Designing an Intrinsically Integrated Educational Game on Newtonian Mechanics

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Abstract. In the current paper we present the design process of an intrinsically integrated educational game on Newtonian mechanics. The design is based on a guiding frame in line with the intrinsic integration theory, which states that in a game, learning goal and game goal should be aligned. This also results in an alignment between a pedagogical approach and game mechanics. Our findings suggest three guidelines within this guiding frame. First, the guiding frame works in a specific order starting with forming a learning goal and ending with the game goal. Also, to optimize the alignment between the learning goal and the game goal, it should only be possible for players to reach the game goal when the desired learning goal is reached. Finally, during the iterations of the design process the focus is on aligning the pedagogical approach with the game mechanics. This proved to be an essential but difficult step.

Keywords: Educational game · Intrinsic integration · Newtonian mechanics

1 Introduction

When we look at a person who is gaming, we see a person fully immersed to master the game. Mastering the game means learning how to play the game. This learning occurs whilst the player, fully immersed in the gaming experience, loses the sense of time and surroundings, resulting in a state of flow [1]. This learning in a state of total immersion is in sharp contrast with the commonly observed lack of engagement in formal education. So, could it be possible to use this immersed learning that occurs whilst playing a game in formal education?

In the past decades, research focusing on using educational games has increased [2]. Research focusing on motivational effects show that educational games sometimes show an increase in intrinsic motivation of students as compared to participating in other instructional activities. However, a meta-analysis [3] shows that educational games in general do not yield positive motivational effects on students. Research focusing on cognitive effects of educational games, on the other hand, show promising results in general [2, 4]. However, the results of individual educational games remain inconsistent. This leads to the question why some educational games yield learning effects and others do not. Of course there could be many factors contributing to the absence or presence of a learning effect. In this paper we investigate the influence of the game design itself.

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Several studies have been devoted to gain insight on the design process and different design elements of an educational game [2, 5–7]. Although this research has led to some interesting insights, much of how to design a good educational game remains unclear.

In the present study we aim to elucidate some design principles by describing the design process of an educational game on Newtonian mechanics. In our analysis of the step by step design process, we search for overarching design guidelines that can be transferred to the design process of other educational games.

The next section presents the theoretical substantiation of the designed educational game, which leads to the research question. Subsequently, the research question will be addressed in a case study that will describe the design process of the game.

2 Theoretical Substantiation

2.1 Educational Game Goals

Every game has a game goal, for instance, freeing a princess, collecting stars or simply surviving. To reach the game goal, players interact with the game through game mechanics and game attributes. Sicart [8] defines game mechanics as 'methods invoked by agents, designed for interaction with the game state' [8]. Examples of game mechanics are jumping, trading and climbing. Game mechanics thus describe an interaction between the player and the game. Game attributes are visualizations of game properties, such as stamina. For instance, a player is only able to climb a wall with enough stamina. In this case the player needs a visualization of their stamina, in a meter for instance, in order to make a decision to continue climbing. Game attributes and game mechanics are strongly connected and essential in reaching the game goal.

In an educational activity, students need to reach a certain learning goal. This means that if a game is to be used as an educational activity, it should always have two goals. So apart from the game goal, the learning goal of an educational game is that players need to learn something of value outside the game context. Within the game context players learn in order to master the game, whereas an educational game aims at learning for a broader context.

2.2 Intrinsic Integration

When designing an educational game, most educators or educational researchers tend to focus on the educational aspects of the game, making sure that the educational content is all there [9]. Then an educator usually adds game properties (such as adding points or a narrative) to make the game more engaging. This approach, however, can easily lead to a discrepancy between learning goal and the game goal. This could result in an unsuccessful educational game [5]. To make this discrepancy as small as possible, the additional educational learning should be integrated with the learning that occurs anyway whilst playing a game, the learning of how to play the game.

This integration of educational learning with the game mechanics is referred to as intrinsic integration. Intrinsic integration in a game is thus defined as subject matter and game mechanics being integrated within the same game idea [10]. Several studies focused on integrating learning content with game environments [5, 6, 11, 12]. However, it proves to be quite challenging to integrate learning with game mechanics while not affecting the enjoyability of games [11].

2.3 Pedagogical Approach

Any educational activity requires an underlying pedagogical approach. A pedagogical approach describes the steps that are seen as important in achieving the learning goal of the game. This means that the game mechanics should be designed in such a way that students will perform thinking activities relevant for learning. For instance, the game mechanics may be such that a real-life situation is mimicked, or that some kind of planning is required that has relevance for the learning goal.

The aim of the current paper is to investigate the way intrinsic integration can be reached, by aligning game goal and learning goal as well as game mechanics and pedagogical approach. We did this in the context of designing a game for learning elementary Newtonian mechanics.

2.4 Research Question and Hypothesis

The main research question in this paper is: How can an educational game be designed where learning is integrated with the game mechanics?

Our hypothesis on designing an intrinsically integrated game is shown in Fig. 1. To optimize the learning effect of an educational game, it is important to align the learning goal with the game goal. Only if the desired learning goal is reached should it be possible for players to reach the game goal. This alignment is in line with the intrinsic integration theory [10]. To optimize this effect, we propose an additional alignment between a pedagogical approach and game mechanics.

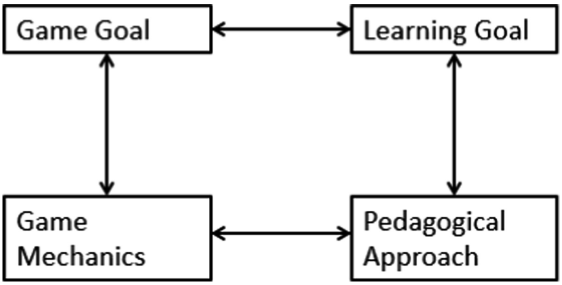

Fig. 1. Guiding frame on alignment between the game goal, learning goal, pedagogical approach and game mechanics.

3 Design Process: Newton's Race

3.1 Concretize the Hypothesis

The design process followed the basic hypothesized elements. First the hypothesis was made concrete by instantiating the learning goal, pedagogical approach, game mechanics and game goal. The results lead to an initial design that was tested on a small scale in two iterations leading to several modifications. The final design was pilot tested on a group of 73 9th grade students, using a pre- and post-test quasi-experimental design.

Learning Goal. The guiding frame (Fig. 1) is used from an educators point of view. As with designing any learning activity, we started with determining the subject matter and thus establishing the learning goal. The subject of Newton's laws was chosen not only because of their importance in the secondary school curriculum but also because the persistence of student's preconceptions resulting in conceptual challenges [13]. In the present research, we define preconceptions as pre-existing ideas based on daily life experiences. One of the conceptual challenges within Newton's laws is that force is proportional with acceleration, not with speed [14]. This means that an object can move without working forces on it and if there is a net force working on an object the object is not just in motion, it is accelerating (or decelerating). The learning goal that matches with this conceptual challenge is that students can understand the effect of forces on different motions. This implies that students can predict motions with given forces and that they can explain the effects of forces when given a certain motion.

Pedagogical Approach. Research has shown that in the case of force and motion, student's preconceptions are quite persistent [13]. Therefore the need to face students with their preconceptions is essential [15–17]. This lead to the choice for the problem posing approach as the pedagogical foundation. In the problem posing approach situations are created in which preconceptions are no longer adequate explanations [18]. The key element of this approach is that students put their preconceptions into the learning activity and experience the effects of those preconceptions. When they are confronted with something that counters their expectations, ideally, they should see the need for new theories to alter their preconceptions.

However, in our real world, students are not able to test all preconceptions, because our world provides a single case in which parameters of the general physical theories, such as friction, are fixed. The advantage of a digital environment is that the effects of students actions can be simulated with high precision, including movements without friction. In this case, students should be able to alter forces working on an object resulting in different motions.

Game Mechanics. A brainstorm session resulted in two possible genres for our game: puzzle and race. For the problem posing approach, it is important that players truly experience the consequences of their ideas and concepts. Therefore, the game mechanics should provide a so-called *setting phase* where players can incorporate their own ideas. Therefore, the game mechanic of setting a force on an object is needed. Then players need to experience the effects of their choice, thus a design is needed were players can clearly see the effects of those forces on the motion of the chosen object. Therefore, a race-like environment seemed fitting with our chosen pedagogical approach. Some other game mechanics that fit with a race game are: navigating through levels and steering.

Game Goal. Traditionally, the goal of a race game is to reach the end of a level as soon as possible. However, that would not fit our chosen learning goal, as the mimicking of a realistic, rather than a fast, movement is paramount. A more fitting game goal then would be to just finish a trajectory. To truly show effects of forces, a non-motorized object, a ball, was chosen for students to complete the trajectory with. A ball is a very familiar object that everybody knows. Thus, players will have experiences with possible motions a ball can make (after one kick, the ball will start to move, followed by a decrease in speed). A conflict with this expectation should occur when players select an scientifically incorrect setting in the setting phase. Ideally, this conflict results in failure to reach the end and this should prompt alteration of their preconception to scientific reasoning. This means that the learning goal of understanding the effects of forces resulting in different motions should be reached. Players then should select the scientifically correct setting and only then are able to finish the trajectory.

3.2 Initial Game Design and Playtesting

In order to seek balance between students' skills and the challenges of the game and thus trying to reach the desired state of flow [1] eight levels of increasing difficulty were included to the game. Each level consists of a different trajectory, starting with easier levels (no friction, straight path) building op to levels with turns, multiple surfaces (different frictions) and green and red platforms where the ball receives additional kicks respectively in the direction of motion or against the direction of motion. For each level the same game goal applies (get the ball to the finish line).

In the setting phase at the beginning of each level players decide if there is a constant force ($F_{constant}$) working on the ball to keep it moving after receiving an initial kick. They can set a value for that force by using a scrollbar. Whenever the ball receives a kick, a pow-icon is shown (see Fig. 2), so that students could see how and where a force is working on the ball. If a scientifically incorrect setting is chosen, the speed of the ball will be too high in turns of the trajectory. Therefore, the ball will fall off and that the game goal cannot be reached.

To strengthen players' experience of motions resulting from their preconceptions, it is important that the kind of motion (acceleration, deceleration, constant speed) of the ball is clearly visible. To make sure players could see the type of motion, several game attributes were added. As shown in Fig. 3, an accelerometer, speedometer and a tail proportional with speed were added to the game.

In order to complete trajectories, players need to be able to change the balls direction. This action must be scientifically correct. Therefore, players can give the ball a sideways kick (using arrow keys), perpendicular to the direction of motion.

To make the game more interactive and add some competition, the challenge of collecting coins was added. The coins were placed in such a way that the trajectory should become more difficult. For instance, coins were placed at harder to reach places, such as the inside of turns. Also, as conventional in race games, an overview map was added for players to anticipate on the trajectory.

In summary, the game design consists of two game mechanics within each level: setting a force and changing direction of the ball. The first mechanic is essential for the alignment with the pedagogical approach. To strengthen the effect of the pedagogical approach, game attributes were added to make the kind of motion visible. The second mechanic is needed to reach the game goal, since there are turns in the trajectories. In addition to the turns, collecting coins and green and red platforms were added to provide challenge for the players.

At this point a demo version (four levels) of the game was tested. Note that with every iteration bugs were eliminated, the game's interface was optimized and difficulty adjustments were made to optimize flow. Only results regarding the game's content will be discussed. This playtest showed a problem with the introductory texts in the setting phase of each level. Due to the length of the texts players were reluctant to read it or did not read it at all, resulting in not knowing what to do in a level.

Fig. 2. The pow-icon when the ball receives a kick

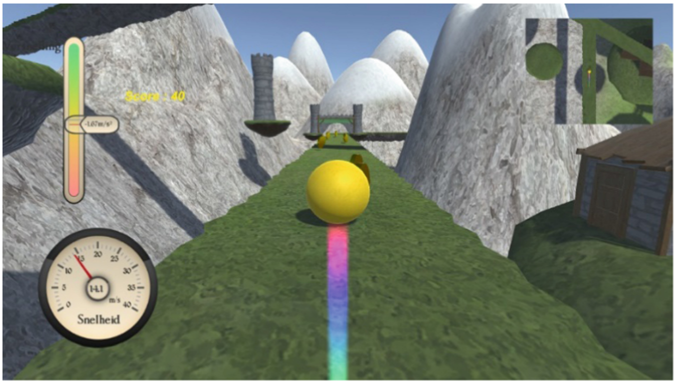

Fig. 3. A snapshot of level 3 with the setting: $F_{constant}$ = 0N. In the upper left corner, the accelerometer is visible, the speedometer in the down left corner and the tail is visible behind the ball. The overview map is visible in the upper right corner.

3.3 First Version

For the next version of the game (eight levels) the introductory texts were adjusted so that they only contained important information regarding completing a level. This version was tested with thirty 10th grade students, aged between 15 and 16.

Results showed three issues with the game. First, none of the players could finish level eight. In this level students were also able to set a value for the mass of the ball. This extra setting provided players with too many options, making the level too difficult. A mass adjustment was not essential to our learning goal, therefore this level was deleted for the following version of the game.

Second, there were doubts as to if students saw the difference between a motion with $F_{constant}$ (acceleration or constant speed, depending on the value of friction) and without $F_{constant}$ (deceleration). In the next version students played the level twice, once with each setting. A fitting adjustment would be playing the same level twice, with these different settings.

Finally, most importantly, it appeared to be unclear for the players that by using the arrow keys to change the balls direction of motion, a small force was exerted on the ball. This indicates a discrepancy between the pedagogical approach and game mechanics. For the pedagogical approach it is necessary that students understand that they need to exert a force on the ball in order to change its direction. To make this more explicit, giving the ball a force needs to be visible. In an attempt to show this, another pow-icon was added whenever the arrow keys are used change the ball's direction, shown in Fig. 4. With this added icon students are more likely to link changes in direction due to a kick, instead of an internal steering system, as is traditional in a racing game.

Fig. 4. The pow-icon when the ball receives a sideways kick.

3.4 Pilot

The three adjustments were implemented for the pilot study. A quasi-experimental pre- and post-test design was used to evaluate the latest version on learning and motivational effects. The game was tested in three groups (73 9^{th} grade students in total). The control group followed a traditional lesson, the game group only played the game and the test group played the game followed by a classroom discussion. The duration of the experiment in all groups was one lesson of 40 min including a pre- and post-test.

Results of the pilot showed a significant motivational effect between the two groups who played the game and the control group. All groups did not yield a learning effect. However, the game group scored significantly lower on the post-test than the other two groups. The complete results of the pilot study go beyond the scope of the present paper, these results are elaborated on elsewhere [19].

However, during the pilot we also found four important issues regarding the design of the game:

1. The learning goal and the game goal are not sufficiently aligned. More experienced gamers (with other games) could finish certain levels without the scientifically correct setting, thus reaching the game goal. This probably means that these players did not reach the desired learning goal.
2. Also, an issue was found with the alignment of the pedagogical approach and the game mechanics. When a ball receives a sideways kick, the ball makes a parabolic movement. This does not become clear in the game. This is probably due to the fact that the trajectory is quite small, therefore there is no room for players to see the parabolic movement. Also players still associate a change of the balls direction with internal steering, not with acting forces. This indicates that a more clear game attribute is needed to visualize acting forces.
3. As mentioned above, students who only played the game scored significantly lower than students who played the game followed by a classroom discussion. This indicates the importance of embedding the educational game in other learning activities.
4. Players did not read texts, resulting in not understanding what to do in the setting phase of the game.

The effects of the four issues on the game design and the relation with our hypothesis will be elaborated on in the next section.

4 Discussion and Conclusion

4.1 Design Process

Our research question was: How can an educational game be designed where learning is integrated with the game mechanics?

A guiding frame was presented (Fig. 1) fitting with the intrinsic integration theory. Then we designed a game by concretizing this guiding frame. During this design process we found three main guidelines fitting with the guiding frame. Firstly, we used the guiding frame in a specific order. From an educators' point of view, any design process starts with forming a learning goal (step 1) and then finding a fitting pedagogical approach (step 2). Then we chose a suitable game genre from game mechanics that strengthened the pedagogical approach (step 3). From these game mechanics followed a game goal (step 4). The main implication is that in order to reach goal alignment, alignment of the game mechanics with the pedagogical approach is essential.

Secondly, to truly align the learning goal to the game goal, it is necessary that the game goal depends on the learning goal. This means that players must reach the learning goal before as a necessity for reaching the game goal. Results of the pilot study show that this is not trivial at all. Experienced gamers are able to finish a level without the scientifically correct setting ($F_{constant}$ = 0N), whereas less experienced gamers have difficulties finishing a level even with the correct setting. To make the discrepancy as small as possible, the scrollbar in the setting phase could be changed to a setting system with less options. Then it will not be possible for experienced players to set a small $F_{constant}$ close to 0N and thus are not able to finish a level with a small constant force. Finally, we also found that aligning the pedagogical approach with the game mechanics was the most essential and difficult step. Therefore, this alignment was the focus during the iterations. In our case a big challenge is the visualization of movement and forces. With the learning goal on the relationship between forces and motion, it is important that players understand when forces are working on the ball and what type of movement (acceleration, deceleration or constant speed) the ball makes. Despite our efforts during the pilot study, we found that the added sideways pow-icons for instance, still did not reach the desired effect of understanding that a force is acting. Another challenge lies in the setting phase. Setting $F_{constant}$ is an essential game mechanic in order for our pedagogical approach to work. However, with players reluctance of reading text in the setting phase, this game mechanic is not optimally used. Even with the reduced text in the pilot study, a trial and error approach is opted by most players.

To our knowledge, few educational games are made with a specific focus on the alignment of game mechanics with a pedagogical approach. However, a clear pedagogical approach is needed to reach any learning goal. Therefore, we recommend giving this alignment explicit attention during the design process. All this applies to integrating the pedagogical approach *within* the game. In addition, with our hypothesis (Fig. 1) in mind the pedagogical approach can also be (partly) offered *outside* the game in additional learning activities. In this case the game should align with the other learning activities, thus alignment between game mechanics and a pedagogical approach is still necessary.

4.2 Further Research

Newton's Race is an educational game still in development. The game can be improved by adjusting mentioned issues. However, additional information is needed on how players interpret and use the game attributes (such as the accelerometer and speedometer) in order to improve the game further. In addition, research is needed on the influence of objects exerting forces on the ball to improve the visualization of acting forces.

Also, if Newton's Race is going to be used in educational practice, additional learning activities are needed. In line with Wouters and colleague's [3] we found that embedding the game in other learning activities is necessary for students to reach the learning goal. However, it remains unclear what additional learning activities that should be. Research is needed to suggest possible effective additional learning activities.

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