhET simulations are flexible tools used by a broad range of educators, with diverse student populations, to support a wide range of pedagogical goals and using a variety of instructional approaches.

A handful of motion simulation programs have been developed in the last decade. These programs drew a lot attention in the physics teaching community. Physics educators from all around the world tried Algodoo [3-5], and showed that these programs can be useful at various parts of undergraduate or high school physics. Çelik et al. [6] developed a questionnaire to explore the participating teachers' opinion about virtual physics teaching. They held an example lesson with Algodoo for the participants and asked them to fill the questionnaire before and after the lesson. They concluded, using a simulation program in physics teaching has a positive impact and can improve the students' understanding.

When our research group started working with motion simulation programs, we realized, that we only have an intuitive impression that these programs help the students. Hence, we decided to conduct an investigation to quantify the impact of long-term usage of the program on student performance. That is extremely important not just for academicals purposes, but for practical teaching also. In the academic year 2014-2015, we organized a pilot education experiment in several schools from different parts of Hungary [7]. Since this experiment was executed in a small number of schools with relatively few students (about 160), we handled those results as possible conclusions giving information for further experiments.

In the present paper we show the results of an extended experiment. In this experiment about 500 students were involved, which allowed us to make statistical analysis. Half of them learned kinematics the usual way, as a control group, while the other half studied with using motion simulation programs for about 3 months. They used the program in the classrooms and also at home. In the end all the students wrote the same test.

2. Education experiments

2.1. The investigated software (FIZIKA)
A small Hungarian company, called Intellisense (http://intellisense.education), realised the possibility in using simulation software in physics education and asked researchers at Eötvös University, to help them to develop their software in the way most fitting for physics education. The other well-known product of Intellisense is LabCamera, which is a motion analyser program. These software are offered for free use for all science teachers in the world as part of the "Intellisense for Science Teachers" Programme (IST).

Program FIZIKA has the same goal as Algodoo: it lets users create their own simulations by drawing objects and choosing their physical parameters. When the user starts the simulation, the program takes these parameters, as well as some constants into account and solves the differential equations of motion of every element numerically. As an advantage, the program does this in a colourful, playful and interactive way, while the graphs and vectors are displayed in a similar way how a teacher would draw them in a physics lesson. Since the program offers graphical representation of motions, it can be an enormous help in teaching kinematics. Detailed information about the FIZIKA program can be find in Ref [8].

2.2. Organising the educational experiment
In our research, we wanted to verify our assumptions that quantitative graphical representation and problem-solving skills are improved by using the program. We hypothesized that the students will perform better in graphical interpretation, graphing data, reading graphs, and graphical representation in problem solving. We also assumed that the students' individual work with the computer develops

personal initiative skills, independent thinking. Furthermore, the possibility to create their own simulations helps them to see the essentials of some problems.

Participants of the educational experiment applied from all across Hungary, from all kinds of schools. Participating teachers were required to teach at least one student group in class 9 (first year of secondary school, 14 year old students). They also had to guarantee another student group from the same school as reference for the test. In their own group they had to teach using the simulation program, while in the other group they (or one of their colleagues) had to teach without it. Teachers were asked to volunteer only if the two parallel groups had similar ability and physics knowledge to ensure that we would have the possibility to compare the results.

Applicants were provided with a full-day technical and methodological guide. During the training each participant used his own computer, so most technical problems were resolved, and the participants gained an overview of the new method of teaching the subject. It should be noted the participating teachers, who used the program were not forbidden to use any other methods, but were asked to use the simulations as an addition to the earlier proven methods. We encouraged the colleagues to use the programs in regular classes, as well as in extracurricular classes. We asked the teachers to encourage their interested students to create their own simulations.

For the school work, teachers received detailed written guides. These included suggestions and ideas for the effective application of the program (see example in next section).

We also provided electronic worksheets for students, which could be used for homework. Our idea was that the students would download the worksheets from the internet and then send them back to the teacher electronically after solving the questions and tasks. To improve the teacher's work, we also provided a solution pattern for the worksheets. An example of a task sheet and its solution is given in Ref [7]. In addition to the written teaching materials and the worksheets, we provided 19 pre-prepared simulations with technical descriptions and evaluations.

The participants also had to ensure that at the end of the topic both groups wrote the same test, to measure the effect of teaching and learning with the program. The end of topic test contained 8 exercises about motions (Ref [9] contains the full test). There were some exercises that required only simple calculations, but there were some, that required creativity, for example analysing a picture. The test did not contain anything that was directly related to computer work, only assessed basic requirements of the topic, such as uniform and uniformly accelerated motions along a straight line, free-fall, vertical and horizontal projection. In this way, we wanted to ensure that the results of the experimental and the reference group were comparable.

2.3. Sample lesson from the teacher's guide

In this section we would like to show an example lesson from the teacher's guide. Since it is only an example of a worksheet, we placed it in a text box.

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4. Galileo's inclined plane experiment for investigating uniform acceleration

Goal:

Repeating the result of the live experiment. Quantitative interpretation of the simulated motion using Galileo's method. Applying the mathematical relationship describing the motion for simulation measurements. Experimenting with the FIZIKA software.

The simulation contains:

A few meters long inclined plane of small inclination. A ball on the top of the slope with a sensor attached measuring the displacement of the ball.
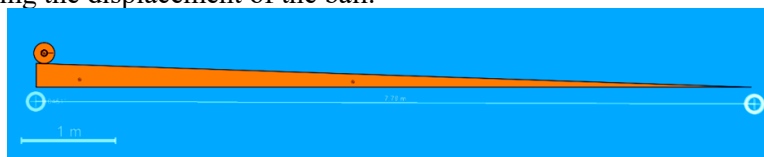
Methodological recommendation:

Before the simulation measurement it is mandatory to perform Galileo's historic experiment in the classroom and it is advised to give the students an optional task to look up the background of the experiment. The measurement can be performed by any of the students under the teacher's guidance. The experiment only requires starting the simulation and reading a graph.

Parameters of the simulation:

Length of the inclined plane: L=7.8 m
Angle of inclination: α = 1.9°

Processing the simulation:

Galileo assumed that the speed of the ball increases proportionally with time throughout the motion. From this assumption he deduced that the distance covered divided by the square of the time taken should be a constant that is independent of the distance covered:

$$\frac{s_1}{t_1^2} = \frac{s_2}{t_2^2} = \frac{s_3}{t_3^2} = \cdots.. = \frac{s_i}{t_i^2} = constant$$

Task:

Read several corresponding distance and time data pairs from the x – t graph of motion (e.g. read the distances covered by the end of the first, second, third... seconds). Prove Galileo's statement and calculate the value of the constant.

Solution:

The graph of horizontal displacement versus time is shown below. This is a typical parabolic curve from which corresponding data pairs can be read as shown in the table below.
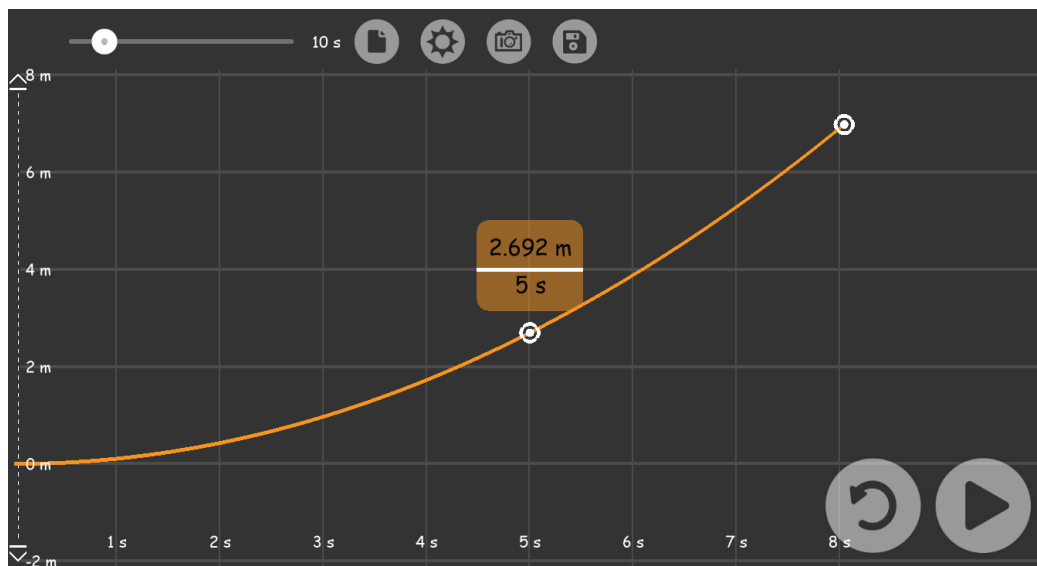
$t_i (s)$	1	2	3	4	5	6	7	8
$s_i (m)$	0.11	0.44	0.99	1.74	2.69	3.90	5.31	6.93
$\frac{s_i}{t_i^2}$	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

The values of the distances divided by the squares of times taken are the same for all data pairs, therefore Galileo's statement is true. Galileo's statement can easily be derived from the well-known distance-time relationship: $s = \frac{a}{2} t^2$. Rearranging the formula gives:

$$\frac{s}{t^2} = \frac{a}{2} = constant$$

Homework

Determining the acceleration of the ball on the slope while rolling and slipping.

Suggested additional tasks

Verifying Galileo's statement about object sliding down on inclined planes arranged on the circumference of a circle.
Competition of balls between two different height points on different slopes.

2.4. Results

A total of 257 and 240 pupils wrote the survey in the experimental and reference groups, respectively. The results of the test are shown in figure 1. In the following, the results of the test are defined as the ratio of the score received by the students and the total number of available points in percentage.
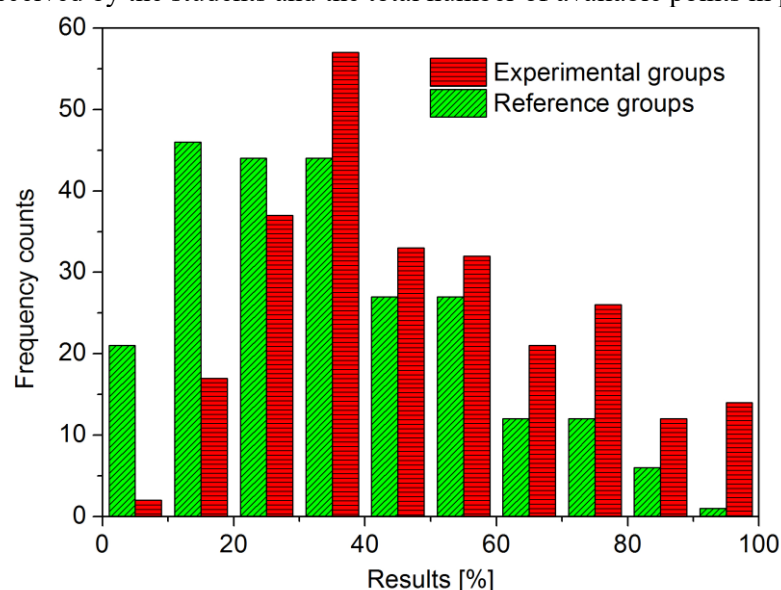

Figure. 1. The distribution of the result for the experimental and reference groups.

The average result was 49% with 23% standard deviation (SD) for the experimental groups (N=257), and 35% with 20% SD for the reference groups (N=240). It can be clearly seen that students showed better performance in the experimental groups. It can be gathered from figure 1. that the result distribution of the groups does not follow normal distribution. This is confirmed by Kolmogorov-Smirnov and Shapiro-Wilk normality tests, which show that at the 0.05 significance level, the data was not significantly drawn from a normally distributed population. Due to the non-normal distribution, the difference between the two groups was evaluated by Mann-Whitney test. The test shows that the difference is significant at the 0.01 significance level.

It is much more interesting if we examine the test exercises separately. Figure 2 shows the results for the different exercises. (The results are also shown in percentages for better comparison.)
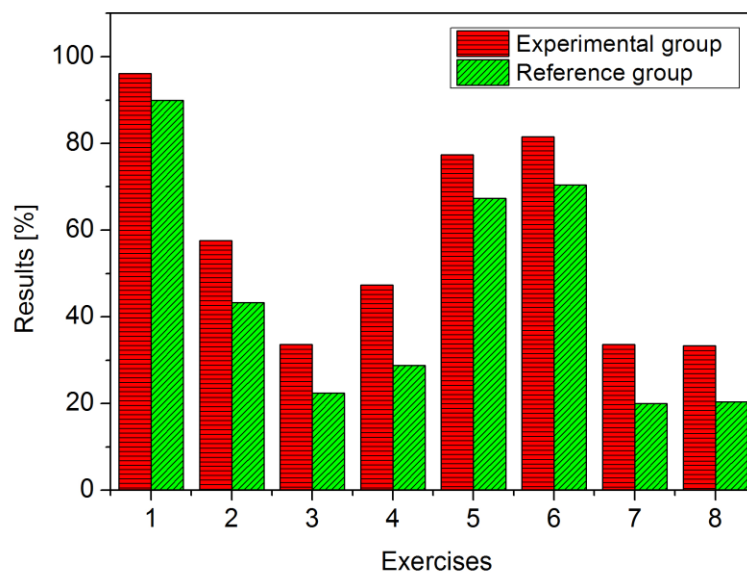
Figure 2. Average result of the end topic test for the different exercise. Test can be find in Ref [9].

Experimental classes (who used the program) had higher average scores for all the exercises. The difference between the two groups is significant in all task with 0.01 significance level except for the first one. The highest differences can be found in the results of tasks 2, 3, 4, 7 and 8. It should be noted that exercises 1, 5 and 6 were the easiest ones in the test.

Exercises 2 and 3 were aimed to test whether the use of the simulation program (and graphical representation) helps the students distinguish between the concepts of displacement, speed and acceleration.

In task 4 the ability to transform between graphs was checked. In this case there were no pre-drawn graphs which the students only had to analyse, the graphs in this question had to be drawn by the students themselves. In part a) a position – time ($x – t$) graph was given and a velocity-time ($v – t$) graph had to be drawn. In part b) a relationship in the opposite direction had to be used, a $v – t$ graph had to be converted to $x – t$.

Number 7 was a very interesting, unusual exercise. In order to be able to carry out the necessary calculations, students first needed to measure distances on a given photo. It seems that those students who took part of the experiment, had to use their own creativity to solve problems (they had to run simulations, evaluate graphs, read data from graphs, etc.,…) therefore showed more self-confidence when encountering an unknown type of problem.

Exercise 8 was a hard horizontal projection task. Part a) of this exercise started with an unusual question. Instead of having to find a vertical displacement corresponding to a given horizontal displacement, students had to decide whether a stunt was feasible with the given parameters. The oddness of this question lies in the fact that students first had to calculate the horizontal displacement for the given level difference and then compare it with the distance of the edges. Thus one of the data given was not used for calculation only for comparison, which is unusual. In part b) the velocity of the car had to be calculated when the car hits the second platform. This required calculating two components separately and then adding them as vectors. In part c) the trace of the centre of mass of the car had to be drawn.

3. Conclusion

In this study the effectiveness of a motion simulation program (FIZIKA) was examined in teaching kinematics. About 500 students were tested in an education experiments. Half of them learned kinematics with the classical way (as reference group) while the other half learned using motion

simulation programs (FIZIKA) for about 3 month. The numbers show that the results of the groups using the simulation program are significantly better than the reference groups studying without simulation programs. Based on the analysis of the tasks, we have come to the following conclusions:

- Use of the program helps students to understand the conceptual difference between distance, displacement, speed and acceleration. The ability to establish relationship between graphs is improved.
- Students who had to act actively (to simulate, rearrange, interpret computer graphs, read data) during the use of the simulation program had a greater courage in solving previously unseen tasks. Their creativity developed.
- In the case of easier tasks it is difficult to detect any differences between the two groups. In the case of moderately and most difficult tasks, the difference is more significant. This indicates that the simulation program can provide significant help in the middle field, and the most talented ones. From the point of view of the minimum requirements, the program apparently does not give much extra.

4. Further investigations

The simulation program can also be used in the topic of dynamics, where vector representation of forces is a powerful tool to make students understand the basic concepts of forces. As a continuation of the project, in the autumn of 2017, we started to conduct another educational experiment on using simulation program in teaching dynamics involving 20 teachers and 600 students. The teachers were trained for the use of the program before the experiment and they also received a ready-made package containing demonstrational and homework simulations with descriptions. In the spring of 2018 we are near to the end of the project and we are waiting for the participating teachers to share their results with us.

Acknowledgements

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