Combining Minecraft redstone and fundamentals of digital systems design for secondary education

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Bachelor Thesis– Informatica

Leiden Institute of Advanced Computer Science (LIACS)
liacs.leidenuniv.nl September 8, 2026

Abstract

Computer science education in the Netherlands is often excluded in the curriculum of secondary schools in the Netherlands. Specifically logic and digital system design is a topic that is not included, even though these are the fundamental building blocks for computers and are one of the first topics discussed in further education. In Minecraft Education, different teaching materials have been build and experimented with. Yet, few studies have explored the implications of logic and digital system design in educational settings is still ongoing. In this experimental study, two groups from two schools in Leiden joined to compare the effectiveness of the gamification of Minecraft in educational settings. For this, we explored the performance of students in a Minecraft class, compared to a class that was taught using the direct instruction strategy. Both classes received the same paper exam and the experimental group received a survey in the form of the Technology Acceptance Model to measure their experience with Minecraft. The study measured lower median grades for the experimental group, likely due to: difficulties balancing focus on the teacher and exploring and experimenting with Minecraft builds and the cognitive load of content within a single lecture. Moreover, the study found that overall students did have a positive experience with Minecraft in an educational settings, though opinions on its usefulness and its future use are mixed.

Acknowledgements

I would like to take the opportunity shortly address my gratitude to a number of people who contributed to this thesis and supported me throughout this study.

First of all, I would like to thank my supervisor Dr. A. N. van der Meulen. Her insights, support and guidance every week for the past seven months have been very valuable to me. Thank you for your time, continuous feedback and ideas. Moreover, I would like to thank Dr. G. Barbero for his feedback and his time for evaluating my thesis.

I am also very grateful for my family and friends who helped me with the pilot study, motivation, feedback and the search for available schools.

Also I would like to thank the students and teachers from the schools. Thank you for your time and your enthusiasm. I had a lot of fun working with you and all your input was very much appreciated.

To end, I want to thank Elayza, for her continuous support and trust.

Without any of this people, this thesis would not be. Thank you all very much!

R. A. V. Ramdas
Leiden, July 2026

Contents

1 Introduction

Logic and digital system design is a topic that is often not included in the curriculum of computer science in secondary education within the Netherlands. Digital systems are the building blocks for computers. It is the design of architectures, which use electrical signals, through which information is passed in binary form. With the mathematical representation, logic, we can simulate and analyse behaviour. These topics can be very relevant to include in computer science education in secondary schools, since they provide fundamental understanding of the behaviour of computers. However, secondary schools still have the option to exclude computer science from their curriculum. The Algemene Onderwijsbond (AOb), the association for general education, mentioned in an article from 2022 that many schools wish to include computer science in their curriculum but are unable to, due to teaching shortages [23][11]. Consequently, since there is a large domain of topics schools can choose from, there is no standardized way to teach computer science yet [35]. Despite logic and digital system design not being included in most computer science curricula in secondary education, the topics are very prominent in not only academia, but also for careers in the industry [26].

To begin, gamification is the use of game elements [10] inside of classrooms. Game elements, such as levels or point collecting, are used to transform course material. This teaching strategy has shown to be effective in previous studies [19] [19]. Minecraft Education is an example of gamification where course material is translated into the game Minecraft. Within this lightweight educational version [28], the controls are shown on the screen at all times. In a study with Minecraft Education, more than 90% of 89 university students found that gamification of subjects (in the context of Minecraft) made classes more motivating [8].

Another, more traditional, teaching strategy is direct instruction. With direct instruction, the material is directly conveyed to the students. Within computer science education it was found that direct instruction works better for acquiring knowledge and learning new practical abilities compared to other strategies [41].

In this research the goal was to gain insight in the gamification of computer science by using Minecraft Education, specifically for the topics logic and digital system design. A control group that was taught direct instruction was compared to an experimental group that was taught using Minecraft Education. For both groups, the same topics were discussed during class. The groups ended with a short exam to measure the impact of Minecraft Education on their performance. Finally, using the Technology Acceptance Model, a survey was formed to gain insight in the students their experience with Minecraft and to understand if they find the gamification of their education interesting and effective. The survey ended with a section with open fields, for students to give more feedback and to share their experiences.

1.1 Research question

In this study we will focus on the question: "How effective is the gamification of Minecraft for explaining fundamentals of digital systems in secondary education?". In other words, we are investigating if Minecraft has any additional educational value to a class, compared to a class with only direct instruction.

To correctly answer this research question, we will also take a look at some sub questions. Answering:
SQ1 - How does the performance of students in a class using Minecraft Education perform compared to a class using direct instruction?
SQ2 - How do students experience the use of Minecraft as part of their education?
For the last sub question, we will use the technology acceptance model [9], a commonly used model for evaluating new technology.

1.2 Thesis overview

In this first chapter, an introduction is given of the study 1 and the research questions are stated 1.1. In the next chapter 2, we take a closer look direct instruction 2.1.2 and study Minecraft and its adaptation in educational settings 2.3. In chapter 3, the study for this thesis is described. Specifically, the set-up 3.3.1 and pilot study 3.1 can be found here. Next, in chapter 4 the results for the exam scores and the survey are described. Chapter 5 contains a discussion of the results and acknowledges limitations. Finally, in chapter 5.6, the conclusion can be found.

2 Background

2.1 Teaching methods

2.1.1 Computer Science in the Netherlands

Computer science education in secondary schools in the Netherlands is lacking behind compared to other European countries [23] [11]. In most European countries, computer science has been adapted as a compulsory course [13], however, in the Netherlands, it is optional to for schools to include computer science in their curriculum. Moreover, schools follow a broad exam program from 2016 [5]. From this program, only four out of twelve domains have to be adopted into the curriculum [35]. Thus, educational developers have considerable autonomy in designing the corresponding course content. Consequently, there is no standardized or widely adopted body of course material available for these topics. This results into a large variation in the skills of students, which makes it difficult to assess the knowledge and skill level of students.

2.1.2 Direct instruction

Direct instruction is an instructional approach in which new material is explicitly explained and demonstrated, before students practice independently. In here, both the materials and the presentation of these materials must be clear and unambiguous, preventing misconceptions [16]. In an interview, Siegfried "Zig" Engelmann, one of the co-founders of direct-instruction, pointed out that direct instruction is designed with the idea that misteaching creates problems that kids have [17]. In other words, the approach was developed from the idea that problems originate from the ineffective instruction, rather than from students themselves.

In a technical report on direct instruction from Barak Rosenshine [6], another co-founder of direct-instruction, Rosenshine identifies multiple characteristics of effective direct instruction. Teachers communicate the goals with their students, allocate enough time for explenation and practice and keep the students close to the material, until knowledge is acquired.

Computer science teachers studied different instructional methods. More than twenty methods were examined in six processes [41] (i.e. build, process, apply, transfer, assess and integrate). Subsequently, these have been ordered in three groups. The acquisition of knowledge (build, process), the transformation of knowledge (apply, transfer) and the evaluation of knowledge (assess, integrate). Teachers included in this study had on average 7.5 years of experience with teaching computer science and at the moment of the study taught computer science at (of German State of Baden-Württemberg) grades 11 and 12/13 (grades 4, 5/6 HAVO/VWO in the Netherlands). Direct instruction was shown to be one of the highest scoring methods, with the highest grand mean for the acquisition of knowledge process. However, it also scored low on the evaluation of knowledge. This shows that direct instruction is effective for: acquiring knowledge, learning new practical abilities and for establishing and structuring what has been learned, but other methods show stronger results for integrating what has been learned, outside of educational settings.

2.2 Gamification in education

In the context of education, gamification is the use of game elements [10] within classrooms. It uses the students' familiarity with games for pedagogical purposes [15]. Traditional teaching strategies are transformed, using game elements as inspiration. For example, in a study students were taught using an online learning platform to learn C (a programming language) [20]. The platform included badges and a leaderboard. With this, students could track their progress and view the top performing students. The study measured an increase of the scores of the students, concluding that the gamified platform did improve their comprehension of C. In another study [31], focused on mathematics, points and a progress bar were used. The study compared a control group to a class that used gamified materials. Although no significant differences were observed in test scores, the study found a positive effect on student collaboration. The two examples used a different set of game elements. Despite these differences, both showed an impact on learning results. This shows that different sets of game elements can be effective in educational settings.

Compared to more other teaching methods, gamification is seen as an additional tool for teachers to use in their lessons. Gamification can be used in combination with other teaching strategies. It is not meant to replace a teacher, but to give them an additional tool to teach certain topics.

Gamification has been shown to be effective in pervious studies. In an educational research review from 2020, with 30 independent interventions from 24 quantitive studies, gamification shows a significant positive effect size over learning without gamification [3]. The study reviewed comparison based intervention studies (i.e. studies that compared gamified to non-gamified practices). First, the study found that gamification can cause higher enthusiasm. In studies that were reviewed, participants, commented that they liked the method and wanted the method to be used in other courses. Second, gamification can provide feedback on performance. With immediate feedback, students can adjust their strategy to better pursue their goals [22]. Third, gamification can fulfil the students their need for recognition. Students reported saying that they felt a desire to collect badges and that it was nice to get an achievement after doing good on problems. Finally, gamification can provide goal setting. One study found that students in the gamified group demonstrated deeper learning compared to those in the non-gamified group [19]. Despite these findings, the reviews shared two major reasons why some students disliked the use of gamification. Some students found that gamification does not bring additional utility, meaning that the find that there was no additional learning value of gamification. Moreover, gamification can cause anxiety or jealousy. Showing scores on a leaderboard was discouraging for students with lower scores, lowering their motivation.

2.3 Minecraft

Minecraft is a sandbox game released in 2011 on personal computers by Mojang. Minecraft has become one of the most popular video games in the world, with more than 204.33 million active players and more than 600 million copies sold [39].

As described on the developers' website:

> Minecraft is the ultimate building game. Craft tools, build a humble shelter, or engineer your base with redstone. Can you build a base in the Nether? Only one way to find out. [30]

All these named examples [37] [32] [40] can be found on a forum page called Planet Minecraft, a popular website where Minecraft players can upload their builds [33]. This creativity is also encouraged why the game itself. There is no clear end, the players have to chase. Players can set their own goals and push the game to its limits using their own creative freedom.

2.3.1 Minecraft redstone

In this research, we will make use of redstone. Redstone is a set of components in Minecraft, used to build different contraptions and digital systems. Usually, Minecraft redstone is used in the game to build automated farms for food and resources [12]. However, people have created large builds that simulate the behaviour of ALU [29] and CPU [7], allowing them to build programmable computers. In this chapter, we will highlight some redstone components that will be used in the course material.

For this project, we will use a minimal set of components, to decrease the mental weight for students who have no experience with Minecraft. Specifically, we will make use of redstone dust, repeaters, levers, redstone torches and redstone lamps. With these components we can build simple versions of AND, OR and NOT gates.

Redstone dust can be placed on top of blocks. When redstone dust is placed adjacent to another piece of redstone dust, it connects. Using this mechanic, the player can lay down paths through which power can flow through. From a power source, redstone dust can carry the power to fifteen blocks. At the sixteenth block, the power is lost. The redstone can be re-powered, by using the repeater. A repeater acts as a new power source, if there is an active redstone input. However, the repeater does have a delay of one to four clock ticks. This delay can be set by the player. The standard clock rate is 20 ticks per second. In figure 1 we can see the redstone dust being powered by a repeater. The resource pack Redstone Template [36] used for better visualization of the power strength at each redstone dust. The resource pack is not used in course material.

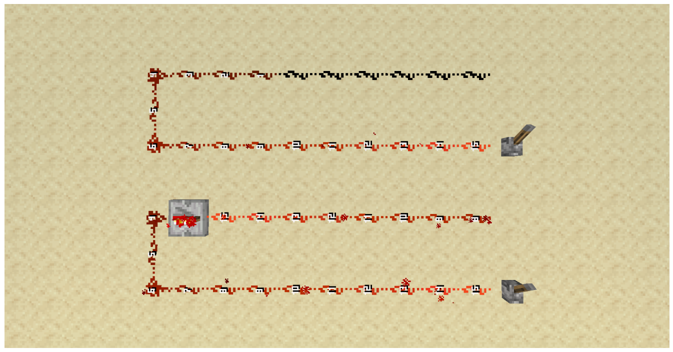


Figure 1: Redstone dust being powered by a repeater.

The last two power sources we will take a look at are the redstone torch and a lever. A lever works as expected, turning it on, powers the redstone dust, turning it off removes the power source. A redstone torch powers redstone dust, however, when a redstone torch is placed on a block that is powered by another source, it will turn off. In figure 2 we can see both a redstone torch powering redstone dust, and one being turned off from a power source. The lever powering redstone can be seen in the previous figure 1. Finally, the redstone lamp is a block that lights up when powered. In this course, the lamp will give a better visualisation of a bit being either one or zero (powered on or off).

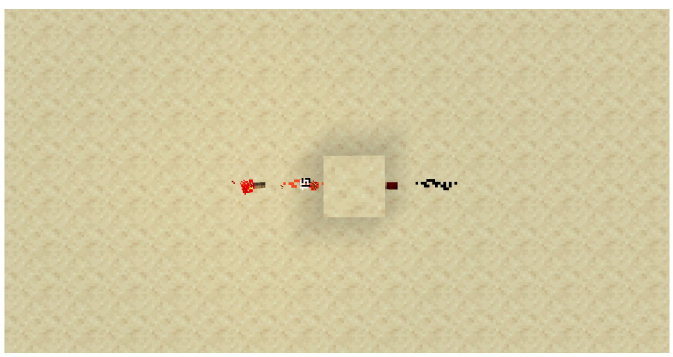


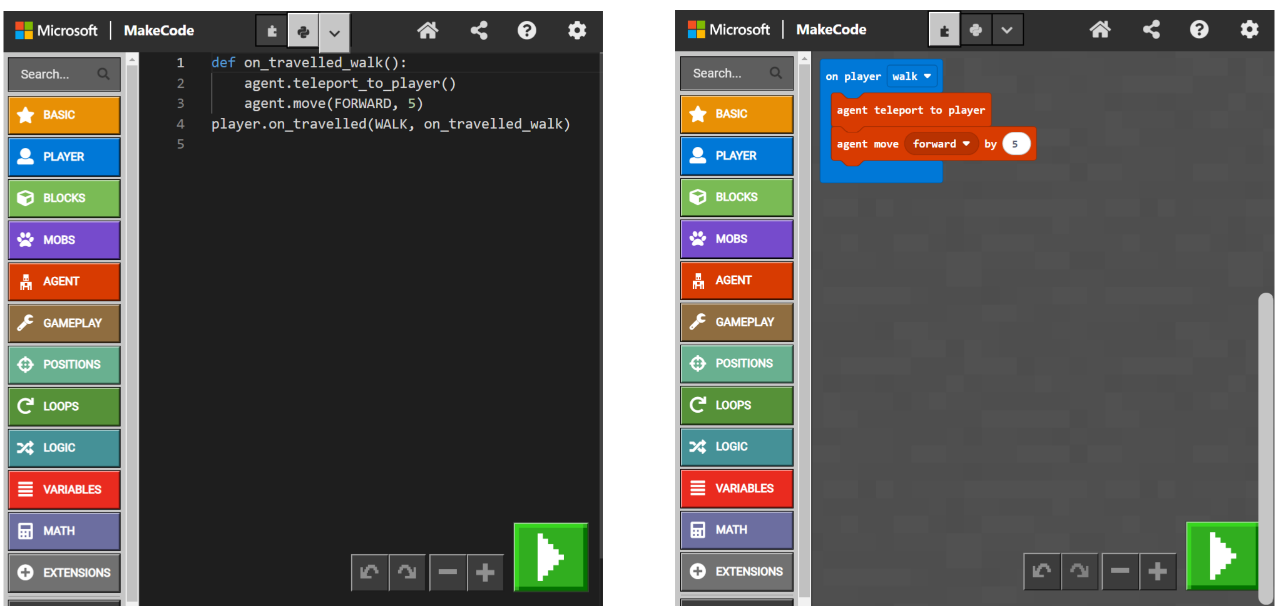
Figure 2: Redstone torch

2.3.2 Minecraft Education

Minecraft education is a form of Minecraft, adapted for learning environments. This version has the same gameplay (i.e. a sandbox world with free movement and the ability to create 3D structures), but is has many additional features for easier use in educational settings. Students have an overview of the controls on their screen at all time, and have easier access to all simple blocks. The software is lightweight and does not have heavy system requirements [28], making it easy to install on school computers. Moreover, Minecraft Education is included in the Microsoft 365 Education package [27], which makes it widely distributed and easily accessible.

In a study by educational professionals, the implications of Minecraft Education were reviewed across different education levels [2]. Here, Minecraft was used across multiple programs, such as biology [34], social studies [4] and mathematics [24]. From the reviewed studies it was found that Minecraft can be successfully integrated into various subjects. Specifically, the reviewed studies show that Minecraft can promote knowledge and skill acquisition. Students' motivation appeared high, which can be associated with persistence to complete tasks, while encouraging critical thinking, collaboration, and creativity. However, some challenges were noted that the integration of Minecraft into a classroom can create a lack of focus on learning.

In one research, Minecraft Education was used as a tool for programming [38]. Extracurricular classes were organized for students in primary schools. Players could press "C"to open an editor (MakeCode) in which they could program using JavaScript, Python or a draggable block-based programming language. In figures 3b and 3a, example code is shown. Although this research has not been finished, a questionnaire conducted with 19 students about their experience with the course material and Minecraft. Over 90% of the students answered that they liked the block programming language, and all students indicated that they wanted to continue. The study does not share any educational results, however, from the questionnaire, it was found that 73.7% did not find the lessons difficult. On the other hand, it was found that if a teacher is not a sufficient authority, students can destroy the world or create an environment in which learning is no longer stimulated.



(a) Python

(b) Block-based programming language

Figure 3: MakeCode editor in Minecraft Education

2.4 Technology Acceptance Model

One approach to evaluate the students' acceptance of the gamification of Minecraft in educational settings is the technology acceptance model. The Technology Acceptance Model (TAM-model) [9] is an information gathering theory designed by Fred D. Davis, Jr. It has often been used to evaluate technology with end-users. With the TAM-model, we aim to find people's acceptance of technology and whether they would use it in the future. To start, the model consists of four categories: perceived usefulness (PU), perceived ease of use (PEU), attitude (A) toward using, and behavioural intention (actual system use) (BI). Davis described PU as: "The degree to which a person believes that using a particular system would enhance their job performance" and PEU as "The degree to which a person believes that using a particular system would be free from effort". Thus, we are looking at whether the tool has a positive impact on their experience and if it is easy enough for them to use. Each category has a set of questions which will be answered by the end users, in our case, the students.

In earlier studies, gamification and the TAM-model as an assessment model have been reviewed. In 2024, a review was published with the aim of improving understanding of the relationship between gamification and the TAM-model [1]. Most studies focus on enhancing motivation and application effectiveness, for example by improving student participation. The review also found that TAM evaluations indicate that the ease of use and enjoyment, is supported by PU. With motivation and satisfaction being beneficial for the usefulness of the technology. Concluding, with gamifications, students were motivated to study. Moreover, perceived usefulness is improved and supported by ease of use and enjoyment.

3 Methodology

Before defining the details of this study, a short pilot study was hosted with a small group of six students. The details and findings of this pilot study can be found in 3.1. In the final experimental study, we made use of three different classes. Two of these classes used the direct teaching method 3.4, the other uses the Minecraft course material 3.4.1, henceforth called the control group and the Minecraft group. The participants in this study were students of 5 VWO (pre-university education) 3.2. The goal of this study was to measure how difficult the course material was for these students and if the Minecraft group would attribute to higher grades. This was measured using a small test 3.4.2. Moreover, we wished to measure how students experienced the use of Minecraft as part of their course material with the TAM-model 3.6. This section will describe the design of the course material, the participants and their education level, the specific survey following the materials used for this experiment and the procedure.

3.1 Pilot study

As we did not find a clear description of the current level of logic and digital systems for students in secondary education, we hosted a pilot study to see if the students were able to comprehend the course material. For this, five students of different backgrounds were gathered. These students had an average age of 22 ($SD = 2$), and all had different study backgrounds, none of which was a science related study. For example, one student studies educational theory and another hospitality management. As the study does not assume any previous knowledge, we determined that this group could be representative in their understanding of logic and digital systems prior to the study, even though their age is higher than that of students from secondary schools.

For this pilot, the group was split in two. Three students followed the lecture in Minecraft, and two students only used pen and paper. The groups were placed across each other to ensure that the control group was not influenced by the visualization of the experimental group. Though this class was planned for only 60 minutes, due to the unexpected difficulty and a short break, the class took in total 90 minutes.

During the class, we focussed on the questions students asked and adjusted the material. This helped us test the lecture and determine whether the difficulty was set to a reasonable level. We found that more visual examples were needed in Minecraft and that it was important to provide enough time for the students' questions. Moreover, due to time constraints, we decided to scale down from five to three digital gates, removing the NAND and NOR gate from the scope of this lecture. Students also gave feedback on the exam. As they advised for more guidance through the exam, with more explanations for each tasks and truth tables they could fill in, instead of drawing them themselves.

3.2 Participants

In this study, two classes of 5 VWO joined the direct instruction class, and the other class joined the Minecraft class. The first class, a control group from a secondary school in Leiden (henceforth school A), consisted of 18 students, with an average age of 17 (with a standard deviation of $SD = 0.58$). This was a homeroom class, which meant that the students had different subject combinations. That is to say, for example, some students had history in their curriculum, while others had physics. The study was designed with this in mind, meaning that there was no background knowledge needed. The other classes both came from another secondary school in Leiden (henceforth school B). The control group had an average age of 16.7 ($SD = 0.47$) and had 15 students. The Minecraft group had an average age of 16 ($SD = 0.60$) and had 16 students. Both groups of school B had physics in their curriculum and followed combinations of science subjects (science and technology or science and health).

3.3 Procedure

The study consisted of three different classes. For both the control and experimental groups, we ensured equal opportunity with the course material. To achieve this, the content of the control group was translated into the Minecraft class. The same examples, exercises, and exam were used for both groups. In the setup 3.3.1, more precise examples of translations are given.

3.3.1 Set up

In all classes, the students sat in their original floor plan. Students all sat next to either one or two classmates, having groups of two or three tables, all facing the teacher. In the direct instruction class, students had pen and paper available to make notes. In the Minecraft class, all students were provided a laptop with an external mouse. The teacher stood in front of the class during the lecture, during the exercises, the teacher moved through the class to check progress and answer questions individually.

The lecture was split into different parts. First, the teacher talked about the basic concepts of boolean algebra, explaining different logic gates and filling in truth tables. In the Minecraft class, students were able to follow this explanation within their Minecraft world, as all slides were translated into Minecraft artifacts. For example, when given an example, the (interactive) example was also build in Minecraft. One of these examples was a toothbrush. The teacher talked about an AND gate and used an electrical toothbrush as an example. Here, the toothbrush would give off a signal if the user pressed too hard on the brush (i.e. $(switched\_on \wedge hard\_pressure) = redstone\_lamp\_on$). In Minecraft, an interactive toothbrush was build (shown in figure 4), which students could turn on and off, while also being able to add pressure to the brush to see whether a redstone lamp would light up. Next, the students had the opportunity to create their own digital circuits and fill in truth tables. In Minecraft, redstone circuits were build and truth tables were shown, which students could fill in. Finally, the lecture ended with a short exam. Here, control group and experimental group received the exact same exam, so that we could measure and compare their performance. Whenever a student finished the exam, consent form was given to them in which they could choose whether they wanted to share their results in this study. In this consent form, the goal of this study was explained, and it shared what information would be used in this study. At the end of the form, students shared if they wanted to share their information, and contact details were shared if they changed their mind.

At the end of the exam, the experimental group was provided a survey in the form of the Technology Acceptance Model. The form contained an extra optional section with open feedback such that we could gain more insight in their personal experience.

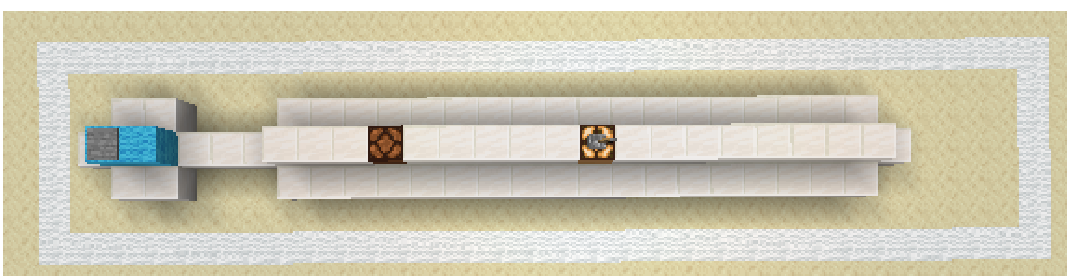


Figure 4: An interactive electrical toothbrush in Minecraft. The left redstone lamp acts as a signal.

3.4 Designing course material

As mentioned before, the course material was designed without prior knowledge on computer science in mind. The topics included were thoroughly explained. The course material included an overview of the lesson. With only an hour available for the class, each part only took about fifteen minutes. Hence, a guideline for timestamps were added for each topic and part of the lesson. Some important requirements for the course material was that it needed to have enough time for exercises and give the students enough opportunities for questions. This course material guide helped us ensure the topics discussed, and the time given to the students for the lecture and exercises were the same for both groups.

3.4.1 Creating a Minecraft map

The Minecraft course material was build into a Minecraft map. This is the world in which players can move and interact with blocks. It was necessary that the students could easily navigate through the map. Moreover, the map needed to make use of meaningful game elements, rather than just writing the lecture slides in text inside the game. Also, to ensure that students had all the tools available they needed, when a student opens the map, they are equipped with all the tools they need during the class.

To make sure that students could navigate easily through the map, the structures were build from left to right. The structures were ordered according to the lecture slides, increasing in complexity. Moreover, a structure was build with buttons students could press, which would teleport them to different parts of the class. To ensure goal setting, colourful borders surrounded the different structures, to split up examples and exercises. Finally, redstone lamps were used, to visualize the output of digital systems and give immediate feedback to the students. In figure 5, the digital system for $\neg(A \wedge B) \wedge \neg C$ is shown. By placing blocks, students could make notes when the example was written on the board as the results were filled in.

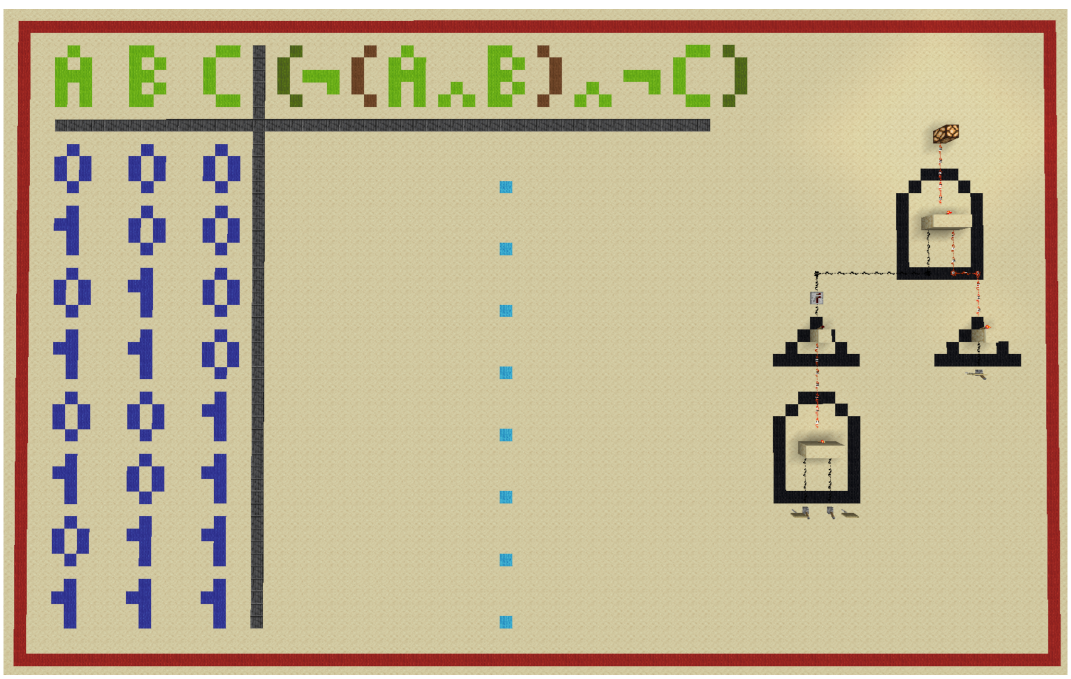


Figure 5: Example 2 in Minecraft

3.4.2 Exam

The exam was meant to measure how much the students learned during the class and if they were able to answer new questions. New questions, are tasks and questions which have not been directly explained before in class. Both the control group and the experimental group were given the exact same exam. Both were given tasks on paper. Since the class is quite short, the questions were directly copied from the examples given during the lecture. Only a single question was given which was slightly more difficult. The difficult question used a combination of more than four logic gates, and introduced a fourth variable. The exam questions and the truth tables are listed in Appendix B.

The exam starts with a short explanation to prepare the students for the upcoming questions. Since this is a new topic, we explicitly state how questions should be answered. A summary of the introduction is shown below translated into English. The complete introduction is written in Dutch and found in Appendix A.

> This lecture, you have been introduced to logic and digital systems. Now, you will get 15 minutes for this short exam. Most questions have been explained directly in class, with a single question that requires a little more thought.
>
> - Skip questions of which you do not know the answer, first answer questions of which you know the answer.
> - The exam consists of two parts, in total there are seven questions.
>   - In the first part, you can fill in the truth tables.
>   - In the second part, you can draw digital/logic gates on your answer sheet.

As stated in the explanation, the exam was split into two sections. In the first section, students filled in truth-tables. These tables were drawn on a separate page, so students only needed to enter the correct values. In figure 6, the truth table is shown for the first question. As shown, the values for the variables (A and B) have been given, as it was not part of the lecture to write down all combinations of inputs. In total there were three questions in this first section. The third one was slightly more difficult, with a third variable being introduced to the truth table.

A	B	$A \vee B$
0	0	
0	1	
1	0	
1	1	

Figure 6: Truth table for question 1 of the exam

In the second section, students will draw their own circuits. To guide them into the drawing process, students are first asked to draw three logic gates. Next, they are asked to draw digital circuits based on the given logical expressions. In total, the second section has four questions. The third question is significantly more difficult, as it has four variables and uses multiple logic symbols in a single expression.

All questions were given one point if correctly answered. In question four, three points were available, as the students needed to draw three different digital gates. The final score was calculated using a standard formula:

$$final\_score = \frac{points\_obtained}{total\_points} * 9 + 1$$

3.5 Materials

The tool used for gamification in this study is the aforementioned game called Minecraft and Minecraft Education. In Minecraft (version 1.18.2), the course material was created. By using WorldEdit (version 7.2.10), a modification for Minecraft, it was easier to build large structures and copy builds into other locations. This was necessary to sort the structures in increasing difficulty, while still having the option to add new ideas later. Since Minecraft was not available on the laptops provided by school B, this version of Minecraft was transformed into Minecraft Education (version 1.21.133) using Chunker [18], an open source Minecraft version converter. Minecraft Education has built in safeguards and instruction, such that the students could easily move through the game. Moreover, Minecraft Education is included in the Microsoft Education package [27], which was available for these students.

3.6 Survey design TAM

The Minecraft group ended with a survey. The Technology Acceptance Model was used to create a survey consisting of four parts, and an optional part for open feedback. The questions in the four main sections were measured using a five-point Likert scale, ranging from strongly disagree to strongly agree. In the survey, all statements were given in Dutch, example statements below have been translated into English.

The first part focussed on perceived usefulness. With five statements, we measured whether the students found the tool useful to learn from. Example statements included were: "Building Minecraft redstone circuit helped me to understand logic gates (AND/OR/NOT)" and "It was easier to fill in a truth table with a redstone circuit next to it, then if I had to do it without a redstone circuit".

The second part focussed on perceived ease of use. With five statements, we measured whether students had an easy experience with Minecraft. Example statements included were: "It was easy to build a circuit in Minecraft", "It was easy to find the materials I needed in Minecraft" and "It was clear to see whether my circuit was wrong or correct".

The third part focussed on perceived attitude. With four statements, we measured the students their attitude towards Minecraft. With this, we gained insight in the feelings of students and their experience with Minecraft as a educational tool. Example statements included were: "I liked using Minecraft as an educational tool" and "I was motivated to work on digital systems, because I was building them in Minecraft".

Finally, the fourth main part focussed on behavioural intention. Here, we measured whether students would want to actually use Minecraft as an educational support tool. Example statements included were: "I would recommend other students and teachers to use Minecraft in their class" and "I would like to use Minecraft again in other classes".

The survey ended with three open questions: "What did you like most about Minecraft in this class", "Was their anything unclear, or did you experience any problems in the Minecraft map" and "Are there any other things you want to share about this class". We used these open questions to gain a lot of insight and feedback from the students 4.

3.7 Analysis

To analyse the results of this study, the exam data and the survey data was gathered. In Microsoft Excel, a table was filled with the points obtained for each question. In the last column, the students' final grade was determined. In all questions students could obtain 1 point, with the exception of a single question in which students had to draw multiple digital gates. With this we could compare the average number of obtained points and the average grade of the control and the experimental group. Moreover, the students' age and class was entered in the same table to create an overview of the participant distribution. With this, we were able to determine if the experimental group and the control group had any significant differences in the exam scores. For this, we used the Wilcoxon Rank-Sum test. The grades were all entered into R (version 4.2.1), corresponding to the control group and experimental group to perform this test.

The survey has also been digitalized into Microsoft Excel. Again, each row has the score of that student for a specific question. The scores ranges from 1 to 5, with 1 corresponding to strongly disagree and 5 corresponding to strongly agree. The data was cleaned, as some students marked multiple answers. Finally, for each part, descriptive statistics, such as mean and standard deviation were calculated. With these results we gained insight in the impact of Minecraft in their experience within education.

4 Results

In this section the results of the study have been noted and described. In section 4.1, the experiences of building the Minecraft map have been shared and the integration of the feedback of the pilot group has been described. Next, in section 4.2, we the final results of the exam have been shown into a table and highlights are pointed out. Finally, in section 4.3, the results of the survey have been visualized into a graph.

4.1 Minecraft map

Before conducting the study, we first finalized the Minecraft map. For this, we used the course material for the control group and the feedback from the pilot study. In this paragraph, we share the experiences from building the Minecraft map.

The course material from the control group was transformed into Minecraft. For this, we started with some inspiration from a Minecraft map created by Mattbatwings. In this map, a large digital system was built that could simulate a simple ripple carry adder, a digital system that adds two numbers. We took inspiration from the logic components he created using redstone and simplified it into smaller, individual, digital gates.

At first, we noticed that building with just redstone was unclear and it would be hard for students to connect these redstone builds with the actual drawings of digital gates. Which is why, each redstone build (each digital gate in Minecraft), was surrounded with colourful borders. Moreover, to improve players understanding of where a new part of the lecture started, we also placed borders around each complete build, both for digital systems and truth tables. With this, digital gates were visually grouped with truth tables that showed their in- and output values.

After the pilot study had concluded, we observed that more visual examples were needed. Based on this feedback, additional examples were added to the Minecraft map and more time was allocated during the lessons to discuss these examples.

Finally, a teleportation system was build. Each structure had a button next to it, which would teleport the player to a wall with buttons on it that would teleport the player to different parts of the lecture. This gave students the opportunity to go to different structures, without the need of searching through the world themselves.

4.2 Exam

The lecture ended with a short exam, consisting of two parts and a total of seven questions. Both groups received the same exam on paper, such that we could measure and compare student performance.

The control group in this study used direct instruction. The first control group (from school A), was a homeroom class. Students all followed different subject combinations. The control and experimental group of school B were all students from physics classes, moreover, all students had science courses in their subject combinations. Since this study assumed no prior knowledge of this subject, neither of the classes had any advantage going into this study.

4.2.1 Exam results

In this section we take a closer look at the results of the exam that was conducted at the end of both groups. We first start with a short explanation of table 1. Next we describe the difference between the age demographic of the control groups and the experimental group.

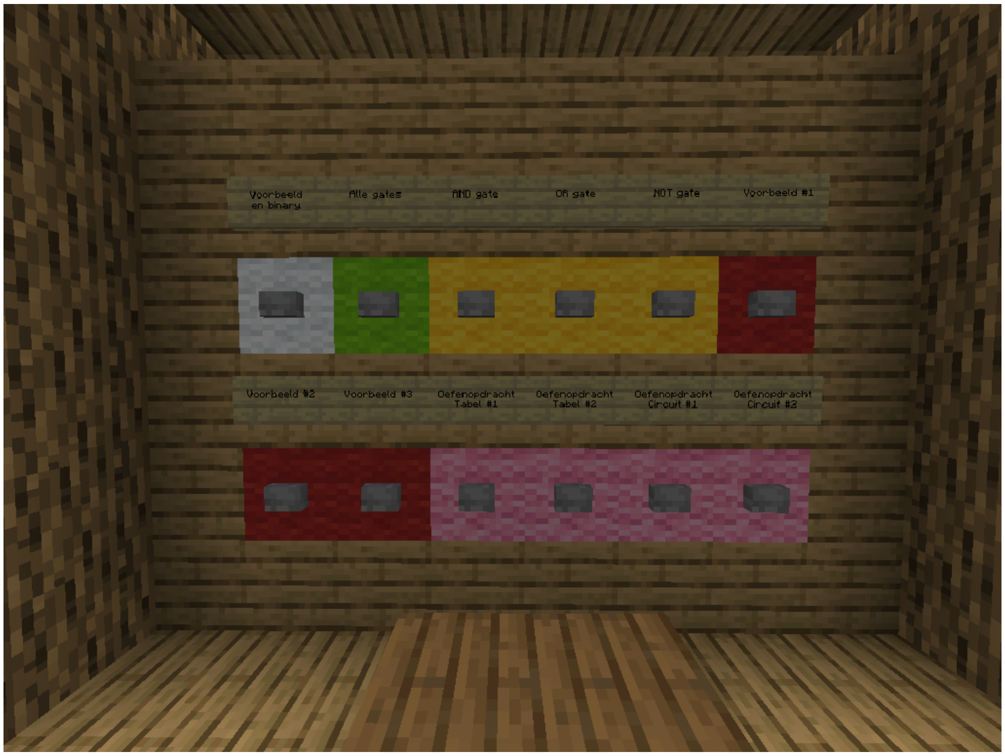


Figure 7: Wall with buttons to navigate in the Minecraft map

To begin, in the first and second column of table 1, we see the group and their average age. In the next columns, we can see the percentage of points obtained for each question. In these columns, this also shows the percentage of students which answered the question correctly. Except for question 2.3, as students could obtain up to three points for this question. In the final column, the average score per class have been denoted.

First, we notice that the experimental group has a slightly lower average age than the other groups. This group had the most (seven) students which were 16 year old. In the control group from school A and the experimental group, ages ranged from 16 to 18, in the control group from school B, ages ranged from 16 to 17.

Next, we observe the first part of the exam results from the different groups. In all groups, the table shows high scores in the first part of the exam. In the control group of school A, on average, 89% of the students answered correct, and the students of the control group of school B answered even all questions correct. However, we do see that the experimental group obtained fewer points in Q1.2. Though discussed in class, this question used two logic operators ($\neg$ and $\wedge$), while Q1.1 and Q1.3 only used one (see Appendix B). This brought the number of students answering a question correct on average down to 75%.

In the second part of the exam, we see a clear decrease in the points obtained. The control group of school A obtained 64% of all points, and the control group of school B obtained 51% of all points. Finally, we find that the experimental group obtained only 25% of the points available.

Q2.3 has the least amount of points for all groups. This question was the more difficult question which needed more insight and understanding of the concepts explained during the lecture. In the experimental group, only a single student answered this question correctly.

Finally, the final score of both control groups was $M = 7.0$ ($SD = 1.9$). The experimental group scored on average 4.2.

To end, the homeroom teacher also noticed that many students had difficulty paying attention to the explanation. As some students would walk within Minecraft to other parts of the lecture, while other students were focussed on experimenting with the structures. This lead to some students not listening to the lecturer and which lead them to not understand any of the material, with one student answering none of the questions correct on the exam. From the other answers given by the students, we noticed that some students drew redstone circuits instead of logical components. Other students, added a redstone lamp or a lightbulb at the end of the circuit.

Group	Average age	Q1.1	Q1.2	Q1.3	Q2.1	Q2.2	Q2.3	Q2.4	Median score	Final score
School A - Control group	17.0	94%	89%	83%	79%	50%	22%	72%	6.7	7.22
School B - Control group	16.7	100%	100%	100%	33%	80%	47%	80%	6.7	6.74
School B - Experimental group	16.6	88%	63%	75%	31%	19%	6%	31%	3.3	4.17

Table 1: Percentage of total points obtained per question per class.

4.2.2 Wilcoxon Rank-Sum test

In this study, all observations from both groups were independent, from different populations, since both classes were separately taught. The Wilcoxon Rank-Sum test was used to see if there was a statistically significant difference in the exam grades of the two groups.

The Wilcoxon Rank-Sum test was performed showing $W = 423$ and $p < .001$. The null hypothesis was rejected, indicating a statistically significant difference in the distribution of scores between the direct instruction and the Minecraft class. The medians for both control groups was the same, 6.7, and the median for the experimental group was 3.3. Here, we also see this in the difference of the medians from the groups.

4.3 Survey

To measure the students their experience with Minecraft as part of their education, a survey was taken in the form of the Technology Acceptance Model. The survey was structured into five sections, with the last section being optional for open feedback. The scores of the survey ranged from 1 (strongly disagree) to 5 (strongly agree). In figure 8, the results have been plotted into a box plot. Here, the average score of each section per student was calculated and sorted. The additional feedback and remarks provided in the optional open-ended section of the survey are included in the analysis of the corresponding sections below where relevant.

To start, we see that students have mixed opinions on the usefulness (PU) of Minecraft in an educational setting. With an average of $M = 3.2$ ($SD = 0.67$), students do not indicate a clear view of finding Minecraft useful or not. From the survey, we found that students did like the visualization of redstone lamps and the output of the digital systems, however, they did seem to find difficulties with building the structures themselves. One student remarked that they were very distracted by the game, making it hard to focus on the lecture itself.

Secondly, we see that students do think Minecraft is easy to use (PEOU). The section for PEOU had a slight increase compared to the PU, with an average of $M = 3.2$ ($SD = 0.37$). All students said they did use Minecraft in their free time, but none had used it in an educational setting before. Moreover, Minecraft Education was something they have not seen before. Since the students had all the items ready for them in the inventory, it is not surprising that they score high when asked about the difficulty of finding the right tools and blocks. During the exercises, some students noted that they incidently lost their inventory. This meant that the pre-loaded items were lost, which took some time, but due to their experience, they were able to find it themselves.

Next, the students liked the use Minecraft as an educational tool and were motivated to work on the course material, because it was being taught within Minecraft. Their attitude (A) had the highest score, with an average of $M = 4.2$ ($SD = 0.73$). All students indicated that they enjoyed Minecraft as an educational tool, with all scores ranging from 4 to 5 for that statement.

Finally, there were a lot of mixed opinions on whether they wanted to use Minecraft in future classes. In figure 8, we can see this in the spread of scores, with an average of $M = 3.5$, but with a standard deviation of $SD = 1.03$, it is clear that opinions are spread. Some students noted that they were too focussed on how redstone worked, which made it hard to learn the actual digital systems. One student even expressed frustration stating: “How on earth do I build this?”However, other students did find the visualization with redstone lamps very insightful.

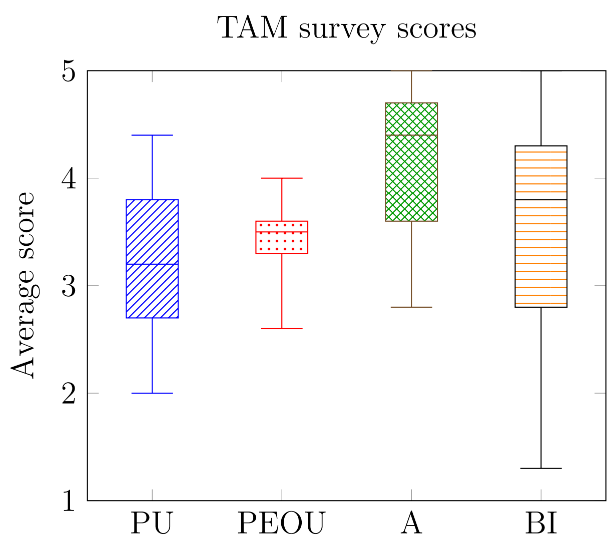


Figure 8: Box plot with the results of the TAM survey

5 Discussion

In this study we wanted to investigate the effectiveness of Minecraft within educational settings in secondary education. Specifically, we introduced logic and digital system design to students of 5 VWO at two different secondary schools in Leiden. Using gamification, the material was translated into Minecraft Education, while still staying close to the original topics. By comparing the students' performance from a direct instruction class and a Minecraft class, we investigated whether Minecraft would attribute to higher grades. Moreover, students in the Minecraft class completed a survey based on the Technology Acceptance Model, from which we gained more insight in their experience with Minecraft as a way to learn new topics.

For this research, we formulated the following research question:
RQ - How effective is the gamification of Minecraft for explaining fundamentals of digital systems in secondary education?

To reach a conclusion for this question, we formulated two sub questions:
SQ1 - How does the performance of students in a class using Minecraft Education perform compared to a class using direct instruction?
SQ2 - How do students experience the use of Minecraft as part of their education?

5.1 Building a Minecraft map

A Minecraft map was built for this study. We took inspiration from previous builds of Mattbatwings. Though we did have experience with building in Minecraft, transforming educational material into redstone builds was challenging.

To start, to build a Minecraft map, we needed a fundamental understanding of the redstone components. To create interactive builds, we also needed an understanding of the digital gates and to create small digital systems. Since we had experience with creating redstone builds in Minecraft, we were able to translate the digital systems into the game.

However, difficulties arose when we wanted to include an educational component. The builds not only needed to visualize the digital gates, but also needed to explain how the digital gates worked, and how students could reproduce it themselves.

Although the pilot study gave us a lot of insight in what the students needed in the Minecraft map to understand the theory of logic and digital systems, the results showed that students found difficulties with the map, specifically with redstone. This could indicate that the map needed more explanations on how redstone components worked, and that the map needed to guide students more on how they could build digital gates in Minecraft themselves.

5.2 Student performance

From the exam results, we see that students scored lower on average in the Minecraft group compared to the direct instruction groups. In each question, students received fewer points than the other groups. With the exam, we wanted to gain insight in the students' understanding of the material. Since the class was under an hour, most questions came from the examples given in class, with only a single question being more difficult. For this question, the students needed to use their own creativity, instead of reproducing what has been told during class. The result was not what we expected when we conducted the study, however, there are several factors that can be taken in to account when we interpret this.

First, during the class, the homeroom teacher noticed that students from the Minecraft group were too focused on the game, which distracted them from paying attention to the explanation by the teacher. In previous research, concerns have been shared on the focus of game elements versus the academic goals [21]. In our study, we see that students were enjoying the materials and liked experimenting with the digital systems, meanwhile the class continued. This likely caused the students to mostly not understand what the inputs actually meant and how they mapped to the truth tables. In a paper that studies the implementation of educational games in formal educational settings, it was found that, specifically in Minecraft, teachers take on an additional set of roles, besides teaching during typical gaming sessions [25]. Teachers need to act as administrators, lecturers, game tutors and authority figures to keep the students focused on the academic goals . In this study, an additional administrator or authority figure would probably help the students to balance their experimenting with listening to the lecturer.

Moreover, one could argue that the control groups had a slight advantage over the experimental group, as the experimental group had no experience with drawing digital gates on paper. The experimental group had only built redstone logic gates. We see this in the answers students had drawn on the second part of the exam, where some students drew redstone components, instead of the digital gates.

Also, in this study, a single lecture of 55 minutes was organized. Within this lecture, students received an introduction, a presentation on the theory, examples from the lecturer, time for exercises, an exam and a consent form and (the experimental group) survey. Especially for the Minecraft group, this might have been an overload of topics to process. Here, we see that there was a lot of content to go through during this class. This might have caused a too large increase in cognitive load. In a social study where cognitive load was related to motivation [14], researchers found that this could cause students to become frustrated and reduce their willingness to engage more deeply with the learning process. This was also shown by the frustration shared in the results.

However, another argument could be made, that perhaps logic and digital systems are topics which are not suited for Minecraft Education. From the literature study we found that logic and digital systems design is a topic that is not always included in the curriculum of computer science in secondary schools. Translating this unknown topic in Minecraft redstone might have been too difficult. This brings us back to the concept of misteaching. In this case, students not only needed to learn about logic and digital systems, but also needed to familiarize themselves with Minecraft Education. We see this in the answers given on the second part of the exam, where some students drew redstone lines and lightbulbs.

Therefore, it can be interpreted that the results do not directly indicate that Minecraft Education is not necessarily ineffective as an educational tool, but that the implementation of course material into Minecraft Education requires careful design.

5.3 Students' experience with Minecraft

When the students finished with the exam, they all received a survey in the form of the technology acceptance model. With this form we gained more insight in the students' experience with Minecraft in an educational setting. In the Minecraft group, all students had previous experience with Minecraft before, however, none of the students had worked with Minecraft Education.

Overall, we see that the students find a positive experience with Minecraft Education and that it motivated them to work on the course material. In all sections of the TAM-model, the average score lies above a neutral standpoint, in favour of Minecraft Education. In PU and BI, the students' opinion is spread and the minimum is quite low. This indicates that the students had mixed opinions on the usefulness of Minecraft Education and that some students do not intend to use it in future educational settings. This could be explained by the performance of this group. As some students might have found it difficult to make a connection in between the paper answers and the builds in Minecraft. Poor performance might have been demotivating, causing them to score low on the survey as well. This is also supported by the review from 2024 [1]. As motivation might have been lower due to the poor performance, it might have impacted their opinion on the usefulness of Minecraft.

5.4 Limitations

The largest limitation for this study was time and availability. Due to the technical limitations, such as the Minecraft Education software and laptops, only school B was able to provide a group for the Minecraft class. Conducting the study with a Minecraft group on both schools would have reduced school-specific factors and provided a broader comparison.

Moreover, the pilot study only indicated an estimation of the students' understanding of logic and digital system design. Because the class was only 55 minutes, it was difficult to measure the long term effectiveness of Minecraft or whether the students would perform differently with more practice.

Also, the TAM-model primarily measured the students' acceptance of Minecraft Education in the context of logic and digital system design in education, which gave us a limited understanding of the students' experience. Other methods, like think-aloud, or semi-structured interviews could provide more insights in the students' experiences, opinions and challenges from using Minecraft Education.

5.5 Future directions

This study provides insight into Minecraft Education and its application in computer science in secondary schools. Since this study used a small group of students, and the class only took 55 minutes, more research is needed to build on these findings and explore the implications of Minecraft redstone and the topics of logic and digital systems design.

First, when building a Minecraft map, future studies could allocate more time for evaluations with not only students from the representative group, but also their teachers. By inviting these groups, more insight could be gained in their needs in Minecraft worlds and a deeper understanding of how to guide them could be provided by their teachers.

Secondly, future studies could investigate whether introducing students to Minecraft redstone before the lesson on logic and digital systems design improves learning outcomes. By separating the students' familiarity with the game from the course material, researchers could find whether lower performance was caused by the educational content within the game, or by the additional cognitive load in the class.

Moreover, future research could investigate the possibilities of creating an exam in Minecraft. This could be achieved by creating a separate map in which the students have to build in. However, practical difficulties might arise in the evaluation of these exams. As it might be very time consuming for teachers to explore different Minecraft maps. Therefore, future research could also investigate in in-game assessment methods.

By focusing on these areas in further research, educators could explore more about Minecraft Education and its implications in educational settings.

5.6 Conclusion

In this study we examined the use of Minecraft Education in the context of logic and digital systems design for secondary schools. A control group using direct instruction was compared to an experimental group using Minecraft Education to investigate gamification in this context.

To answer **SQ1**, the students who followed the direct instruction class achieved better results on the exam compared to the students who followed the Minecraft class. However, these results need to be interpreted carefully, as we also find improvements in the Minecraft class. The Minecraft class required more guidance with redstone, and the written exam may have favoured the direct instruction class. Therefore, further research is needed to conclude whether students in a Minecraft class perform better or worse compared to a class using direct instruction.

For **SQ2**, we see that the students show a positive response to Minecraft in an educational setting. However, we also found that students have mixed opinions on the usefulness of Minecraft within the context of logic and digital system design.

Finally, to answer the main research question: "How effective is the gamification of Minecraft for explaining fundamentals of digital systems in secondary education?", we look back on the answers of the two sub questions. Though in this study, student performance was lower in the Minecraft group, student enjoyment and motivation of Minecraft showed that they did find this educational setting interesting. This shows that Minecraft Education has potential as a learning tool, but its effectiveness for improving learning outcomes is unclear. While students enjoyed building in Minecraft, the game also distracted them from the learning objectives. Therefore, this could indicate that careful design is needed, and more guidance with redstone is needed for the students to achieve better exam results.

Further research is needed to evaluate the long term impact of Minecraft Education and its effectiveness to teach logic and digital systems design. Future studies could focus on more evaluations with educators and students with the Minecraft map, before conducting the research with an experimental group. Also, future research could investigate whether a separate introduction to redstone could improve exam results.

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A Introduction to the exam

Below, the complete introduction to the exam is found. This explanation was used for both the direct instruction class and the Minecraft class. The introduction is in Dutch, as Dutch students were invited for this study.

> Zojuist hebben jullie een introductie gekregen naar logica en digitale technieken. Nu krijgen jullie 15 minuten voor deze korte toets. Veel vragen zijn direct in de les uitgelegd, bij elk onderdeel is er één vraag waar je iets verder voor moet nadenken.
>
> - Sla de vragen over die je niet weet, maak eerst de vragen waar je wel het antwoord op weet.
> - Schrijf aan het begin van je antwoord op welke vraag je antwoord geeft.
> - De toets bestaat uit twee onderdelen, in totaal zijn er zes vragen.
>   - In het eerste onderdeel kan je de waarheidstabellen invullen die op de laatste pagina staan.
>   - In het tweede onderdeel mag je de digitale poorten/gates tekenen op je antwoord blad.

B Exam questions

Below, the logic formulas and tasks for the exam are listed. The inputs and variables for the truth tables were given on the exam, the students only needed to fill in the output column. On the exam, all questions were written in Dutch.

1. Part 1 - Truth tables. Below are all the logic formulas for the truth tables of this exam.
   1.1. Fill in the truth table for: $A \vee B$
   1.2. Fill in the truth table for: $\neg(A \wedge B)$
   1.3. Fill in the truth table for: $A \vee B \vee C$
2. Part 2 - Digital system design. In this part, students needed to draw digital circuit themselves. Below are the formulas for which they needed to draw a circuit.
   2.1. Draw three different digital gates and write their names below.
   2.2. Design a digital system for: $(A \vee B) \wedge \neg(A \wedge B)$
   2.3. Design a digital system for: $((A \vee \neg B) \wedge C \wedge (D \vee A)) \wedge \neg B$
   2.4. Design a digital system for: $(\neg(A \wedge B) \wedge \neg C)$