Supporting Conceptual Change in Physics with a Serious Game

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Abstract Serious games can play a role in physics education, especially in elementary mechanics, as they can provide hands-on experience with force and motion in a simulated environment. In this study, we used a serious three-dimensional immersive game to provide students with an environment in which they needed to search for explanations beyond their preconceptions. We expected that students would see the need for new theories. The goal of the game was for students to direct a ball to a target using forces they could regulate. In a quasi-experimental evaluation between a game group and a traditional group (receiving no game) with 73 participants no significant gain in knowledge was measured in either group. However, students who played the game were more motivated than students who experienced the traditional lesson). Implications for renewed game design and research are discussed.

1 Introduction

1.1 The Role of Preconceptions in Physics Teaching

Students encounter different kinds of motion on a daily basis. In many cases, these can be described on a superficial level using a small set of simple ideas in which terms such as energy are not clearly defined. For more complex kinds of motion, these ideas lead to wrong predictions (Hestenes et al. 1992). For instance, when students are faced with the following problem, they often predict a straight path for the engine: A rocket drifting sideways in outer space is subject to no outside forces; at a certain point, the rocket's engine starts to produce a constant thrust perpendicular to the previous line of movement. However, the correct answer is a parabolic path. One goal of physics

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teaching is to tackle these existing ideas about the laws of motion and promote student comprehension based on physical concepts (Clement 1982). Studies have shown that an effective way to do so in science education is by giving explicit attention to existing preconceptions (Chi et al. 1994; Duit and Treagust 2003; Vosniadou 1994). More specifically, giving preconceptions a central role when teaching the first and second laws of Newton has been shown to yield positive comprehension effects (Muller et al. 2008). Also, using preconceptions as a basis for instruction can contribute to building scientific literacy (De Boer 2000). By creating situations in which preconceptions are no longer sufficient as an explanation, students are exposed to the need to engage in scientific reasoning such as the development of new hypotheses and theories. In the problem-posing approach (Klaassen 1995), this idea is employed: By creating situations in which preconceptions are no longer adequate explanations, learners will see the need for new theories. Students may be able to describe simple motions on a superficial level; however, more complex kinds of motion must be described with more in-depth explanations. Therefore, students need to alter their existing preconceptions and use a formal physical approach to explain more complex kinds of motion. Students will find the need to alter their preconceptions if these are no longer sufficient explanations; therefore, students need to see the behavior of their preconceptions on more complex kinds of motion. However, an important drawback is that teachers have to start from the 'correct' physics situations and problems. In our real world, behavior according to preconceptions cannot be shown, because our world simply behaves according to our known physical laws. If a preconception leads to a certain motion that contradicts the motion according to the physical laws, the motion according to the preconception cannot be shown in reality. To truly show the effect of students' preconceptions, there is need for an environment that is not bound to real physical laws. Such an unreal environment is possible—it is a digital one. Students can be put in an unreal world. There they can set their preconceptions and experience their effects without being bound to the physical limits of this world.

1.2 Serious Games

A serious game is a computer game with the aim of facilitating learning in addition to entertaining users. In a serious game, the entertainment value of video games is used to influence learners' motivation (Charsky 2010). Recent studies show that training with serious games can be more effective in improving knowledge and cognitive skills than training with conventional instructional methods (Sitzmann 2011). The use of a serious game leads to a better retention effect in comparison with conventional instruction methods. Serious games lead to well-structured prior knowledge on which learners can build during their learning careers (Wouters et al. 2013). Wouters et al. (2013) argue that it is possible that immediately after learning from conventional instruction, students are able to remember texts or notes given during instruction, leading to no difference between conventional instruction and game conditions. However, after several days, students benefit more from game conditions due to their deeper level of knowledge processing in games (Kintsch 1998). To make practice with serious games more effective than practice with conventional instruction methods, it is important to supplement the game with other instruction methods such as a class discussion (Wouters et al. 2013). The meta-analysis conducted by Wouters et al. (2013) shows that serious games are more effective in combination with other instruction methods than in isolation. Whilst playing the game, students gain intuitive knowledge; however, in the absence of additional instruction methods, students are not given a chance to verbalize this knowledge and anchor it more profoundly in their knowledge base (Wouters et al. 2008).

1.3 Motivation

A major reason for serious game usage in lessons is that the use of a serious game will likely influence students' motivation. A serious game is intended to be more enjoyable than conventional instruction methods, thus students will likely be more intrinsically motivated to engage in the learning activity (Charsky 2010). Intrinsically motivated behavior refers to doing something because it is inherently interesting or enjoyable (Ryan and Deci 2000). Extrinsic motivation, in contrast with intrinsic motivation, refers to behavior that is driven by external rewards (Brown 2007). Whilst playing a serious game, students can also be extrinsically motivated to learn. For example, students' learning can be rewarded with points in a game, thus they are extrinsically motivated. In addition to the two types of motivation, Ryan and Deci (2000) developed a taxonomy of human motivation where different types of external motivation are defined. A distinction is made between external and internal motivation. External motivation is a controlled form of extrinsic motivation. More autonomous forms of extrinsic motivation are referred to as internal motivation. Since intrinsic motivation is completely autonomous, intrinsic motivation is the ultimate form of internal motivation (Ryan and Deci 2000). An example of internal behavior is when students identify the importance of an activity or when an activity is enjoyable. In this research, the focus lies on internal motivation.

The meta-analysis conducted by Wouters et al. (2013) shows that serious games do not have positive motivational effect on students, contrary to expectations. Wouters et al. (2013) provide several possible reasons for current serious games not being more motivating than conventional instructional methods. The first is that students often lack control over decisions in serious games. As autonomy supports internal motivation (Deci et al. 1991), conditions in the game that limit students' sense of control lead to lower internal motivation. In contrast, when autonomy is stimulated, students are more internally motivated to engage in the learning activity (Connell and Wellborn 1991). The second is that the connection between entertainment design and instructional design is not a natural one. This means that design choices that are good for instructional purposes often have a negative effect on entertainment value (Wouters et al. 2013). For instance, for instructional purposes, it is effective to prompt the student to reflect. The designer could use a pop-up screen to do so. However, this pop-up interrupts the flow of the game which leads to a negative effect on its entertainment value. To counter the disruptive nature of pop-up messages, it is important that the learning goal and the game goal are intertwined. By doing so, students learn without constant reminders of the game's learning purpose. Hence, if the aforementioned ideas are incorporated in a serious game, students will likely be more internally motivated to engage in the learning activity and therefore positive learning outcomes can be expected (Ryan and Deci 2000; Ryan et al. 2006). To measure such internal motivation to engage in an activity, specific statements of the Situational Motivation Scale (SIMS) can be used (Guay et al. 2000). The SIMS measures different kinds of situational motivation, including situational intrinsic motivation and identified regulation which both belong to internal motivation. Situational intrinsic motivation is intrinsic motivation that occurs during the engagement in an activity (Guay et al. 2000). Several existing games were developed with the purpose of improving the comprehension of Newton's laws. Students are often put in an ideal frictionless environment so that their in-game motions represent the effects of forces in a theoretically ideal form. These serious games have shown positive learning outcomes (Koops and Hoevenaar 2011; White 1984). However, these games do not yield a positive motivational effect. Also, due to the ideal theoretical environment of the games, students are not confronted with flaws in their existing ideas, while a confrontation with their preconceptions leads to positive comprehension effects (Chi et al. 1994; Duit and Treagust 2003; Vosniadou 1994).

1.4 Incorporating a Problem-Posing Approach in a Serious Game

By implementing a problem-posing approach in a serious game, students can actually experience the physical effects of their preconceptions. Students are thus directly confronted with their existing ideas of motions, which naturally leads to several problems. Students will find out that some motions are impossible in the world of their own preconceptions. Hence, physical reasoning is stimulated and concept development is needed to adjust students' existing ideas to formal physics.

In a serious game, students are able to experience the effects of their preconceptions. For instance, they can see if their preconceptions lead to an unrealistic movement. Confronted with this unrealistic movement, students encounter the fact that their preconceptions no longer sufficiently explain realistic movements. Therefore, students will find the need to discover new ideas that will lead to explanations for realistic movement. Since this need for explanation will come from the students themselves, students are more likely to engage in the learning activity (Vollebregt et al. 1999).

1.5 *The Case Study: Newton's Laws*

A very suitable subject for a serious game is Newton's laws. Not only are the laws of motion an important part of the secondary school curriculum, there is also a lot of didactical information available about this subject. The preconceptions of students in the field of mechanics are well known (Driver et al. 1994). There is also a valid research instrument available: the Force Concept Inventory (FCI) (Hestenes et al. 1992). With this information already validated, this research can truly focus on the learning and motivational effects of a developed serious game. Therefore, the aim of this research is to improve students' comprehension and motivation regarding Newton's laws. This leads to the following research question: How can the use of a serious game foster both students' comprehension and their motivation with respect to learning Newton's laws, in comparison with conventional instruction methods?

2 Method

2.1 *Research Design*

The study used a design-based approach followed by a quasi-experimental evaluation. First design criteria for the serious game were formulated and a first version of the game was developed. The practicality of the game was evaluated by observing several students playing the first version and the game was further developed in a second version. This version was evaluated on the content level of the game and improvements were made to develop the final version. A quasi-experiment using the final version evaluated its effective learning effects and motivational effects.

2.2 *Participants*

The participants during the design phase included 30 4VWO (Dutch: "*voorbereidend wetenschappelijk onderwijs*"; literally "preparatory scholarly education") students. The participants in the quasi-experimental evaluation included 73 3VWO students between the ages of 14 and 16 (grade 10).

2.3 *Instruments*

The developed game consists of seven levels. In each level, students need to guide a ball to the finish line (see Fig. 1). They can do this by giving the ball an initial kick—a force (F_{kick}). They also decide if there is another constant force ($F_{constant}$)

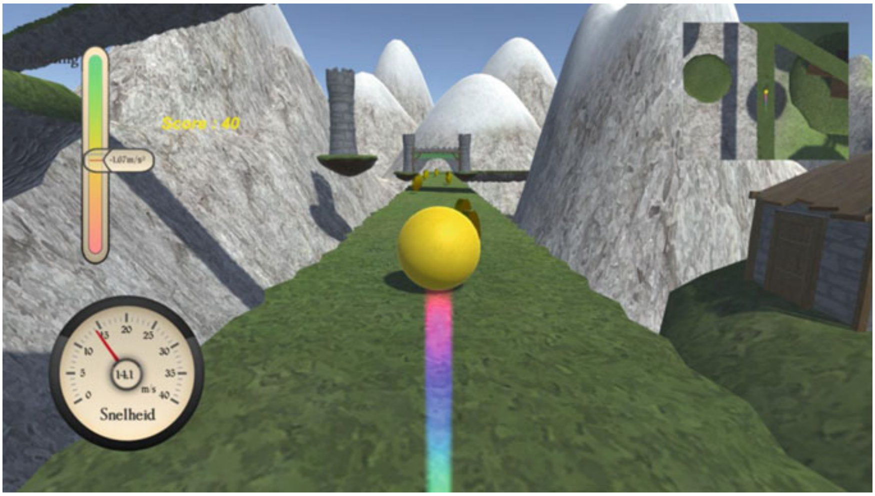

Fig. 1 Screenshot of the simulation game with indictions for speed and accellarion. The goal is to reach the goal at the end over increasingly difficult tracks

Table 1 An overview of each level in the game. The first three levels and fifth level are introductory levels

Level	Settings	Friction	Specifications of track
1	F_{kick}: scrollbar	No	Straight and short
2	$F_{constant}$: yes/no	No	Straight and short
3	$F_{constant}$: scrollbar	Yes	Straight and short
4	$F_{constant}$: scrollbar	Yes	Curves, can only finish with realistic physics
5	F_{kick}: scrollbar	No	Introduction of acceleration platforms and deceleration platforms
6	$F_{constant}$: scrollbar	Yes	different roads to finish, curves and platforms, can only finish with realistic physics
7	$F_{constant}$: scrollbar	Yes and no	Different pavements, different roads to finish, curves and platforms, can only finish with realistic physics

working on the ball to keep it moving, which they can set a value for. After the initial kick, students can alter the direction of the ball by giving a small kick to the sides of the ball, perpendicular to the direction of motion. The difficulty of the levels slowly increases. Students start on a straight road with no friction. In later levels, friction is added and curves occur. Platforms on the road are also added where the ball speeds up or slows down. Students lose a level if the ball falls off the road or if the ball becomes stationary. In each level, students are able to collect coins—each worth 10 points—that determine their level score (Table 1).

The first version of the game was evaluated through the observation of students' performances during and between levels in combination with a post-game interview conducted by the researcher. An observational scheme was used in which the researcher noted whether the student finished the level and how and where it went wrong, in the event of failure. The researcher also noted the score per level and whether in-game texts were read. There was also room to note any faults in the level. After each level, several interview questions were asked:

- What do you think about the difficulty of the level?
- Was there anything unclear in the level?
- What do you think about the length of the level?
- Was the control of the ball intuitive?
- Would you play this level again with different settings?

To evaluate the second version of the game, students answered a post-test immediately after playing the game. The post-test included specific items of the FCI (Hestenes et al. 1992). For the quasi-experiment, a pre- and post-test were used which included the same FCI questions. To evaluate the motivational effect of engaging in the learning activity, statements of the SIMS were incorporated in the post-test (Guay et al. 2000).

2.4 Data Collection and Analysis

The researcher's observations and participants' answers to interview questions were used to improve the first version of the game. The second version was improved based on the post-test data from the 4VWO students. To evaluate the final version of the game, a quasi-experiment was held in three 3VWO classes. These classes divided naturally into three groups. The first group (the control) experienced a traditional lesson: They listened to a classroom instruction then completed assignments and revised those assignments based on feedback by the teacher. The second group played the game without other classroom activities. The third group started the lesson by playing the game, followed by a classroom discussion. This discussion included images from several levels of the game. All groups started with a pre-test and ended the experiment with a post-test. The duration of the experiment in all groups was a single lesson of 40 min including the pre- and post-test. All experiments were held on the same day.

One week after the experiment, the control group also played the game. Instead of a post-game classroom discussion, the students received a worksheet with questions they needed to fill in after each level. The motivational effect of playing the game whilst answering a worksheet was thus evaluated.

Table 2 The results of the evaluation of the first version of the game and the improvements that were made for the second version

Observation/participant Response	Improvement for the 2nd version
When the ball falls off the track, it keeps moving	When the ball falls off the track, the ball comes to a stop and students are able to restart the level
Levels 4 and 6 are too difficult	The initial force (F_{kick}) in level 4 and 6 was lowered
The scrollbar does not work properly for the setting of forces	Scrollbar was fixed
In-game text is mostly not read	In-game text was shortened
If in-game text was not read, setting the forces is unclear	In-game text and setting were featured in the same pop-up
The deceleration platforms do not work	Deceleration platforms were fixed

3 Results

There were several observations and participant responses during the evaluation of the first version of the game that led to game improvements (Table 2).

The results from the evaluation of the second version of the game led to improvements to the final game. In the second version, a short kick animation was shown when the player kicked the ball, for instance at the start of a level. On the post-test for the second version, 92.3% of students correctly answered a question about the meaning of this animation. The group scored 52% on the FCI questions of the post-test. However, the students scored the lowest on the questions about direction of a moving object. To provide more clarification in the final game version for the influence of a sideways kick on the ball motion, a kick animation was added to the sides of the ball when the direction of the ball was changed via the arrows on the keyboard. With these added animations, students were more likely to see changes in direction due to a kick, instead of an internal steering system. To give students more insight on the effects of a $F_{constant}$ in comparison with no $F_{constant}$, it was decided that level 2 had to be played twice: once with an $F_{constant}$ working on the ball and another time without $F_{constant}$. This way, students could see the effects of such a force at least once and use this information in the later levels where a realistic movement had to be made.

Most students were not able to finish all levels. In the second version's last level (level 8), students were able to set F_{kick}, $F_{constant}$, and the mass of the ball. This level was deleted in the final version of the game (Table 3).

A paired samples t-test was performed to examine the mean differences between the pre-test and the post-test of each group. For the control group, there was no significant difference in the pre-test ($M = 2.40$, $SD = 1.14$) and post-test ($M = 2.88$, $SD = 1.301$) scores; $t(25) = 0.755$, $p = .252$. For the game group, there was also no significant difference in the pre-test ($M = 2.19$, $SD = 0.895$) and post-test ($M = 2.00$, $SD = 1.020$) scores; $t(24) = -1.174$, $p = .446$. Finally, no significant differences

Table 3 The results of the pre- and post-test (with a minimal value of 0 and a maximal value of 6) and the results of the motivation scale (with a minimal value of −2 and a maximal value of 2)

	Control group Mean(SD)	Game group Mean(SD)	Experimental group Mean(SD)
Pre-test	2.40 (1.258)	2.19 (.895)	2.32 (1.041)
Post-test	2.88 (1.301)^{a}	2.00 (1.020)^{b}	2.68 (1.171)^{a}
Motivation	−.3125 (.933)^{a}	.7019 (1.061)^{b}	.9773 (.873)^{b}

Statistically significant differences are indicated with an index. If the indices of two means in a row are different (i.e. a and b), the two means significantly differ from each other. If the indices of two means in a row are identical, there is no statistically significant difference between the means

were found between the pre-test (M = 2.32, SD = 1.041) and post-test (M = 2.68, SD = 1.171) scores of the experimental group; $t(21) = -1.093$, $p = .287$. Overall, the intervention had no significant effect on the learning results in all three groups.

A post hoc analysis (Fisher's Least Significant Difference [LSD]) was performed to examine the mean difference between the post-tests. The results show that a significant difference can be found at the .05 level between the control group and the game group ($p = .009$). Furthermore, the Cohen's effect size value ($d = -.753$) is. A significant difference can also be found between the game group and the experimental group ($p = .048$) with a moderate to high effect size ($d = .619$). However, no statistical significant differences were found between the control group and the experimental group ($p = .563$). These results show the importance of embedding the game in a lesson. The final results of the students who only played the game are significantly lower than those of students who experienced a traditional lesson or students who discussed the game afterwards.

A second post hoc analysis (LSD) was performed to examine motivational effects. The results show that a significant difference can be found at the 0.05 level between the control group and the game group ($p < .001$). The effect size is high ($d = 1.02$). A significant difference can also be found between the control group and the experimental group ($p < .001$, $d = 1.43$). In contrast, no statistically significant difference can be found between the game group and the experimental group ($p = .327$). These results support the motivational effect of the game: Both groups who played the game showed a significant motivational effect in comparison with the group who experienced a traditional lesson. When students filled out a worksheet whilst playing the game, a significant motivational effect can be found in comparison with a traditional lesson ($p < .001$). Further, the Cohen's effect size value ($d = 2.47$) suggested a very high effect size. The use of a worksheet also produced a statistically significant difference in comparison with the game group ($p = .012$) with a high effect size ($d = .911$). However, no significant differences can be found in motivation between using the worksheet and a class discussion following the game ($p = .131$).

4 Conclusions and Discussion

The aim of this study was to improve both students' comprehension and their motivation regarding Newton's laws. To achieve the research goal, the following research question was answered: How can the use of a serious game foster students' comprehension and motivation with respect to learning Newton's laws in comparison with conventional instruction methods?

With the current version of the game, participants' comprehension of Newton's laws does not improve more than from a traditional lesson. There was no significant difference found between the pre- and post-tests of all three conditions. This means that in all groups, the learning effects—if any—were low. This could possibly be due to the very short intervention time of 40 min. As both pre- and post-tests were conducted during that time period, the effective intervention time was only 25 min. Results show that the traditional lesson is about as effective as the experimental lesson regarding learning effect. That learning effects do not differ between the students who played the game and the students who practiced with conventional instruction methods corresponds with the results of Wouters et al. (Wouters et al. 2013). Students completed the post-test directly after the intervention, so measuring retention effects was not possible. In addition, it is important to embed the game in a lesson to improve comprehension. Students who only played the game scored significantly lower on the post-test than both other groups, which again corresponds with the results of Wouters et al. (2013).

Students who played the game as a lesson activity were clearly more motivated than students who received traditional instruction methods. To achieve this motivational effect, several criteria were implemented in the game. Students were able to incorporate their own ideas about motion and forces in the game, and they could instantly see the effects of those ideas and come to a conclusion about how realistic their ideas were. Then they could alter their ideas and try to achieve a realistic movement. The learning goal and the game goal are intertwined with each other. Lastly, students were able to make their own decisions in the game. They could set their own rules for motion and there were even multiple routes to the finish line in some levels. To foster a motivational effect, it was expected that not disturbing the flow of the game would be important. However, even when using a worksheet while playing the game, a significant motivational effect was found in comparison with a traditional lesson.

Before using the developed game in further research, it should be noted that the game itself needs some improvements. With the current version of the game, it was possible for students who had some experience of the game to complete it with the use of nonrealistic physics. This outcome should be made impossible. Also, before each level in the game, short texts appeared with information on how to play the game. However, students generally did not read those texts while playing the game, so it took them some time to figure out what they were supposed to do. Lastly, students scored lowest on the questions about direction of motion. Replacing the currently narrow track with a broader track would allow students to more clearly see the influence of a kick on the ball's movement.

To achieve a comprehension effect regarding Newton's laws, several aspects need to be taken into account for further research. It has been shown that just playing the game is not an effective learning method. Therefore, the game should be embedded in a series of lessons, lengthening the intervention time and thus solving the earlier stated problem of the short intervention time as well. To gain more insight into students' reasoning and comprehension of the subject, their reasoning should be made explicit during or after playing the game. To measure a learning effect, a retention measurement should be performed. Wouters et al. (2013) argue that it is possible that immediately after learning from conventional instruction, students are able to remember texts or notes given during instruction, leading to no difference between conventional instruction and game conditions. However, after several days students benefit more from game conditions, due to the fact that in a game students process a deeper level of knowledge (Kintsch 1998). To improve students' comprehension and to achieve a learning effect, students need some guidance whilst playing the game, since they generally did not read in-game texts. A worksheet is one possibility, but are there more effective methods? What should the role of the teacher be in the lessons? To answer these questions, further research is needed.

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