Universiteit Utrecht

Drawing in a Virtual 3D Space

Introducing VR Drawing in Elementary School Art Education

MASTER THESIS

WENDY BOLIER

ICA-5728223

Supervisors:
Dr. Wolfgang Hürst
Guido van Bommel

Second examiner:
Prof. Remco Veltkamp

July 22, 2017

ING

KLEUR IN CULTUUR

Abstract

Virtual reality (VR) technology makes it possible to directly interact with virtual 3D spaces. This enables the realization of VR drawing tools that allow everyone to create 3D drawings in a simple and intuitive manner. Introducing this new method of drawing to children at elementary schools can benefit them in multiple ways. One of the potential benefits is the enhancement of spatial skills. Previous work suggests that both the drawing of 3D objects and the usage of VR can improve mental rotation and spatial visualization skills. Since VR drawing is a combination of the aforementioned activities, it seems promising to investigate its effect on these spatial abilities. So far, no research has been done into the educational use of VR drawing or its relation with spatial abilities. This thesis takes a first step in gaining a better understanding of the benefits and obstacles that VR drawing brings when introduced at elementary schools. We performed an experiment with 18 children (ages 10-12). Several drawing exercises were implemented and tested. Furthermore, our tests studied the correlation between the participants' spatial ability test scores and proficiency in creating a VR 3D drawing and whether a few VR drawing sessions are enough to increase these spatial ability test scores.

Our results show improvement in the children's 3D drawing skills but not in their spatial skills. Their drawing skills do seem to be correlated with their mental rotation ability, although further research is needed to conclusively confirm this. This thesis lays the foundation for future research into the educational use of VR painting tools and shows that it is indeed a promising direction for further evaluation.

Acknowledgements

I would first like to express my deep gratitude to Dr. Wolfgang Hürst, my thesis supervisor, for his guidance, support and useful feedback throughout this master thesis. I also am particularly grateful for the enthusiasm, support and valuable input provided by Joost Bosman and Guido van Bommel from ING and Harriët Bosman from KLEURinCULTUUR. Without them this project would not have been possible. I would also like to acknowledge ING and KLEURinCULTUUR for enabling this project and making sure that I had all necessary hardware at my disposal.
Assistance provided by Amanda de Gast during the experiments and her valuable insights as an art teacher were indispensable and greatly appreciated. I also would like to thank Bastiaan van Meerveld from Sterrenschool de Ruimte for allowing me to use his students for the experiments, and of course the students themselves for their cooperation and time. Furthermore, I would like to express my appreciation to Heleen Lingers for proofreading this thesis and providing me with valuable comments.
Finally, I must express my very profound gratitude to my family, friends and in particular my boyfriend for their unwavering support during the entire process.

Contents

List of Abbreviations

2D	**2**-**D**imensional
3D	**3**-**D**imensional
3DC	**3**-**D**imensional **C**ube
AR	**A**ugmented **R**eality
CAVE	**C**AVE **A**utomatic **V**irtual **E**nvironment
CSCW	**C**omputer-**S**upported **C**ooperative **W**ork
CVE	**C**ollaborative **V**irtual **E**nvironment
DAT:SR	**D**ifferential **A**ptitude **T**est: **S**pace **R**elations
GD	**G**raded **D**rawing
GD2D	**G**raded **D**rawing with a **2D** example
GD3D	**G**raded **D**rawing with a **3D** example
HMD	**H**ead **M**ounted **D**isplay
HTML	**H**yper**T**ext **M**arkup **L**anguage
MCT	**M**ental **C**utting **T**est
MGD	**M**ean **G**raded **D**rawing
MRT	**M**ental **R**otation **T**est
PSVT:R	**P**urdue **S**patial **V**isualization **T**est: **R**otations
RCCT	**R**otated **C**olour **C**ube **T**est
SBS	**S**tep-**B**y-**S**tep
S&D	**S**ketching and **D**rawing
SRT	**S**patial **R**easoning **T**est
VE	**V**irtual **E**nvironment
VR	**V**irtual **R**eality

Preface

This thesis, entitled Drawing in a Virtual 3D Space, has been written to fulfill the graduation requirements of the MSc Game and Media Technology programme at the Utrecht University (UU). It investigates the potential for educational use of painting in Virtual Reality (VR) at elementary schools. The idea of this research was proposed by ING and KLEURinCULTUUR. The main deliverables of this thesis are:

- A scientific paper, which can be found in Part 1 of this document.
- An annotated appendix to complement the scientific paper, which can be found in Part 2 of this document. The appendix contains:
  - A concise review of the broad initial literature study.
  - Additional information and data of the experiments that are relevant for the thesis, but not contained in the paper.
- The extended version of A-Painter that was created for this research project, which can be found at: https://wendybolier.github.io/, and its source code at: https://github.com/WendyBolier/WendyBolier.github.io.
- A summary video targeted at a broad audience containing footage of the tests and painting sessions: https://youtu.be/uEWCSmAXxMI.

Wendy Bolier
Utrecht, July 22, 2017

Part I

Scientific Paper

Drawing in a Virtual 3D Space - Introducing VR Drawing in Elementary School Art Education

WENDY BOLIER, Utrecht University

Virtual reality (VR) technology makes it possible to directly interact with virtual 3D spaces. This enables the realization of VR drawing tools that allow everyone to create 3D drawings in a simple and intuitive manner. Introducing this new method of drawing to children at elementary schools can benefit them in multiple ways. One of the potential benefits is the enhancement of spatial skills. Previous work suggests that both the drawing of 3D objects and the usage of VR can improve mental rotation and spatial visualization skills. Since VR drawing is a combination of the aforementioned activities, it seems promising to investigate its effect on these spatial abilities.
So far, no research has been done into the educational use of VR drawing or its relation with spatial abilities. This research takes a first step in gaining a better understanding of the benefits and obstacles that VR drawing brings when introduced at elementary schools. We performed an experiment with 18 children (ages 10-12). Several drawing exercises were implemented and tested. Furthermore, our tests studied the correlation between the participants' spatial ability test scores and proficiency in creating a VR 3D drawing and whether a few VR drawing sessions are enough to increase these spatial ability test scores.
Our results show improvement in the children's 3D drawing skills but not in their spatial skills. Their drawing skills do seem to be correlated with their mental rotation ability, although further research is needed to conclusively confirm this. This research lays the foundation for future research into the educational use of VR painting tools and shows that it is indeed a promising direction for further evaluation.

Additional Key Words and Phrases: Virtual Reality, Painting, Drawing, 3D, Spatial Visualization, Mental Rotation, Spatial Abilities, Children, Art education

1 INTRODUCTION

A new way of drawing arose with the advent of VR: the possibility to draw directly into a virtual 3D space. One of the big advantages of this way of drawing is that it provides a very natural, intuitive way to draw in 3D without the need for graphical projections or complicated software. It also brings opportunities that are impossible in the real world. As Brody and Hartman wrote:

> "Painting in space, unfettered by gravity or a matrix to hold the paint, is like painting in a world of pure imagination." - Brody and Hartman [11]

By introducing this technology to children at elementary schools, they get acquainted with new technologies and new ways to create art. Children also find drawing in VR very interesting, thus this might encourage them to draw more often. This is desirable as drawing has many benefits related to creativity, memory, problem solving skills and mental health. [12, 16, 23, 41]
Furthermore, research suggests that both the drawing of 3D objects and the usage of VR can be beneficial for the improvement of spatial abilities, which are essential cognitive abilities used to interpret incoming visuo-spatial information [32, 33]. Not only are spatial abilities used in everyday activities, such as navigating around the house, they are extremely important in fields such as engineering, science and technology [7, 21, 33, 35]. Given the importance of spatial skills and the fact that VR drawing is a combination of the abovementioned activities, we consider it worthwhile to investigate its effect on spatial abilities.

This work was supported and initiated by ING and KLEURinCULTUUR.

This research investigates how drawing in a virtual 3D space can be used beneficially in art education of younger children (ages 10 to 12). We have implemented several drawing exercises to teach children how to draw in 3D. In our experiment, we evaluate their effect on the participants VR drawing skills. Furthermore, we study the relationship between the children's spatial abilities and their proficiency in creating a VR 3D drawing. Finally, we examine whether a few VR drawing sessions are enough to increase the children's scores on a spatial ability test.
In addition to these findings, we identify and describe potential issues children face when learning to draw in VR. We also provide suggestions based on our experiences and the responses of the children during the experiment.

The remainder of the paper is structured as follows: Section 2 discusses the related work. The experiment is described and discussed in Sections 3, 4 and 5. Section 6 closes with a conclusion and ideas for future research.

2 RELATED WORK

2.1 VR Painting

The development of VR technologies has made it possible to directly interact with virtual 3D spaces, allowing everyone to create 3D drawings intuitively and without the need of experience [39, 40]. Furthermore, artists are offered the ultimate freedom and the chance to immerse themselves and their public into their works [8, 17]. Since the only difference between digital painting and drawing is the material that is being simulated, which is not relevant for our research, we will use both terms interchangeably in this paper.
Since the emergence of head-mounted displays (HMDs) on the consumer market, many VR painting tools have been released. Some well-known examples are Tilt Brush [3], Quill [2] and A-Painter [1]. For this study, the choice was made to use A-Painter, as it is open source and thus allows us to make the changes necessary for our research.
Although a lot of research exists on the technologies behind this new form of drawing, there is no research on the drawing itself and the teaching of it. Wanting to introduce this new form of art to elementary school children, it is important to know what could be possible pitfalls and benefits. Given the lack of previous research in this area, we study several aspects of introducing 3D VR drawing

to children in an exploratory manner.
A broad initial literature study identified spatial abilities as the most promising research direction in relation with VR drawing. The following sections will discuss the related research of this direction in more detail.

2.2 Spatial ability

Although it is generally agreed upon that spatial ability is an important component of intellectual ability, many interpretations exist as to what it is exactly. Spatial abilities have been defined and subdivided in many different ways and there is no one universal definition [22, 35, 36]. For our purpose, we will however only distinguish two components: spatial visualization and mental rotation. Linn and Petersen [22] describe spatial visualization as "the ability to perform complicated, multistep manipulations of spatially presented information". Mental rotation is described as "the ability to rotate two or three dimensional figures rapidly and accurately".
The difference between spatial abilities and spatial skills is that people are born with the first, while the second is acquired through training [36]. However, in the literature these terms are often used interchangeably, since distinguishing between those in practise is nearly impossible.
The development of spatial ability is influenced by gender, age and spatial-related experience [33]. Many studies have revealed that the spatial visualization skills of men are better than those of women [13, 19, 33, 36]. Theories aiming to explain this difference include biological factors, such as male cerebral lateralisation and the male sex hormone, and environmental factors, such as gender-typed socialisation [19, 33, 36].
Spatial ability is not fully developed until adolescence is reached [33] and research has shown that spatial activities during childhood are very important to support this development [9, 13]. Activities that have been found to improve spatial abilities include playing with construction toys, participating in some types of sports and playing certain computer games [37]. Another activity that is often mentioned in combination with the development of spatial skills is sketching and drawing (S&D), which is discussed in the next section.

2.3 Improving spatial abilities with drawing

A considerable number of studies suggest that the sketching or drawing of 3-dimensional objects improves spatial visualization skills [6, 21, 28, 33, 38]. However, in these studies the drawing activities are often combined with other spatial visualization improving activities, making it impossible to attribute the performance improvements solely to drawing. This corresponds with Braukmann and Pedras' statement that not all drawing activities improve spatial skills and that a spatial context is critical [28]. Nevertheless, the drawing itself does seem to play a major role in the development of spatial skills; Leopold, Górska, and Sorby [21, 28] found that courses that relied heavily upon S&D activities were more effective in developing spatial skills than courses that did not. Alias et al. [7] also found the attitude towards S&D to be relevant; they found a statistically significant correlation between the usage tendency of S&D and spatial visualization ability.
Both Rafi et al. [33] and Alias et al. [6] investigated the effect of S&D activities on spatial visualization skills and both found a statistically significant improvement in the spatial visualization ability of their participants. Rafi et al. [33] also found a significant performance gain in mental rotation accuracy but not in mental rotation speed. No significant improvements in mental rotation ability were found by Alias et al. [6]. A possible explanation presented by Alias et al. is the lack of shared characteristics between the exercises and the test. They mention that studies reporting improvements mostly use practise tasks that are very similar to the tasks on the test. Alias et al. also mention the implicit teaching of mental rotation skills as a probable cause, as, for example, they did not ask their subjects to draw the objects from different views. This might also explain the difference between the results of these two studies, as Rafi et al. did include different views in their training.
Although many studies suggest that the drawing of 3D objects is beneficial for the improvement of spatial visualization skills, more research is needed to prove the exact influence of S&D by itself. Furthermore, the existing studies all apply to drawing 3D objects onto a 2D surface using graphical projection. No research exists yet evaluating the benefits of drawing 3D objects in a 3D space.

2.4 Improving spatial ability with VR

Developing spatial skills using VR is a very popular research topic in which many promising results have been obtained [24, 26, 29, 30, 32, 34, 35]. The main advantage of using VR is that it allows students to observe and manipulate 3-dimensional objects directly in 3D space, which helps them understand spatial concepts and relations [20, 32]. Additionally, many of the advantages of VR as an educational tool, such as increased engagement [10, 18, 25, 27], apply here as well.
Gutiérrez et al. [24] compared the improvement of spatial skills after training with various 3D virtual technologies and traditional methods; the various 3D virtual technologies being Augmented Reality (AR), VR and PDF3D. Their results showed a significant difference in improvements favoring the 3D virtual technologies over the traditional methods. They however did not find a significant difference between the various technologies.
Besides the studies that have successfully employed VR to improve spatial skills, there are also studies that have not yielded positive results; in particular the large-scale study (215 participants) carried out by Dünser et al. [15]. In this study the effectiveness of spatial ability training with an AR application was investigated. The results did not show significant differences between the AR and non-AR groups. It is hypothesized that traditional spatial ability tests might not be suited very well to detect skills that are required or trained in 3D space. This is a likely cause for the lack of positive results in this study, seeing as students in VR, or AR, can directly see and manipulate 3-dimensional objects without having to interpret or mentally transform 2-dimensional representations of these objects, something that is necessary in traditional spatial ability tests. Other studies that did achieve improvements on the traditional tests, generally implemented some association with the 2-dimensional representations or used an adapted VR test [34].
Finally it needs to be emphasized that the VR applications in these studies are completely focused on the training of spatial skills. Concerning spatial visualization and mental rotation, no proof exists that an arbitrary VR application will have a positive influence on

(a) The setup during the individual VR drawing sessions.

(b) The classroom setup during the spatial ability tests.

Fig. 1. Photos of the different setups during the experiment.

these abilities. However, given the fact that activities such as playing with construction toys have proven to benefit spatial abilities, we assume that VR applications with suitable activities can achieve this as well without the need to focus mainly on training spatial skills.

3 EXPERIMENT

This section describes the setup of our experiment. A pre-study and trial run have been conducted beforehand with the aims of gathering initial information, testing the software and optimizing the setup.
Section 3.1 outlines the objectives of the experiment. Section 3.2 discusses the materials and implementation. Section 3.3 contains information about the participants and finally the setup and procedure are described in section 3.4.

3.1 Objectives

To obtain as much information as possible, our experiment is set up in such a way that multiple objectives can be fulfilled.
Our first objective is taking a first step in investigating how VR 3D drawing can be taught best. For this we developed a number of training exercises to see whether they would be effective and how they would be received by the children. The exercises are based on existing drawing exercises, results gathered during the pre-study and advice given by the involved art teacher. Our first research question and accompanying hypothesis are phrased as follows:

Research question 1 - Are training exercises helpful to improve children's drawing skills in a virtual 3D space, even with only a small number of training sessions (e.g., four sessions of 35 minutes)?
Hypothesis 1 - We expect that due to the targeted training exercises, children's drawing skills will improve even after only very few sessions.

Since spatial visualization is used to create mental 3D images, we expect well-developed spatial visualization skills to be an advantage when painting in a virtual 3D space; especially when painting from memory or creating a 3D painting based on a 2D image. However, this has not yet been studied. Therefore, our next research question and hypothesis are:

Research question 2a - Is there a connection between a person's spatial visualization ability and their proficiency in creating a 3D drawing in a virtual 3D space, with a 2D image as example?
Research question 2b - Is there a connection between a person's spatial visualization ability and their proficiency in creating a 3D drawing in a virtual 3D space, with a 3D model as example?
Hypothesis 2 – We suspect that these skills are directly related. That is, children with a high score in the spatial visualization test will also have high grades for their 3D drawings, and vice versa. Since spatial visualization encompasses the ability to create mental 3D images out of limited information, we suspect it to have a bigger influence on *2a* than on *2b*.

Our third objective is investigating the potential positive impact of VR drawing on spatial skills. Despite the fact that the research in both areas is still quite incomplete, we believe that enough evidence exists to suggest that both drawing and the use of VR, when properly employed, can be beneficial for the development of spatial visualization and mental rotation. We phrase the final research questions and hypothesis as:

Research question 3a - Can children's spatial visualization skills be improved by 3D drawing in VR, even with only a small number of sessions (e.g., four sessions of 35 minutes)?
Research question 3b - Can children's mental rotation skills be improved by 3D drawing in VR, even with only a small number of sessions (e.g., four sessions of 35 minutes)?
Hypothesis 3 - Already after a small number of sessions, we expect

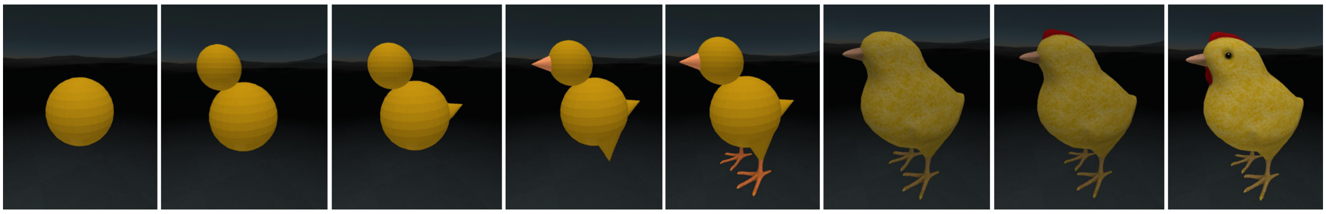


Fig. 2. The steps of the step-by-step chicken exercise.

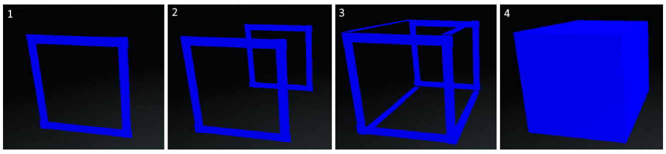


Fig. 3. The optional extra steps that show a possible way to construct a cube.

Fig. 4. The 'previous step' and 'next step' buttons. They turn yellow when the controller is close enough to select them.

that children will score higher on the spatial ability test.

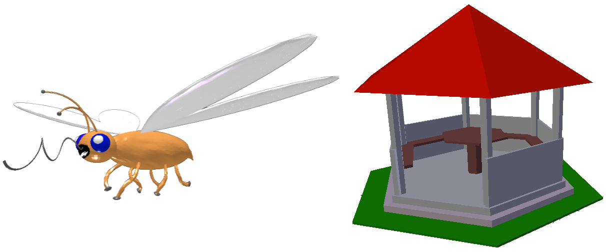
Besides the experimental research questions described above, our experiment investigates multiple aspects of learning to draw in VR in an exploratory manner. This includes observing the children during the drawing sessions, having an interactive conversation with them and letting them fill out questionnaires. Interesting findings, such as issues that children encounter when learning to draw 3D figures in VR, are discussed in section 5.

3.2 Materials and Implementation

3.2.1 Hardware. The VR hardware consisted of an HTC Vive, which is a VR set with a head mounted display (HMD), two handheld controllers and two base stations. The base stations were placed diagonally to create a room-scale setup of 3 x 2.5 m (see Figure 1a). The laptop used to operate the HTC Vive was an Asus ROG GL502VS-FY038T with an Intel Core i7-6700HQ processor and NVIDIA GeForce 1070 GTX graphics card. The headset was used in Extended Mode, with the HMD showing the painting environment and a separate screen showing both the view of the participant and additional controls. This allowed the experimenter to follow and manage the experiment.
Finally, a simple digital camera was used to record parts of the experiment.

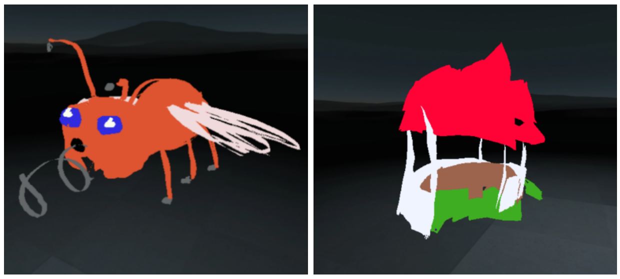
3.2.2 Software. The main software used for this experiment was A-Painter. A-Painter is an open-source, web-based VR painting tool. It was created by the Mozilla VR team using A-Frame, which is a web framework for building VR experiences. A-Frame is based on HTML but has an entity-component architecture with access to JavaScript, DOM APIs, three.js and WebGL. To run A-Painter, a WebVR-enabled browser is needed. In this research the experimental build of Chromium with WebVR support was used.
During the experiment, an adapted and expanded version of A-Painter was used. Changes to A-Painter were made in HTML and JavaScript using JetBrains WebStorm 2016. The adaptations include the addition of a menu, to enable the experimenter to control the experiment, and the implementation of several drawing exercises. Section 3.2.3 discusses these exercises in more detail.
The used 3D models were downloaded from TurboSquid, with a Royalty Free License, and adjusted with Blender. Finally, SteamVR was used to set up and handle the HTC Vive, Paint.NET to create all 2D images, Open Broadcaster Software (OBS) to record all sessions and IBM SPSS Statistics 23 to perform the statistical analysis.

3.2.3 Drawing exercises. Based on insights gained during the pre-study and advice of the involved art teacher, it was decided to implement two kinds of drawing exercises: basic shapes and step-by-step (SBS) exercises.
During the basic shape exercises, a 3D model of a shape is shown in the virtual environment. The children are asked to copy this shape. If they find this difficult or do not know where to start, they are able to ask for help by pressing a button. This button starts step by step instructions that show a possible way to create that shape. Figure 3 shows the steps that are shown for the construction of a cube. The children are able to control the steps themselves by pressing the 'previous step' and 'next step' buttons (shown in Figure 4). The included basic shapes are: a cube, a pyramid, a sphere, a cylinder and a cone.
The SBS exercises make use of the same mechanics as the help function of the basic shapes. The exercises start with a simple shape that is expanded every time the child presses the 'next step' button. The main goal of these exercises is to show the children that they



(a) Firefly (b) Garden House

Fig. 5. The example figures for the graded drawings.



(a) Drawing of the firefly (b) Drawing of the garden house

Fig. 6. Graded drawings made by two of the participants.

can create complicated figures by combining the basic shapes they practised earlier. Three SBS exercises were created: a tree, a church and a chicken. The steps for the latter are shown in Figure 2.

3.2.4 Spatial ability test. A spatial ability test consisting of two parts was created. The first part contains the questions of 123test's Spatial Reasoning Test (SRT) [5] to test the spatial visualization skills of our participants. This test is very similar to the well-known DAT:SR; it also consists of mentally folding 2D patterns into 3D objects. The SRT from 123test was chosen based on its scientific foundation [4], the simplicity and clarity of the questions, its length (only 10 questions) and its free use policy.
The second part, which tests mental rotation skills, contains ten questions of the redrawn Vandenberg and Kuse Mental Rotations Test created by Peters et al. [31]. The Vandenberg and Kuse MRT was chosen due to its popularity and known reliability. Since the original version of this test is difficult to obtain and of poor quality, it was decided to use a redrawn version.
In order to be able to measure if any differences have occurred due to the VR drawing sessions, everyone made the spatial ability test twice; once before the sessions (the pre-test) and once after (the post-test). To make sure that the participants would not perform better the second time by remembering the answers, for example because they discussed them with classmates after the first test, two different versions were made. Both versions contained the same questions in order to keep the results comparable. However, the orders of both the questions and the answers were shuffled.

3.3 Participants

18 elementary school children (seven boys and eleven girls) participated in this experiment. They were 10, 11 or 12 years old and all in the same grade. The children had no prior knowledge of the experiment, participated voluntarily and did not receive any form of compensation. Both the children and their teacher signed a consent form before the start of the experiment.
The participants were divided into three groups of six. While creating the groups, only gender was taken into account. Gender is an important factor in spatial abilities (see Section 2.2), therefore groups were created with boys and girls divided as evenly as possible. Besides gender, the division was completely random.
The different groups and their descriptions can be found in Table 1.

3.4 Setup and Procedure

The whole experiment ran over the course of five weeks. It started and ended with a 40 minute classroom session involving all participants. In between, all group A and B participants had individual VR drawing sessions once a week, except for one holiday week in the middle. Since we assume that only a short amount of training is sufficient, we decided to restrict the number of individual sessions to four. The duration of each individual drawing session was 35 minutes.

3.4.1 Classroom sessions. During the classroom sessions, the participants made the spatial ability tests, filled out the questionnaires and received information about the experiment.
Before starting the spatial ability test for the first time, the children were asked to form groups of two and solve four example exercises. Additionally, each group received printed 2D patterns of the example SRT questions. These could be folded into cubes, helping them understand how the SRT exercises work. Their answers were jointly discussed and more explanations were given when necessary.
When everyone understood the example exercises, the spatial ability tests were made individually. Half of the participants received version 1 during the pre-test and version 2 during the post-test, the other half of the participants received version 2 during the pre-test and version 1 during the post-test.
They were asked to not discuss the VR drawing sessions with each other and to not use VR painting software anywhere else for the length of the experiment.
Figure 1b shows the setup during the classroom sessions.

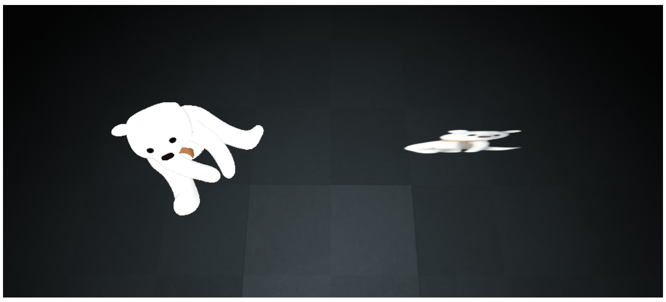


Fig. 7. The example scene seen from above, the left polar bear is 3D while the right one is 2D.

Group	Description	Gender distribution
Experiment group (A)	This group will participate in the VR painting training sessions with exercises.	4 female, 2 male
Training control group (B)	This group will spend the same amount of time painting freely in VR, without instructions or exercises.	4 female, 2 male
Spatial control group (C)	This group will not participate in any VR painting activities.	3 female, 3 male

Table 1. The different participant groups.

3.4.2 Individual drawing sessions. At the beginning of the first session, each participant received extensive instructions on the controls and was given time to try out everything. Once they had mastered the controls and were familiar with the virtual environment and painting software, an example scene was started. This scene (Figure 7) contains both a 2D image and a 3D model of a polar bear to help explaining the purpose of the first assignment and the concept of 3D.
The first assignment was the creation of the first part of the so-called graded drawings (GDs). These drawings were made during the first and last session with the purpose of rating the participants' VR 3D drawing skills. To be able to measure progress, the subjects received the same examples in the last session as in the first session.
The examples are shown in Figure 5, each subject saw one of them as a 2D image and the other as a 3D model. The distribution of 2D/3D is based on the Latin square design in order to reduce the amount of conditions and moreover to avoid participants having to draw the same figure twice, with the only difference being the dimension of the example. The orders of the graded drawings were mixed across and within groups.
The main reason for having two graded drawings, one with a 2D example (GD2D) and one with a 3D example (GD3D), is the expectation that spatial visualization will play a more important role when drawing from memory or creating a 3D drawing based on a 2D image than when copying a 3D model. Since a drawing from memory is more difficult to grade than one based on an example, it was decided to study the difference between 2D and 3D examples. Also for the exploratory part of our research it is quite interesting to see how children deal with the task of creating a 3D drawing while only provided with a 2D example. Since they themselves have to imagine what the figure would look like in three dimensions, we expect this to be more difficult than copying a 3D model.

During the second and third sessions, the participants from group A made the drawing exercises while group B received the same amount of time to draw freely.
The exercises in session two consisted of the drawing of the five basic shapes (see Section 3.2.3). The children were encouraged to try it themselves first, but were also allowed to use the 'help' button as often as needed. It was emphasized towards the participants that the extra instructions only show one of many ways to construct the 3D shape and that this is not necessarily the best way or the one they should use.
The exercises in the third session consisted of the three SBS exercises.
Halfway every session a two minute break was scheduled, however, in practise these breaks were taken whenever the children indicated that they wanted or needed one. The participants in group A all completed the exercises within the scheduled session times, although some needed to be told to draw faster and less precise in order to finish in time. When participants in group A finished their exercises before the scheduled ending time of their session, they were allowed to draw freely until their time was over.

3.4.3 Grading. The grading of the graded drawings was done separately by both the experimenter and the involved art teacher. When the two grades were relatively close together (a difference of 1.5 or less), the mean of the two grades became the final grade. The drawings with a bigger difference in grades were discussed and graded collectively.
The grades of the graded drawings are based on the following aspects:

a Usage of the 3D space (0 - 5 points)
b Correctness of the proportions (0 - 5 points)
c How it looks from different perspectives (0 - 5 points)
d Overall appearance (0 - 5 points)

Subsequently, the grade was calculated as follows:

Grade = (a+b+c+d)/2 + process points.

In line with the Dutch grading system, the maximum grade was 10 points.
Process points are bonus points with a maximum of 1.5 that could be rewarded when the participant showed remarkable insight during the process of the drawing. The choice for these process points was made during the trial run, when it was noted that some students started very promising with the creation of a well-constructed skeleton of the 3D figure, but then coloured it very messy, causing their skills not to be reflected in the final drawing.

4 RESULTS

4.1 Research question 1

To answer the first research question, a mixed design setup was used with between-subjects factor *group* and within-subjects factor *time*. *Group* has two categories; group A, the group that made the exercises, and group B, the group that did not make the exercises. *Time* has two categories as well: before and after the VR drawing sessions.
Multiple two-way mixed ANOVAs were conducted to determine

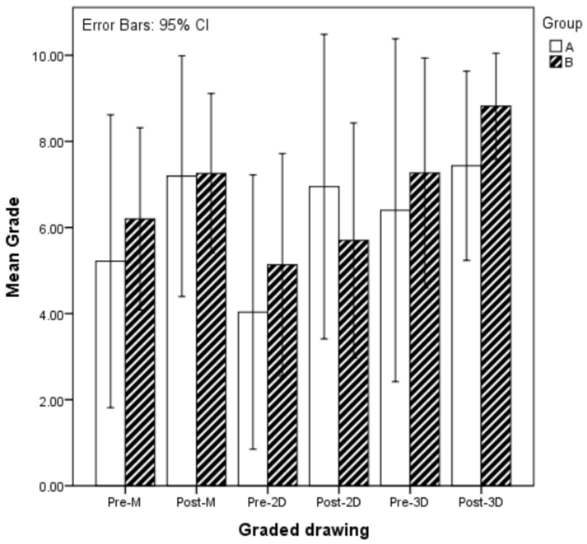


Fig. 8. The mean grades for the graded drawings. M = Mean grade of GD2D and GD3D combined, 2D = GD2D and 3D = GD3D.

whether the exercises influenced the grades. The need for multiple tests was due to the fact that all participants made two graded drawings; one with a 2D example and one with a 3D example. The dependent variable *grades* in this first test is the mean grade of GD2D and GD3D combined (MGD). Thereafter, we test for GD2D and GD3D separately as well.
The mean grades for all selections can be found in Figure 8.

4.1.1 Testing the assumptions. All data were separately tested for the assumptions of the two-way mixed ANOVA. There was one outlier in the post-MGDs of group A, as assessed by inspection of a boxplot for values greater than 1.5 box-lengths from the edge of the box. Also, established by Shapiro-Wilk's test ($p < .05$), the same data were not normally distributed. Removing the outlier resulted in normally distributed data. Therefore it was decided to run the test with and without the outlier included in the analysis. Since the results for both tests are essentially the same, the analysis was continued with the outlier in the data.
Except for the one mentioned, there were no further outliers in the data, as assessed by both boxplots and examination of studentized residuals for values greater than ±3. The grades were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). There was homogeneity of variances, as assessed by Levene's test of homogeneity of variance ($p > .05$), and covariances, as assessed by Box's test of equality of covariance matrices ($p > .05$).

4.1.2 Effect of the exercises on the MGDs. There was no statistically significant interaction between *group* and *time* on the grades ($F(1, 10) = .770, p = .401, partial\ \eta^2 = .071$). The main effect of *time* did show a statistically significant difference in grades before and after the sessions, $F(1, 10) = 8.430, p = .016, partial\ \eta^2 = .457$. The main effect of *group* showed that there was no statistically significant difference in grades between the different groups, $F(1, 10) = .154, p = .703, partial\ \eta^2 = .015$.

		pre-SRT	pre-MRT
pre-GD2D	Pearson Correlation	-.045	.021
	Sig. (2-tailed)	.889	.947
	N	12	12
pre-GD3D	Pearson Correlation	.115	-.264
	Sig. (2-tailed)	.723	.407
	N	12	12
		post-SRT	**post-MRT**
post-GD2D	Pearson Correlation	.137	.514
	Sig. (2-tailed)	.670	.088
	N	12	12
post-GD3D	Pearson Correlation	.291	.600*
	Sig. (2-tailed)	.358	.039
	N	12	12

Table 2. Pearson correlations for the spatial ability test scores and drawing grades. * = statistically significant at p<.05 level.

4.1.3 Effect of the exercises on the GD2Ds. There was no statistically significant interaction between *group* and *time* on the grades ($F(1, 10) = 3.187, p = .105, partial\ \eta^2 = .242$). The main effect of *time* did again show a statistically significant difference in grades before and after the sessions, $F(1, 10) = 7.003, p = .024, partial\ \eta^2 = .412$. The main effect of *group* showed that there was no statistically significant difference in grades between the different groups, $F(1, 10) = .002, p = .962, partial\ \eta^2 = .239 \cdot 10^{-3}$.

4.1.4 Effect of the exercises on the GD3Ds. Again, there was no statistically significant interaction between *group* and *time* on the grades ($F(1, 10) = .129, p = .727, partial\ \eta^2 = .013$). The main effect of *time* showed that there was no statistically significant difference in grades before and after the sessions, $F(1, 10) = 3.215, p = .103, partial\ \eta^2 = .243$. The main effect of *group* showed that there was no statistically significant difference in grades between the different groups, $F(1, 10) = .744, p = .409, partial\ \eta^2 = .069$.

4.2 Research question 2

A Pearson's product-moment correlation was run to assess the relationship between the spatial ability test scores and the grades of the drawings. Preliminary analyses showed the relationships to be linear. All variables were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$), and there were no outliers.
There was a strong, positive correlation between the post-MRT scores and the grades for the post-GD3D, which was statistically significant ($r(10) = .600, p = .039$). Besides this correlation, no statistically significant correlations were found between the spatial test scores and the drawing grades (Table 2).

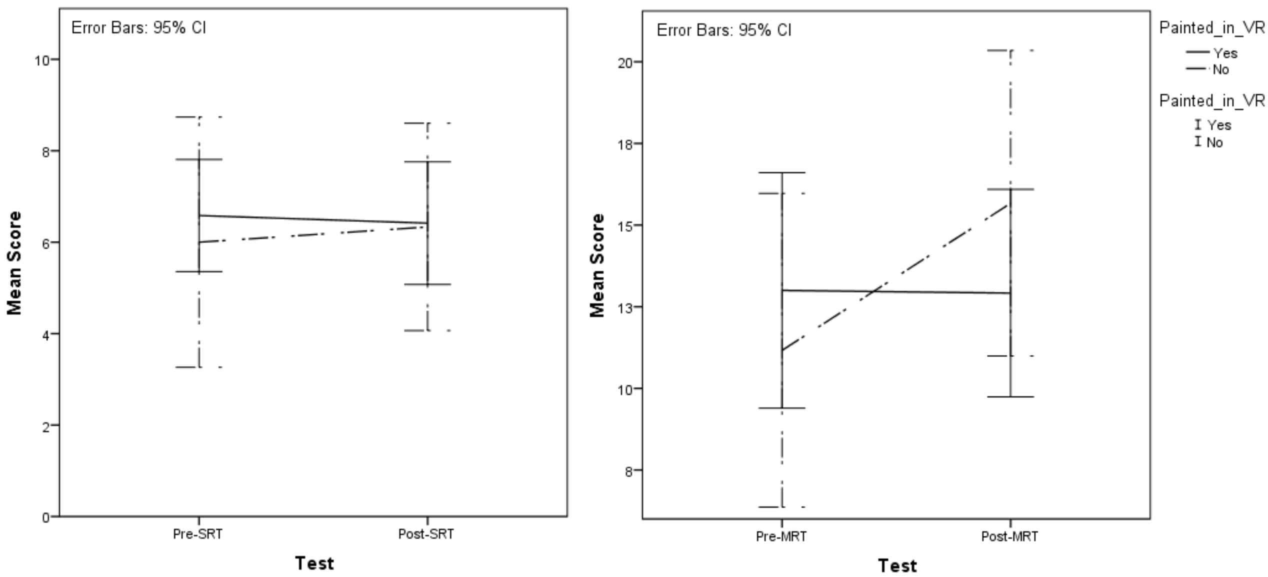


Fig. 9. The mean scores of the spatial ability tests. The left graph shows the scores for the SRT and the right graph for the MRT.

4.3 Research question 3

Two two-way mixed ANOVAs were conducted to determine the effect of VR painting on the subjects' spatial ability test scores. The within-subjects factor is *time*, with the categories pre-test and post-test. The between-subjects factor is *painted_in_VR* with the categories yes and no. Figure 9 shows the mean scores for the different tests.

4.3.1 Testing the assumptions. There were no outliers, as assessed by examination of studentized residuals for values greater than ±3. The post-MRT score data of the group that did not paint in VR was not normally distributed, as assessed by Shapiro-Wilk's test ($p = .024$). As all other data were normally distributed and since ANOVAs are considered to be fairly robust to deviations from normality, it was decided to run the test regardlessly. There was homogeneity of variances ($p > .05$) and covariances ($p > .05$), as assessed by Levene's test of homogeneity of variances and Box's test, respectively.

4.3.2 Effect on SRT scores. There was no statistically significant interaction between *painted_in_VR* and *time* on the SRT scores, $F(1,16) = .152, p = .701$, $partial\ \eta^2 = .009$. The main effects of both *painted_in_VR* and *time* showed that there are also no statistically significant differences in SRT scores between the groups, $F(1,16) = .150, p = .703$, $partial\ \eta^2 = .009$, or pre- and post-tests, $F(1,16) = .017, p = .898$, $partial\ \eta^2 = .001$.

4.3.3 Effect on MRT scores. There was a statistically significant interaction between *painted_in_VR* and *time* on the MRT scores, $F(1,16) = 5.785, p = .029$, $partial\ \eta^2 = .266$.
The simple main effects for *painted_in_VR* on the pre-MRT scores, $F(1,16) = .469, p = .503$, $partial\ \eta^2 = .028$, and post-MRT scores, $F(1,16) = 1.293, p = .272$, $partial\ \eta^2 = .075$, are both not significant.
There was a statistically significant effect of *time* on MRT score for the group that did not paint in VR, $F(1,5) = 10.210, p = .024$, $partial\ \eta^2 = .671$. For the group that did paint in VR, the MRT score was not statistically significantly different between the pre- and posttest, $F(1,11) = .005, p = .943$, $partial\ \eta^2 = .482 \cdot 10^{-3}$.

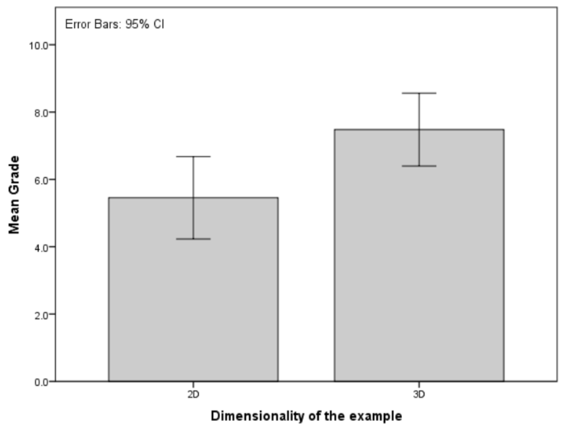


Fig. 10. The mean grades for the GD2Ds and GD3Ds.

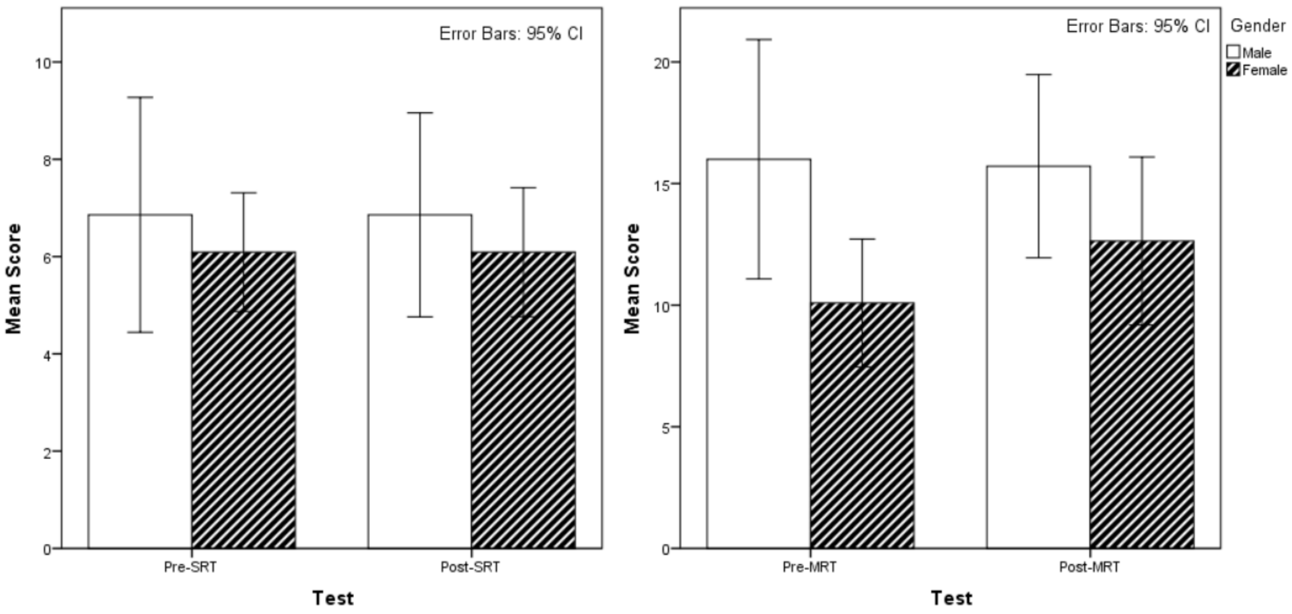


Fig. 11. The mean scores of the spatial ability tests, grouped by gender. The left graph shows the scores for the SRT and the right graph for the MRT.

4.4 Effect of the dimensionality of the example on the grades.

To test our assumption that drawing a 3D figure based on a 2D image is more difficult than copying a 3D model, we used a within-subjects design to test whether the participants performed better on the GD3Ds than the GD2Ds. The dependent variable is *grade* and the independent variable is *dimensionality* with levels 2D and 3D.
A paired-samples t-test was used to determine whether there was a statistically mean difference between the grades for the GD2Ds and the GD3Ds. Data are mean ± standard deviation, unless otherwise stated. There were no outliers in the data, as assessed by inspection of a boxplot. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = .101$). The grades for the GD3Ds (7.48 ± 2.56) were higher than the grades for the GD2Ds (5.45 ± 2.90); a statistically significant difference of 2.025 (95% CI, 1.0341 to 3.0159), $t(23) = 4.227, p < .0005, d = .86$.
The main grades for the GD2Ds and GD3Ds can be found in Figure 10.

4.5 Effect of gender

Since gender is proven to be an important factor in spatial abilities, we divided boys and girls as evenly as possible between the groups. To test whether gender indeed influenced our results, multiple statistical tests were conducted to determine if there were significant differences between the male and female participants.

4.5.1 Effect of gender on the spatial ability test scores. Our spatial ability test was made by seven male and eleven female participants. An independent-samples t-test was run to determine if there were differences in scores between males and females. There were no outliers in the data, as assessed by inspection of boxplots, and the scores for each test were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). There was homogeneity of variances, as assessed by Levene's test for equality of variances ($p > .05$).
The pre-MRT scores of the male participants (16.00 ± 5.32) were higher than the pre-MRT scores of the female participants (10.09 ± 3.91), a statistically significant difference of 5.91 (95% CI, 1.31 to 10.51), $t(16) = 2.721, p = .015, d = 1.32$. The mean scores of the other tests were also higher for the male participants (see Figure 11), although these differences were not found to be significant.

4.5.2 Effect of gender on VR drawing skills. Four male and eight female subjects participated in the VR drawing sessions. Since the grades, grouped by gender, violated the outlier and normality assumptions of the independent-samples t-test, it was decided to use the nonparametric alternative: the Mann-Whitney U test.
Distributions of the pre-grades for males and females were not similar, as assessed by visual inspection. The pre-grades of the females (mean rank = 8.00) were statistically significantly higher than the pre-grades of the males (mean rank = 3.50), $U = 28, z = 2.038, p = .048$, using an exact sampling distribution for U [14]. Distributions of the post-grades for males and females were similar, as assessed by visual inspection. Median post-grade for females (7.58) and males (7.10) was not not statistically different, $U = 17, z = .170, p = 1.000$. The mean grades of the participants, grouped by gender, are shown in Figure 12.

The results above suggest that the male participants improved more than the female participants. A two-way mixed ANOVA was

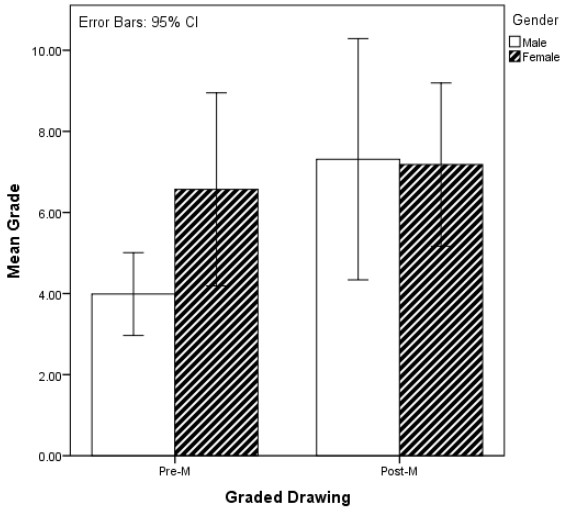


Fig. 12. The mean pre- and post-grades combined for GD2D and GD3D, grouped by gender.

conducted to determine whether gender indeed influenced the improvement of the participants. A mixed design setup was used with between-subjects factor *gender* and within-subjects factor *time*.
There were no outliers, as assessed by examination of studentized residuals for values greater than ±3. The pre-grades of the female participants were not normally distributed, as assessed by Shapiro-Wilk's test ($p = .007$). As all other data were normally distributed and since ANOVAs are considered to be fairly robust to deviations from normality, it was decided to run the test regardlessly. There was homogeneity of variances ($p > .05$) and covariances ($p > .05$), as assessed by Levene's test of homogeneity of variances and Box's test, respectively.
There was a statistically significant interaction between *gender* and *time* on the grades, $F(1, 10) = 12.540, p = .005, partial\ \eta^2 = .556$.
The simple main effects for *gender* on the pre-grades, $F(1, 10) = 3.065, p = .111, partial\ \eta^2 = .235$, and post-grades, $F(1, 10) = .009, p = .926, partial\ \eta^2 = .001$, are both not significant.
There was a statistically significant effect of *time* on grade for the male participants, $F(1, 3) = 18.118, p = .024, partial\ \eta^2 = .858$. This effect was not statistically significant for the female participants, $F(1, 7) = 2.524, p = .156, partial\ \eta^2 = .265$.

5 DISCUSSION

Our research was aimed at investigating how drawing in a virtual 3D space can be used beneficially in art education of younger children. Several aspects were investigated including how to improve the children's drawing skills in VR, the effect of certain spatial skills on the ability to draw in VR, whether drawing in VR might improve spatial abilities and issues that might arise when learning to draw in VR.

In our first hypothesis, we expect that due to the targeted training exercises, children's drawing skills will improve even after only very few sessions. The results show that the grades of the graded drawings have significantly improved; the post-grades are on average 1.52 points higher than the pre-grades. Although the children in group A had a mean improvement of 1.98 and the children in group B a mean improvement of 1.06, this difference was not statistically significant. Therefore we cannot assign these improvements to the training exercises. We do however expect the aforementioned difference to become statistically significant with a larger sample size.

The second hypothesis stated that we suspect a person's spatial visualization ability and their proficiency in creating a 3D drawing in a virtual 3D space to be directly related. We also suspected one's spatial visualization to have a bigger influence on creating a drawing with a 2D image as example than a drawing with a 3D model as example.
The results, however, do not show a clear relationship between spatial visualization ability and VR drawing skills; all correlations between SRT scores and GD grades were small and not found to be statistically significant. Looking at the results, we also do not expect significant correlations to be found in experiments with a bigger sample size. A possible explanation is that our hypothesis is incorrect and that there is no relation between a person's spatial visualization and their VR drawing skills. Or that there is a relation, only too small compared to other factors to be able to test it without knowing the other variables. Another possible explanation is that our SRT test was inadequate to measure the kind of spatial visualization that is used when drawing in a virtual 3D space.
We did find a strong, positive correlation between the post-MRT scores and the post-GD3D grades that was statistically significant. The correlation between the post-MRT scores and the post-GD2D grades was strong and positive as well, although not statistically significant. However, it was close to being significant with a p-value of .088, thus we expect that it might become statistically significant as well when testing with a larger sample size. The correlations with the pre-MRT scores are both small and not significant. We suspect that during the pre-drawings, other factors, such as getting used to the controls, influenced the drawings too much to be able to reveal a correlation.
Our results fail to reject the original null hypothesis but do seem to suggest that a relation between mental rotation skills and proficiency to draw in a 3D virtual space does exist, although only detectable after a few sessions. The correlation coefficient of the correlation with the GD2D grades is smaller than with the GD3D grades, which means the correlation between the MRT scores and the drawings with a 3D example is stronger. This contradicts our hypothesis, however, due to the lack of significance of the correlation with the GD2D grades, it is too early to draw a conclusion from this.

Thirdly, our experiment investigated whether a small number of 3D drawing sessions in VR could improve children's spatial visualization and mental rotation skills. The results show that the children who participated in the drawing sessions did not improve at either the SRT or MRT, thus we fail to reject the null hypothesis and are unable to accept our hypothesis.
It is however not possible to say whether the lack of improvement

is simply due to the fact that drawing in VR does not actually affect spatial abilities. It may be that the sessions were too few to result in a measurable effect, or that the tests we used are not suited to detect skills that are trained in a 3D space.
An unexpected finding is that the children that did *not* participate in the VR drawing sessions, did significantly improve at the MRT. An obvious explanation would be that the results were exchanged, but this was double checked afterwards. Another explanation could be that group C did mental rotation ability improving activities in class, while groups A and B participated in the drawing sessions. However, the participants from groups A and B were taken out of the classroom one by one and spread over several days, thus this seems highly unlikely. In lack of other explanations and given the small sample size, we can only attribute this result to chance.

This study served as exploratory research into teaching elementary school children to draw 3D objects in VR. The main obstacle encountered by the children when asked to draw a 3D object was not knowing where to start. Especially at the beginning, they were not sure how to deal with the extra dimension and how to create the more difficult 3D shapes. A cube was simple for most, an ovoid, however, caused quite some problems. Both the children and the involved art teacher fully agreed that assignments, such as our basic shapes and step-by-step assignments, are really helpful in these situations.
We noted major differences in 3D drawing skills between the children. Some were truly talented and did not need any help or instructions, while others had great difficulties. Therefore we would suggest to implement several difficulty levels or optional help buttons. This way, every child can receive the instructions they need, without making it tedious for the talented students.
As we already expected, creating a 3D drawing based on a 3D model was found to be much easier than creating one based on a 2D image. This was also supported by the grades, which were on average 2 points higher for the GD3Ds than for the GD2Ds.
Overall, the children became quickly familiar with the controls and painting software. In most cases, only brief instructions during the first session were needed. A few children had more difficulties getting used to the controls, but also they mastered everything before the last session.
In the questionnaire, the participants from group A all answered that they liked freestyle drawing the best, but were divided over the best way to improve at VR drawing; three answered the basic shape exercises and three answered the step-by-step exercises. During the sessions, however, they seemed to have a preference for the basic shapes. The children often mentioned how helpful they were and that it was convenient that they could reuse them for the more complicated shapes. The cone was by far chosen most often as the hardest basic shape.
The children were really enthusiastic about the VR drawing sessions. Most of them did not want their sessions to end. Although they were 35 minutes long, only one participant assessed the duration of the sessions as "too long". Two children answered "too short" and all others answered "exactly right".
When asked how often they would like these sessions, 42% answered "every week" and 33% even answered "every day". Before and after the sessions, the children were asked to write down their favorite method(s) of drawing. After the sessions, two children changed their answer to include VR and five children even completely changed their answer to VR only.

Finally, since gender is proven to be an important factor in spatial abilities; we also expected it to affect our results. This expectation proves to be justified, as our results show that the boys scored on average 5.91 points higher on the pre-MRT, which is a statistical significant difference. Furthermore, the girls performed significantly better on the pre-GDs, while the boys significantly improved more during the sessions. This improvement of the male participants led to almost equal mean post-grades for both genders.

6 CONCLUSIONS AND FUTURE WORK

The work presented in this paper was motivated by the goal to a gain better understanding of the benefits and obstacles that drawing in VR might bring when introducing it to elementary school children. Our experiment shows that children quickly improve at drawing 3D figures in a virtual 3D space. The participants that made the training exercises improved more than the participants that did not. However, since this difference was not statistically significant, the effect of our training exercises is inconclusive. We assume that the effect size was too small to be significant for our small sample size, as we only had six participants per group. Therefore, further research should be conducted with more participants.
Our results also show that gender is indeed an important factor to take into account when conducting research in this area. Not only was a significant difference found in the spatial ability test scores, gender also seems to influence the initial proficiency in VR drawing and the rate of improving at VR drawing. However, our research was not aimed at investigating gender differences. Further research with a larger sample size and a more equal male-female ratio should be conducted in order to draw final conclusions on this subject.
The children indicated that they considered the training exercises incredibly helpful. Especially for teaching them the basic shapes, which they could later reuse in more complicated figures. The biggest obstacles encountered by the children were not knowing where to start and how to handle the extra dimension. The step-by-step exercises were experienced as helpful in these situations.
A strong, positive correlation was found between the children's scores on the post-MRT and their grades for the post-drawings with a 3D example. It seems that a direct relation between mental rotation skills and proficiency to draw in a virtual 3D space does exist, although only detectable after a few sessions. The correlations between the SRT scores and grades were all small and a significant effect could not be discovered. Although these results are not conclusive, they do suggest that this is indeed a promising direction for further evaluation.
The VR drawing sessions did not improve spatial visualization or mental rotation abilities in our participants, at least not the kind that is measurable with traditional tests. This would support Dünser et al.'s [15] hypothesis that traditional spatial ability tests might not be suited very well to detect skills that are required or trained in 3D space. However, further research using a spatial ability test in

VR is needed to prove this.
Although additional experiments are needed to conclusively answer our research questions, this study has laid an important foundation for future research in this area. Our results point out opportunities, points of attention and interesting follow-up research.
Furthermore, we experienced that there is a vast interest among both the teachers and the children in this new technology. Even after several sessions, the children are still motivated and wishing for more sessions. These observations, together with the feedback provided by the involved art teacher, suggest that VR drawing can make a good and beneficial complement for traditional art classes. Even if further evaluations will not confirm expected benefits such as the assumed increase in spatial ability.

REFERENCES

[1] 2016. A-Painter. https://blog.mozvr.com/a-painter/. (2016). Accessed: 2017-03-07.
[2] 2016. Quill. https://www.oculus.com/experiences/rift/1118609381580656/. (2016). Accessed: 2017-03-07.
[3] 2016. Tilt Brush. https://www.tiltbrush.com/. (2016). Accessed: 2017-03-07.
[4] 2017. About 123test. https://www.123test.com/about_123test/. (2017). Accessed: 2017-06-25.
[5] 2017. Spatial reasoning test. https://www.123test.com/spatial-reasoning-test/. (2017). Accessed: 2017-06-25.
[6] Maizam Alias, Thomas R Black, and David E Gray. 2002. Effect of instruction on spatial visualization ability in civil engineering students. *International Education Journal* 3, 1 (2002).
[7] Maizam Alias, David E Gray, and Thomas R Black. 2002. Attitudes towards sketching and drawing and the relationship with spatial visualisation ability in engineering students. *International Education Journal* 3, 3 (2002), 165–175.
[8] Lisa Avila and Mike Bailey. 2016. Art in the Digital Age. *IEEE Computer Graphics and Applications* 36, 4 (2016), 6–7.
[9] David Ben-Chaim, Glenda Lappan, and Richard T Houang. 1989. Adolescents' ability to communicate spatial information: Analyzing and effecting students' performance. *Educational Studies in Mathematics* 20, 2 (1989), 121–146.
[10] Meredith Bricken. 1991. Virtual reality learning environments: potentials and challenges. *ACM SIGGRAPH Computer Graphics* 25, 3 (1991), 178–184.
[11] Arthur W Brody and Chris Hartman. 2001. Painting in space. In *Photonics West 2001-Electronic Imaging*. International Society for Optics and Photonics, 602–614.
[12] L Caddy, Frances Crawford, and AC Page. 2012. 'Painting a path to wellness': correlations between participating in a creative activity group and improved measured mental health outcome. *Journal of psychiatric and mental health nursing* 19, 4 (2012), 327–333.
[13] Richard De Lisi and Jennifer L Wolford. 2002. Improving children's mental rotation accuracy with computer game playing. *The Journal of genetic psychology* 163, 3 (2002), 272–282.
[14] LC Dinneen and BC Blakesley. 1973. Algorithm AS 62: a generator for the sampling distribution of the Mann-Whitney U statistic. *Journal of the Royal Statistical Society. Series C (Applied Statistics)* 22, 2 (1973), 269–273.
[15] Andreas Dünser, Karin Steinbügl, Hannes Kaufmann, and Judith Glück. 2006. Virtual and augmented reality as spatial ability training tools. In *Proceedings of the 7th ACM SIGCHI New Zealand chapter's international conference on Computer-human interaction: design centered HCI*. ACM, 125–132.
[16] Kellah Edens and Ellen Potter. 2007. The relationship of drawing and mathematical problem solving: Draw for math tasks. *Studies in Art Education* 48, 3 (2007), 282–298.
[17] Nicholas Fearn. 2016. Painting a new perspective: how virtual reality is transforming art. http://www.techradar.com/news/painting-a-new-perspective-how-virtual-reality-is-transforming-art. (2016). Accessed: 2017-07-11.
[18] Kristan Harris and Denise Reid. 2005. The influence of virtual reality play on children's motivation. *Canadian Journal of Occupational Therapy* 72, 1 (2005), 21–29.
[19] Nady Hoyek, Christian Collet, Patrick Fargier, and Aymeric Guillot. 2011. The use of the Vandenberg and Kuse mental rotation test in children. *Journal of Individual Differences* (2011).
[20] Hannes Kaufmann, Dieter Schmalstieg, and Michael Wagner. 2000. Construct3D: a virtual reality application for mathematics and geometry education. *Education and information technologies* 5, 4 (2000), 263–276.
[21] Cornelie Leopold, Renata A Gorska, and Sheryl A Sorby. 2001. International experiences in developing the spatial visualization abilities of engineering students. *Journal for Geometry and Graphics* 5, 1 (2001), 81–91.
[22] Marcia C Linn and Anne C Petersen. 1985. Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child development* (1985), 1479–1498.
[23] Philippa Lyon, Patrick Letschka, Tom Ainsworth, and Inam Haq. 2013. An exploratory study of the potential learning benefits for medical students in collaborative drawing: creativity, reflection and 'critical looking'. *BMC medical education* 13, 1 (2013), 86.
[24] Jorge Martin Gutierrez, Melchor Garcia Dominguez, and Cristina Roca Gonzalez. 2015. Using 3D virtual technologies to train spatial skills in engineering. *International Journal of Engineering Education* 31, 1 (2015), 323–334.
[25] Jorge Martín-Gutiérrez, Carlos Efrén Mora, Beatriz Añorbe-Díaz, and Antonio González-Marrero. 2016. Virtual Technologies Trends in Education. (2016).
[26] Mark L Merickel. 1992. A Study of the Relationship between Virtual Reality (Perceived Realism) and the Ability of Children To Create, Manipulate and Utilize Mental Images for Spatially Related Problem Solving. (1992).
[27] Tassos A Mikropoulos, Anthimos Chalkidis, Apostolos Katsikis, and Anastassios Emvalotis. 1998. Students' attitudes towards educational virtual environments. *Education and Information Technologies* 3, 2 (1998), 137–148.
[28] James L Mohler and Craig L Miller. 2009. Improving spatial ability with mentored sketching. *Engineering Design Graphics Journal* 72, 1 (2009).
[29] Kimberley Osberg. 1997. Spatial cognition in the virtual environment. (1997).
[30] David Passig and Sigal Eden. 2001. Virtual reality as a tool for improving spatial rotation among deaf and hard-of-hearing children. *CyberPsychology & Behavior* 4, 6 (2001), 681–686.
[31] Michael Peters, Bruno Laeng, Kerry Latham, Marla Jackson, Raghad Zaiyouna, and Chris Richardson. 1995. A redrawn Vandenberg and Kuse mental rotations test-different versions and factors that affect performance. *Brain and cognition* 28, 1 (1995), 39–58.
[32] Ahmad Rafi, Khairul Anuar, Abdul Samad, Maizatul Hayati, and Mazlan Mahadzir. 2005. Improving spatial ability using a Web-based Virtual Environment (WbVE). *Automation in construction* 14, 6 (2005), 707–715.
[33] Ahmad Rafi, Khairul Anuar Samsudin, and Azniah Ismail. 2006. On improving spatial ability through computer-mediated engineering drawing instruction. *Journal of educational technologyand society* 9, 3 (2006), 149.
[34] Albert A Rizzo, J Galen Buckwalter, Ulrich Neumann, Carl Kesselman, Marcus Thiébaux, Peter Larson, and Andre van Rooyen. 1998. The virtual reality mental rotation spatial skills project. *CyberPsychology & Behavior* 1, 2 (1998), 113–119.
[35] Cristina Roca-González, Jorge Martin-Gutierrez, Melchor García-Dominguez, and M del Carmen Mato Carrodeguas. 2017. Virtual Technologies to Develop Visual-Spatial Ability in Engineering Students. *Eurasia Journal of Mathematics, Science & Technology Education* 13, 2 (2017).
[36] Sheryl A Sorby. 1999. Developing 3-D spatial visualization skills. (1999).
[37] Sheryl A Sorby. 2009. Developing 3-D spatial visualization skills. *Engineering Design Graphics Journal* 63, 2 (2009).
[38] Sheryl A Sorby and Beverly J Baartmans. 2000. The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students. *Journal of Engineering Education* 89, 3 (2000), 301–307.
[39] Adario Strange. 2016. The artist blowing people's minds in virtual reality. http://mashable.com/2016/12/20/virtual-reality-art-oculus-vive-tilt-brush-medium/. (2016). Accessed: 2017-07-11.
[40] Neal Ungerleider. 2016. Google's Tilt Brush Is The First Great VR App. https://www.fastcompany.com/3056668/googles-tilt-brush-is-the-first-great-vr-app. (2016). Accessed: 2017-03-21.
[41] Jeffrey D Wammes, Melissa E Meade, and Myra A Fernandes. 2016. The drawing effect: Evidence for reliable and robust memory benefits in free recall. *The Quarterly Journal of Experimental Psychology* 69, 9 (2016), 1752–1776.

Part II

Annotated Appendix

1. Motivation & Overview

Technology can inspire art in many ways. Currently, Virtual Reality (VR) is quickly gaining popularity among artists as it brings entirely new ways of creating and experiencing art. With this new technology, paintings are no longer restricted to the canvas but can be created in a virtual 3D space. Artists are able to paint all around themselves in a very intuitive way, creating an immersive 3D painting, which the spectators can be brought into. It also enables a form of exploring the painting, walking through it and viewing it from different perspectives, that is not possible with traditional paintings.

Besides inspiring new forms of art, technology can also benefit art education. The initial goal of this project, commissioned by *ING* and *KLEURinCULTUUR*, was to create or extend existing VR painting software for educational use at elementary schools. Aims were to make the software more appropriate for younger children (ages 10 to 12), to research how it can be used beneficially in art education and to identify and address difficulties that they might encounter when learning to paint in a virtual 3D space.
In pursuance of finding a good way to achieve these aims and identify the direction with the most promising potential, various fields have been explored in a broad initial **literature study**. This study is summarized in Section 2. This section also identifies and introduces the research questions addressed in this thesis.

Based on the results of the literature study it was decided to focus on the connection between painting in VR and spatial ability. Spatial ability is an essential cognitive ability used to interpret incoming visuo-spatial information. It consists of multiple components. The focus in this project lies on spatial visualization and mental rotation. Spatial visualization can be defined as the ability to mentally manage figures. Mental rotation is the ability to mentally turn figures and recognize them in another position.
Previous studies show that the drawing of 3D objects can be beneficial for the development of spatial visualization. However, this applies to drawing 3D objects onto a 2D surface using graphical projection; no research existed yet on drawing 3D objects in a 3D space. As the use of VR is also found to be beneficial for the development of spatial abilities, we deemed it worthwhile to research the effect of this combination. Likewise, since spatial visualization encompasses the ability to create a mental 3D image out of limited information, we suspect well-developed spatial visualization skills to be an advantage when painting in a virtual 3D space. Especially when painting from memory or creating a 3D painting out of a 2D image. However, no research on this existed yet either.

While there is no conclusive evidence on the relation between VR painting and spatial abilities, the combination of findings in the literature do suggest a huge potential in this area. Motivated by this, this thesis presents a number of experiments that provide a first step into gaining knowledge on this subject:

- **Pre-study: gaining initial insight into teaching VR drawing to children** (Section 3) - Since no previous work was available to build upon, initial information was gathered using an exploratory research approach. The main goal was identifying issues that might arise when children learn to draw in VR, so that they could be addressed in the succeeding experiments.
- **Trial run: testing and improving the implemented exercises** (Section 4) - In order to test our implemented software for usability and defects, a small user test was conducted. In addition to obtaining information on how to improve our software, this also resulted in more valuable insights on the subject.
- **Main experiment: answering the research questions** (Section 5) - Based on the literature study and previous experiments, we addressed the identified research questions of this thesis in an experimental study.

The major results are summarized in the scientific paper from Part 1. Additional comments and further details are presented the sections above.

2. Literature Review

This review concisely discusses the literature that has been studied during the preparation phase of this thesis project.
In order to investigate how to properly add educational value to our software, Section 2.1 describes the advantages and challenges of using VR in education. Section 2.2 explores painting in VR since it plays a major role in this project and is still a new and relatively unknown concept. As spatial ability is both related to drawing and a desirable skill to develop in primary schools, Section 2.3 is focused on spatial abilities. Finally, the teachers involved in this project also mentioned the lack of collaboration being a problem. As VR completely shuts one off from the outside world, interaction with other students and the teacher is difficult. Therefore Section 2.4 dives into collaboration in VR.

2.1 Education in VR

Given the aim of this project, this section explores the educational aspect of VR. The majority of the literature agrees that the use of VR as an educational tool is very promising. In this section we will discuss the advantages and recommendations.

One of the advantages of the usage of VR is that it increases motivation and engagement [9, 41, 23, 39]. Virvou and Katsionis [71] even claim that, when the VR-environment is sophisticated enough, educational VR applications can become equally attractive as commercial games of no educational content.
Another frequently mentioned advantage is the fact that VR allows for a constructivist approach of learning [10, 9, 39, 67, 72, 17], which entails learning through experience. Many educational theorists have emphasized the fundamental importance of this approach to learning [9]. Brown et al. [12] argue that didactic teaching is inherently limited in its effectiveness as the context of the knowledge is lost. Moreover, the constructivist approach allows students to play an active role in their learning process, increasing their engagement [39, 67, 6].
VR is the ideal platform for learning through experience as it can immerse students in every thinkable scenario [67, 72], this allows for experiencing things that would normally be impossible, dangerous or expensive. Examples are visiting places that are unreachable, such as the moon, or places that no longer exist [58], seeing phenomena that are usually invisible, such as physical forces, and interacting with things that are beyond our reach, such as the solar system.

In order to make the best possible use of these advantages, some challenges still need to be overcome. The first one being the additional costs the introduction of educative VR tools will bring [9, 67, 26], especially considering that schools are always short of money. Although the hardware itself is quite affordable nowadays, the real

cost will be in the development of appropriate educational software and the training of the teachers. The teachers also might be reluctant to use this new technology as they do not have experience with it and might not be convinced of the added value [9, 47]. However, as with all new technology, this reluctance will probably disappear with time as VR becomes more common.
Since all students, even those without VR experience, should be able to use the educational VR tools without any problems, usability is another important challenge [9, 26]. During their experiment, Virvou and Katsionis [71] observed usability problems among novice VR-users. Although they did not discourage the students from playing the educational game, they did distract from the main educational content. Therefore, in order to maximize the learning benefits, Virvous and Katsionis recommend addressing these usability problems.
Furthermore, in order to achieve the desired learning outcomes, it is crucial for educational VR applications to have a sound pedagogical foundation [39, 20, 17]. To realize this, academic staff should actively be involved in the designing process and pedagogical frameworks should be informed. Additionally, educational VR applications should not just present knowledge to the students, as this will not result in full learning benefits [39]. They should invite them to act and take decisions, whereupon they will receive feedback on which they can react again. This will allow students to learn through analysis and reflection, which is in line with the constructivist approach.
Finally, learning through conversation and discourse is also a part of the constructivist approach [17]. However, as normal conversation with other students is made inconvenient by the HMD, another collaboration possibility should be built in. More on collaboration in VR can be found in Section 2.4.

2.1.1 Discussion & Conclusion

Educational opportunities with VR is a popular subject in the literature. This section discussed the advantages and challenges of incorporating VR in education. For this thesis project, it is of particular importance that interaction and learning by doing are key components in maximizing the learning benefits of VR. We will apply this knowledge in our research by using a constructivist approach of learning and encouraging the students to try instead of just showing them what to do.
Although information on learning about 3D structures is plenty, a lack in the literature exists concerning learning how to create them. This might be because the required hardware for applications such as Tilt Brush is rather new. However, a large share of the encountered research on VR had also already been done before the technology was good and affordable enough for general use.

2.2 Painting in VR

This section summarizes the research in the field of VR painting. Since the only difference between digital painting and drawing is the material that is being simulated, which is not relevant for our research, both terms are used interchangeably in this thesis.
We will start with the advantages of using VR for painting, then we will look into the development of intuitive 3D drawing systems, explaining the different components and why certain choices were made.

The most evident advantage is that VR allows for direct interaction with a 3D space, providing a natural way to draw in 3D without the need for graphical projections or complicated controls. The only non-digital alternative that comes close to this are the 3D printing pens that recently emerged on the market [19, 24]. They allow for drawing in the air as they use melted plastic which cools and hardens as soon as it comes out of the pen. However, many limitations still exist and the possibilities will always be limited by gravity.
Besides providing an intuitive way to draw in 3D, painting in VR brings much more in terms of creating and experiencing art. As Brody and Hartman [11] wrote:

> "Painting in space, unfettered by gravity or a matrix to hold the paint, is like painting in a world of pure imagination."

Artists are able to paint all around themselves, creating an immersive 3D painting which the spectators can be brought into. It also enables a form of exploring the painting, walking through it and viewing it from different perspectives, that was not possible before [5].
Vice versa, painting might also turn out to be beneficial for VR. One of the most popular VR painting applications, Tilt Brush [68] is seen as an introductory application to VR [69, 37]. *MacPaint* and *Microsoft Paint* have introduced people to computers and taught them how to use the mouse. Tilt Brush has the potential to do the same for VR.

Traditional 3D drawing software often has a steep learning curve, making it unapproachable for a broad audience. Therefore, researchers have been looking into ways to facilitate intuitive 3D drawing for some time now. The most obvious solution is enabling direct interaction with a 3D space, which requires both 3D input and 3D feedback.
3D input can be obtained by using the user's hand movements; tracking them with for example a glove or controller [16, 29, 11, 38, 13] or using cameras [2]. As our hands can naturally control 6 axes (xyz positions and three axes of rotation), while a computer mouse can only directly control 2, they are much better suited for drawing in 3 dimensions [16]. Although hand tracking with cameras has the advantage that the user does not need to hold a controller or wear a glove, it is much more error prone. It also raises the question whether no controllers would be preferable as people are used to holding something when drawing and it would cause the need for learning gestures instead of simply pressing buttons.
As the main feedback in drawing is generally visual, we will only focus on visual feedback here. In order to deliver 3D visual feedback, stereoscopy can be used as it provides a perception of depth. Systems have been created using Fish Tank VR [16], CAVE VR [29, 11, 38] and head-mounted displays (HMDs) [13]. Considerable disadvantages of using Fish tank VR are the limited drawing range and the inability to walk around the drawing. However, Deering [16] argued that when he was doing his research, HMDs still had ultra-low resolution and extremely distorted optics, making Fish Tank VR the better solution for fine 3D drawing. Nowadays, the advancement of technology has solved these problems, shifting the preference back to HMDs. The advantage of CAVE VR over HMDs is that users are not completely isolated from the real world and still able to see their own bodies. However, the size of the needed setup for a CAVE system makes it far less suitable for consumer usage than HMDs.
Since the emergence of HMDs on the consumer market, many VR painting tools

have been released. Some well-known examples are Tilt Brush [68], Quill [50] and A-Painter [1]. For this study, the choice was made to use A-Painter as it is open source and thus allows us to make the changes necessary for our research.

2.2.1 Discussion & Conclusion

The initial motivation for the development of VR painting systems was the wish for more intuitive 3D drawing tools. Thanks to recent advances in technology, including the emergence of affordable, high-resolution HMDs, these systems are now a reality. They enable everyone to create 3D drawings without the need of experience. Furthermore, artists are offered the ultimate freedom and the chance to immerse themselves and their public into their works.
Although it might seem as if the search for an intuitive 3D drawing system is now complete, there are still several things left to investigate. For example, current systems can still be improved in areas such as user friendliness, image quality, intuitiveness of the controls etc. However, the main lack in the literature is related to the 3D drawing itself. No research exists for example on how intuitive drawing in 3D truly is, considering that most people have only drawn in 2D their entire life. Furthermore, as already mentioned in the previous section, no research has been done on the learning or teaching of drawing in a virtual 3D space. It also is unknown what issues might arise and how to solve them, what abilities might be important or what benefits can be obtained by painting in VR. By addressing the research questions specified below and in Section 2.3.1, our research will implicitly contribute to overcome this gap of knowledge.

Since drawing 3D figures directly into a virtual 3D space is quite different from other methods of drawing, it might be that new methods of teaching are needed. The question that hereby arises is: *How to teach (children) how to draw 3D figures in a virtual 3D space?* This question is too broad to completely answer within the scope of this project. However, by using an exploratory research approach ánd answering the following more concrete research question, we aim to take a first step in that direction:

> **Research question 1:** Are training exercises helpful to improve children's drawing skills in a virtual 3D space, even with only a small number of training sessions (e.g., four sessions of 35 minutes)?

Before being able to answer the previous questions effectively, it is necessary to identify the obstacles that children might encounter when they start drawing 3D figures in VR. This allows for creating training exercises that address these issues. Therefore we present the following exploratory research question: *What issues are encountered when learning to draw 3D figures in a virtual 3D space?*

2.3 Spatial Abilities

Many studies have investigated the improvement of spatial abilities using VR. Likewise, drawing is known to have a positive influence on the development of spatial skills. In the following, we will therefore discuss spatial ability, including activities that are beneficial for its development and ways to test it.

Spatial ability is an essential cognitive ability used to interpret incoming visuo-spatial information [52, 51]. Not only are spatial abilities used in everyday activities, such as navigating around the house, they are extremely important in fields such as engineering, science and technology [34, 4, 51, 55].
Spatial abilities have been defined and subdivided in many different ways and there is no one universal definition [61, 55, 35]. For our purpose, we will however only distinguish two components: spatial visualization and mental rotation. Linn and Petersen [35] describe spatial visualization as "the ability to perform complicated, multistep manipulations of spatially presented information". Mental rotation is described as "the ability to rotate two or three dimensional figures rapidly and accurately".
The difference between spatial abilities and spatial skills is that people are born with the first, while the second is acquired through training [61]. However, in the literature these terms are often used interchangeably since distinguishing between those in practise is nearly impossible.
The development of spatial ability is influenced by gender, age and spatial-related experience [51]. Many studies have revealed that the spatial visualization skills of men are better than those of women [51, 61, 15, 25]. Theories aiming to explain this difference include biological factors, such as male cerebral lateralisation and the male sex hormone, and environmental factors, such as gender-typed socialisation [51, 61, 25].
Spatial ability is not fully developed until adolescence is reached [51] and research has shown that spatial activities during childhood are very important to support this development [15, 7]. Activities that have been found to improve spatial abilities include playing with construction toys, participating in some types of sports and playing certain computer games [61]. For example, the computer game Tetris has been shown to improve students' performance on the Mental Rotation Test (MRT) [45, 15].

Another activity that is often mentioned in combination with the development of spatial skills is sketching and drawing (S&D). A considerable number of studies suggests that the sketching or drawing of 3-dimensional objects improves spatial visualization skills [51, 62, 42, 34, 3]. However, in these studies the drawing activities are often combined with other spatial visualization improving activities, making it impossible to attribute the performance improvements solely to the drawing. This corresponds with Braukmann and Pedras' statement that not all drawing activities improve spatial skills and that a spatial context is critical [42]. Nevertheless, the drawing itself does seem to play a major role in the development of spatial skills; Leopold, Górska, and Sorby [42, 34] found that courses that relied heavily upon S&D activities were more effective in developing spatial skills than courses that did not. Alias et al. [4] also found the attitude towards S&D to be relevant; they found a statistically significant correlation between the usage tendency of S&D and spatial visualization ability.
Both Rafi et al. [51] and Alias et al. [3] investigated the effect of S&D activities on spatial visualization skills and both found a statistically significant improvement in the spatial visualization ability of their participants. Rafi et al. [51] also found a significant performance gain in mental rotation accuracy but not in mental rotation speed. No significant improvements in mental rotation ability were found by Alias et al. [3]. A possible explanation presented by Alias et al. is the lack of shared characteristics between the exercises and the test. They mention that studies reporting improvements mostly use practise tasks that are very similar to the tasks on the test.

Alias et al. also mention the implicit teaching of mental rotation skills as a probable cause, as they did for example not ask their subjects to draw the objects from different views. This might also explain the difference between the results of these two studies, as Rafi et al. did include different views in their training.

Furthermore, developing spatial skills using VR is a very popular research topic in which many promising results have been obtained [52, 22, 55, 53, 46, 40, 48]. The main advantage of using VR is that it allows students to observe and manipulate 3-dimensional objects directly in 3D space which helps them understand spatial concepts and relations [28, 52]. Additionally, many of the advantages of VR as an educational tool, such as increased engagement, apply here as well.
Gutiérrez et al. [22] compared the improvement of spatial skills after training with various 3D virtual technologies and traditional methods. The various 3D virtual technologies being Augmented Reality (AR), VR and PDF3D. Their results showed a significant difference in improvements favoring the 3D virtual technologies over the traditional methods. They however did not find a significant difference between the various technologies.
Besides the studies that have successfully employed VR to improve spatial skills, there are also studies that have not yielded positive results. In particular the large-scale study (215 participants) carried out by Dünser et al. [18], in which the effectiveness of spatial ability training with an AR application was investigated. Their results did not show significant differences between the AR and non-AR groups. It is hypothesized that traditional spatial ability tests might not be suited very well to detect skills that are required or trained in 3D space. Seeing as students in VR, or AR, can directly see and manipulate 3-dimensional objects without having to interpret or mentally transform 2-dimensional representations of these objects, something that is necessary in traditional spatial ability tests, this is a likely cause for the lack of results in this study. Other studies that did achieve improvements on the traditional tests, generally implemented some association with the 2-dimensional representations or used an adapted VR test [53].
Finally it needs to be emphasized that the VR applications in these studies are completely focused on the training of spatial skills. Concerning spatial visualization and mental rotation, no proof exists that an arbitrary VR application will have a positive influence on these abilities. However, given the fact that activities such as playing with construction toys have been proven to benefit spatial abilities, we believe that VR applications with suitable activities can achieve this as well without the need to solely focus on training spatial skills.

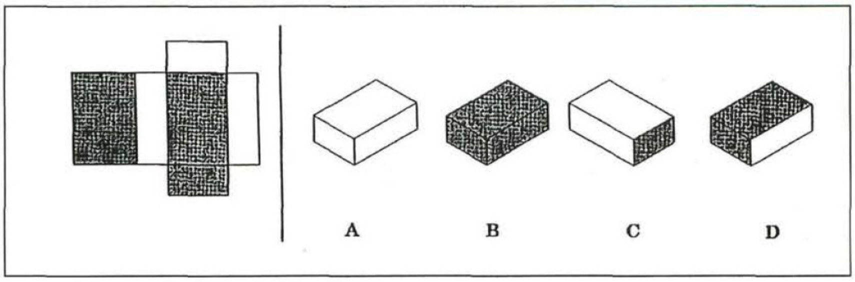


FIGURE 2.1: Example exercise of the Differential Aptitude Test: Space relations. (from [61])

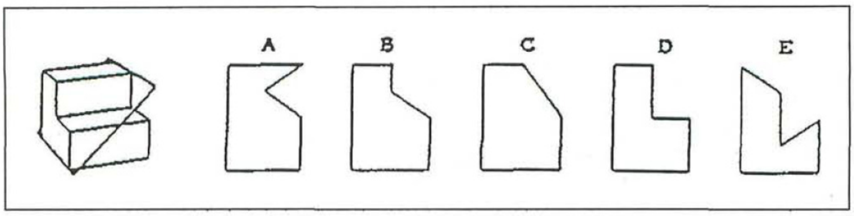


FIGURE 2.2: Example exercise of the Mental Cutting Test. (from [61])

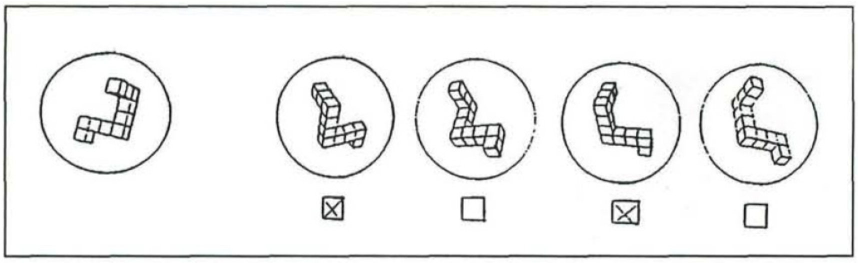


FIGURE 2.3: Example exercise of the Mental Rotation Test. (from [61])

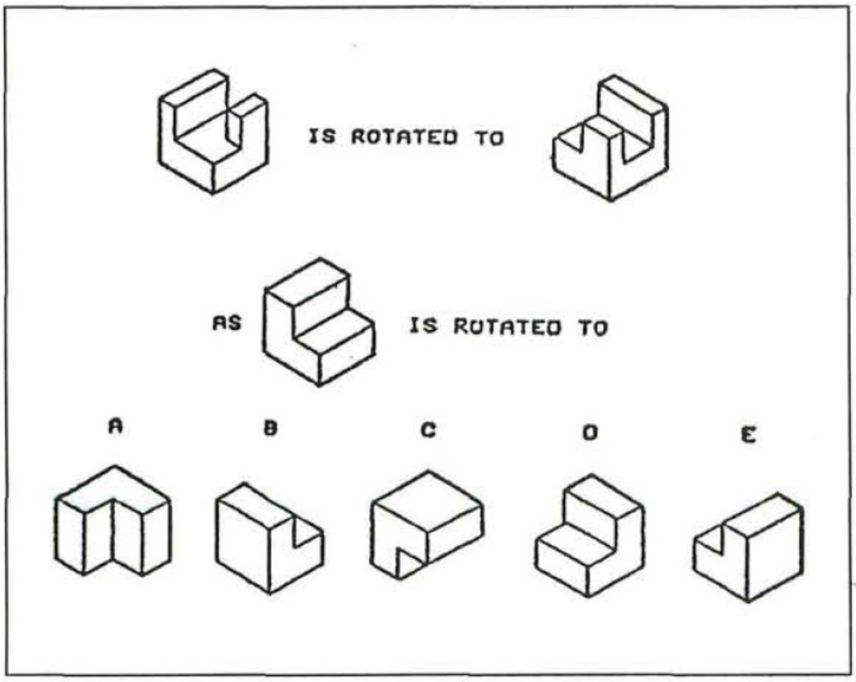


FIGURE 2.4: Example exercise of the Purdue Spatial Visualization Test: Rotations. (from [61])

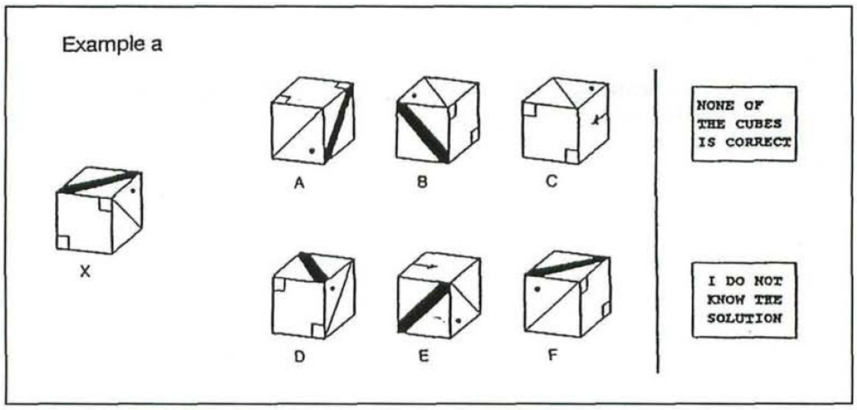


FIGURE 2.5: Example exercise of the 3-Dimensional Cube Test. (from [61])

Since drawing in VR is a combination of two things that have been found to improve spatial visualization and mental rotation, it seems worthwhile to investigate the effect of this activity. In order to investigate this, we must also know how to test these spatial abilities.

One of the most well-known spatial visualization tests is the Differential Aptitude Test: Space Relations (DAT:SR) [8, 61]. In this test, the student has to choose the correct 3-dimensional object that would result from folding a given 2-dimensional pattern. Figure 2.1 shows an example exercise from the DAT:SR. Studies have shown that the DAT:SR is an effective predictor of academic performance in engineering courses which are known to heavily rely on spatial visualization skills [8, 61].

Another well-known visualization test is the Mental Cutting Test (MCT) [61]. The task is to choose the correct cross-section, resulting from a figure that is to be cut with an assumed plane. An example exercise can be found in Figure 2.2.

For the testing of the mental rotation ability, several well-known tests exist as well. The most commonly used is the Mental Rotation Test (MRT), see Figure 2.3. Shepard and Metzler [57] originally came with the idea to test mental rotation ability with pairs of 3-dimensional, asymmetrical cubed objects. Based on this, Vandenberg and Kuse [70] developed the MRT.

Another well-known test is the Purdue Spatial Visualization Test: Rotations (PSVT:R) [61]. The exercises in this test show an object before and after a certain rotation in space, the task is then to select the correct view of a second object after it has been subjected to the same rotation. Figure 2.4 shows an example exercise.

Lastly, the 3-Dimensional Cube (3DC) can also be used to assess mental rotation ability [21, 61]. The exercises in this test show a cube with patterns visible on three sides. The task is to choose a view that could belong to the cube after it has been rotated in space, the students are told that the cube has different patterns on each of its six sides. An example exercise can be found in Figure 2.5.

In most studies where spatial abilities are evaluated, a combination of tests is used. For example Leopold et al. used the MRT, MCT and DAT:SR to test spatial ability levels in their study [34].

Since most of the spatial ability tests above were created for students or adults, they might not directly be suitable for the children in our experiment [63, 25]. Only the DAT:SR has already been developed for the right age group [8]. The literature however illustrates multiple possibilities to adapt the other tests in order to make them suitable for younger children [63, 15, 25, 36].

De Lisi and Wolford [15] adapted the French Kit Card Rotation Test, a test very similar to the MRT, to make it suitable for testing mental rotation ability in children aged 8/9 years old. By replacing the multiple choices by a single choice, the need to scan across a series of figures is eliminated. According to the authors this makes the test more appropriate for young children.
Furthermore, 2-dimensional MRTs are deemed easier than 3-dimensional MRTs [25]. Thus, using a 2-dimensional MRT for young children seems to be more appropriate. However, as our project comprises 3D training, which leads to improvements in both 2D and 3D tasks [43], it would be incomplete to solely test 2D improvements.
Furthermore, based on results of other studies, Hoyek et al. [25] assume that familiar items, such as figures of animals, are easier to encode and mentally rotate by children than abstract shapes.
Finally, Lütke and Lange-Küttner [36] designed a mental rotation test suitable for young children by adding colour and simplifying the complex geometric cube aggregates used by Shepard and Metzler [57]. Their Rotated Colour Cube Test (RCCT) has the same multiple choice test format as used by Vandenberg and Kuse [70], but contains single multi-coloured three-dimensional cubes that have to be matched. Lütke and Lange-Küttner argue that colour information is a facilitating factor in mental rotation performance, in particular for children as they are especially sensitive to colour signals.

2.3.1 Discussion & Conclusion

Spatial ability is a very important skill, especially in fields as engineering and science. It can be divided into multiple aspects. In this study we will focus on spatial visualization and mental rotation.
Since spatial visualization is used to create mental 3D images, we suspect well-developed spatial visualization skills to be an advantage when painting in a virtual 3D space. Especially when painting from memory or creating a 3D painting out of a 2D image. This has however not yet been studied, raising the following research question:

> **Research question 2:** Is there a connection between a person's spatial visualization ability and their proficiency in creating a 3D drawing in a virtual 3D space?

Furthermore, multiple studies suggest that the drawing of 3D objects is beneficial for the improvement of spatial visualization skills. However, since most of these studies combine the drawing activities with other spatial visualization improving activities, it is impossible to attribute the performance improvements solely to the drawing. Thus, more research is needed to prove the exact influence of S&D by itself. Besides, the existing studies all apply to drawing 3D objects onto a 2D surface using graphical projection. No research exists yet where the benefits of drawing 3D objects in a 3D space are evaluated.
Spatial ability training in VR has produced many promising results as well. However, no research exists yet that investigates whether an arbitrary VR application has a positive influence on the development of spatial visualization or mental rotation skills.
Despite the fact that the research in both areas is still quite incomplete, we believe that enough evidence exists to suggest that both drawing and the use of VR, when properly employed, can be beneficial for the development of spatial visualization

and mental rotation. Seeing as painting in VR is a combination of both, we deem it worthwhile to investigate the effect of this activity on these spatial abilities. To verify this assumption, we defined the following research question:

> **Research question 3:** Can children's spatial visualization / mental rotation skills be improved by 3D drawing in VR, even with only a small number of sessions (e.g., four sessions of 35 minutes)?

A potential obstacle that is associated with the research questions formulated above is Dünser et al.'s [18] hypothesis that traditional spatial ability tests might not be suited very well to detect skills that are required or trained in a 3D space. Although this has not yet been tested, it is certainly plausible. New tools that are able to measure spatial ability skills directly in 3D would be desirable solution for this, however the creation of such a tool is outside the scope of this project.
On the other hand; traditional spatial ability tests are suited to test spatial skills that are trained in the real world, which is a 3D space as well. Therefore we believe that it should be possible to obtain results using the traditional tests.

2.4 Collaboration in VR

The teachers involved in this project raised the issue that children 'disappear' into their own world when painting in VR. They would like to see more interaction and collaboration between the students and with the teacher(s) when one or more students are in the virtual environment (VE). Therefore, this section discusses collaboration in VR. We will first discuss multiple incentives for adding collaboration opportunities, then VR components that affect collaboration and finally interaction between users inside and outside the VE.

The first question to answer: "Why do we want children to collaborate?" Simply to prepare them for the future, as the ability to co-operate is a desirable skill and in most jobs even a necessity, or is there more to it? A look into the literature demonstrates that there is indeed more to it and that collaboration has many benefits.
The first benefit being that social interaction plays an important role in the learning process [9, 27, 67]. Jean Piaget's theory implies that collaboration leads to conflict when students disagree with each other, forcing them to re-evaluate their own conceptions [27, 67]. Vytgosky's theory suggests that higher mental functions, such as reasoning and critical thinking, are learned through cooperative interactions with peers [27, 67]. Furthermore, Vytgosky argued that children learn best when the task is within their zone of proximal development [67]. This zone encompasses tasks that a child can do with help, but not yet alone. Therefore, efficient learning occurs when working together with a peer performing tasks at a slightly higher cognitive level.
Furthermore, collaboration is said to increase student engagement. Jackson et al. [27] facilitated peer collaboration by enabling the students to communicate with each other through an intercom system, this appeared to increase feelings of presence and student engagement. However, these claims are based only on casual observations, so more research is needed to be able to determine the exact effect of collaboration on these variables.
Finally, collaborative learning is claimed to build diversity understanding, increase students' self esteem, reduce anxiety, help develop students' oral communication skills and more [33].

To achieve a complete experience in a collaborative virtual environment (CVE), Theoktisto and Fairén [66] listed the following required sensations:

- a shared sense of location in (3D) space;
- a shared sense of time;
- a shared sense of co-presence;
- a shared communication channel;
- a shared mechanism for object manipulation.

We will now discuss several VR concepts and how they contribute towards these requirements or otherwise relate to collaboration.
The first two concepts are immersion and presence. As there is no universal agreement on the definitions of both terms, they are often used interchangeably within the VR literature [32]. We will however use the same distinction as Slater et al. [59]: presence is a state of consciousness defined as 'the sense of being in an environment' [65], while the degree of immersion can be objectively assessed by looking at the characteristics of a VR system. Presence is thus important in order to fulfill the first requirement listed above. Furthermore, Slater et al. [60] found it to increase agreement within groups. By increasing the immersive qualities of a VR system, higher feelings of presence can be elicited [65, 59, 14]. Cummings and Bailenson [14] did however find that this effect is only medium-sized and that the impact differs between factors.
Besides increasing feelings of presence, immersion benefits collaboration in multiple ways [59, 54, 44, 31]. Since the terminology used for variables contributing to immersion varies across the literature, we will solely use Steuer's definitions [65] here to avoid confusion.
The first factor to be discussed is vividness, which stands for the sensory richness of the portrayed environment. Two contributing factors are sensory breadth, which refers to the quantity of senses that are simultaneously addressed, and sensory depth, which refers to the quality of these inputs. Research in Computer-Supported Cooperative Work (CSCW) [59] shows that sensory depth is an important aspect in CVEs as it directly affects the effectiveness of both verbal and nonverbal interaction. An example would be providing a higher image resolution, allowing users to see each other's facial expressions and other small social interaction cues. According to Slater and Wilbur [59], the impact of sensory breadth is harder to demonstrate. Although many studies could not prove that accommodating more sensory modalities improved collaboration, it has been hypothesized that it affects the process rather than the outcome [59].
The next factor is interactivity, which is defined as the extent to which users can modify the form and content of the VE in real time [65, 59]. Seeing as collaboration almost always involves jointly creating or manipulating objects such as documents and designs, hence the last requirement in the list above, it is important to have sufficient interactivity for the purpose of the collaboration [59]. Finally, one of the factors contributing to interactivity, speed, refers to the time it takes to assimilate input into the VE [65]. In order to fulfill the second requirement, a shared sense of time, interaction should have (almost) no delay.
A study performed by Narayan et al. [44] shows that the level of immersion can affect user performance on collaborative tasks. During their experiments, two immersive factors were varied; stereo and head tracking. While head tracking did not seem to affect the task performances, stereo proved to be extremely important for performing their specific task. Narayan et al. also found that it is more effective to

maximize the total level of immersion instead of making sure that everyone has a similar level of immersion.
Another interesting discovery regarding the effect of immersion on collaborative performances is the finding that the most immersed user tends to emerge as leader [60].

In order to fulfill the need for a shared communication channel, several options can be considered. Examples are communication through chat [17], avatar movement [67], speech [27, 60] or a combination of multiple channels [67]. In CVEs, spoken communication is used more frequently than communication by text. Probable explanations are that speaking is the most natural way of conversing, that it is faster, that the hands do not need to be occupied and that speaking allows for conveying additional information by intonation. Avatar movement is especially useful for mediating unspoken social interaction cues such as emotions and looking at somebody.

The last requirement to satisfy is a shared sense of co-presence, which is the feeling of being with other people. Slater et al. [60] found a positive relationship between presence and co-presence, although the causality is still unknown. Visualizing the other users, by means of an avatar, is also important in creating a sense of co-presence [66]. Besides, as mentioned before, avatars can be used to communicate nonverbal behaviours [67]. These behaviours serve at least two central functions in face-to-face interaction: the communication of emotion and conversation management [56]. Examples of these nonverbal behaviours are raising one's eyebrows and nodding one's head.
Different approaches exist towards the controlling of avatar behaviour. One approach is manual control, which has the advantage that the user is in total control of which behaviours are being expressed. The disadvantages are that it requires continuous attendance to its state and that unconscious behaviours will be lost. A completely different approach is tracking the user's real-life expressions and movements and using these to control the avatar. The advantages are that it provides the most faithful representation of the user's nonverbal behaviours and that no attention is required. However, disadvantages are that tracking equipment can be both expensive and intrusive and that user's might prefer control over their avatar's actions. Moreover, it is hard to track user's facial expressions and gaze when they are wearing a HMD. Finally, different approaches in between exist. Such as partly automated avatar behaviour. The main disadvantage of this approach is that it may result in misleading behaviours.
Both the appearance and behaviour of avatars can influence interaction between users in a VE [56]. According to research in social psychology, people consider similar looking people to be more attractive and persuasive [56]. They are also more likely to make a sale and receive altruistic help. This effect can also be achieved by digitally morphing one's face with the person they want to influence. Schroeder and Axelsson [56] demonstrated this by showing that participants are more likely to vote for a candidate that is morphed with their own face than a candidate that is morphed with someone else's face.
Another way to become more persuasive is by directing gaze at someone [56]. In the real world, it is not possible to look directly at more than one person at the time. However, in VR it can be programmed that it appears to all participants as if they are gazed at directly by the speaker.
Finally, mimicking nonverbal behaviour also increases persuasion and makes one appear more likeable [56]. Schroeder and Axelsson [56] performed a study where

they made a virtual agent mimic the participants' head movements with a 4 second delay. The results showed a huge difference compared to a virtual agent whom's head movements were a playback from a previous round. The mimicking agent was far more successful at persuading the participants and was also seen as more likeable.

The majority of the literature focuses on collaboration between users that are all inside the VE. However, collaboration between users inside and outside the VE might also bring interesting opportunities. One subject in this area is the creation of telepresence using VR. For example Khan et al. [31] created a system that allowed for collaboration with a remote person, making them feel as if they were at the local site. Combining VR with their previously developed Embodied Telepresence system (ETS), allowed the remote user to look around, specify their gaze, do side conversation, etc.
Besides the papers on telepresence, no literature was found regarding to collaboration between users inside and outside the VE. We did however find one game that illustrates how this form of collaboration could be used: *Keep Talking and Nobody Explodes* [30]. The idea behind this game is that the player wearing the HMD has to dismantle a bomb, while the player without the HMD holds the manual. Collaboration and good communicative skills are thus very important to win this game.

2.4.1 Discussion & Conclusion

A great amount of research has been done in the area of collaboration in VR. However, a lack exists concerning interaction between users inside and outside the VE. The cause of this lack is not clear; perhaps this form of interaction is just not as promising as interaction between users within VEs.
The fact that collaboration in a VE for art creation has not been studied before, raised the general research question: *How to facilitate collaboration and interaction in a virtual environment for art creation?* We can further specify this to: *How to facilitate collaboration and interaction between users in a virtual environment and users in the real world, aimed at teaching VR drawing in a classroom?* Besides addressing the lack in the literature, this new research question also helps schools as they almost always have more students than HMDs, but still want everyone engaged.
Despite this high relevance, the decision was made to not include the collaboration aspect in this research. Addressing it would be a good topic and is recommended for a potential follow-up thesis project.

3. Pre-study: gaining initial insight into teaching VR drawing to children

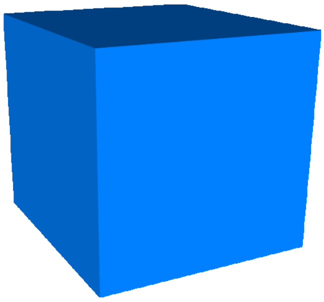
The main experiment presented in the scientific paper is preceded by two exploratory experiments. These experiments are briefly mentioned in the paper but not further discussed. This section contains all information of the first exploratory experiment: the pre-study. Section 3.1 presents the motivation for this experiment and Sections 3.2 and 3.3 describe the implementation and setup. Encountered issues are mentioned in Section 3.4. The findings are discussed in Section 3.5 and Section 3.6 closes with conclusions and the impact on the succeeding experiments.

3.1 Motivation

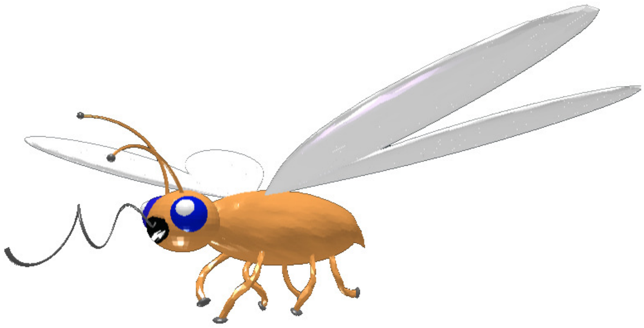
Since no research exists yet on VR painting for younger children, the issues that might hereby arise are still unknown. Therefore it was decided to conduct an exploratory experiment in order to acquire more insight on this topic. The goal was to identify the issues that might arise when teaching children to draw in VR, so that they can be addressed in the main experiment.
Additionally, this experiment served as an initial test to collect information needed for setting up an appropriate main experiment; information such as what level of drawings the children can handle, how long they need to complete a drawing, whether they understand the controls and where extra instructions might be needed. Finally, some spatial ability exercises were tested to see whether they were suitable for children of this age.

3.2 Implementation

The used hard- and software is largely similar to the hard- and software used during the main experiment, described in the scientific paper. The main difference is that the modified version of A-Painter only included minor changes; the training exercises and menu were not implemented yet. These minor changes included the translation of A-Painter to Dutch, to make sure that the children would understand everything, and the addition of a warning prompt to the 'Clear' button to prevent them from accidentally erasing their entire drawing.



(A) Blue cube



(B) Firefly

FIGURE 3.1: Example figures of the pre-study.

3.3 Setup and Procedure

Four children participated in this exploratory experiment. Beforehand they received instructions and signed a consent form. During the experiment, the children created virtual 3D drawings using the two handheld controllers. In contrast to the main experiment, the drawing sessions were not individual; all four participants were present the entire experiment. Each child started with five minutes of freestyle drawing to become familiar with the HTC Vive and A-Painter.
The participants were all asked to copy two figures. The first one being a simple blue cube (3.1a). The scene, shown in Figure 3.2, contained both a 3D model and a 2D perspective image of this cube. Based on this example it was explained that their drawings should be 3D, just as the 3D model of the cube. The second figure was a firefly (3.1b). Two participants received a 2D example (Figure 3.3b) while the other two participants received a 3D example (Figure 3.3a).
During the creation of these drawings, we closely watched the children and asked them questions. An art teacher was present to assist in asking the right questions and interpreting the answers from her field of expertise.
The children were also asked to make a number of spatial ability exercises while thinking aloud. This allowed us to judge whether the children understood the questions.
Afterwards, everyone sat together for a joint discussion about the session and a number of questions. Everything was recorded to allow for a more closer evaluation afterwards.

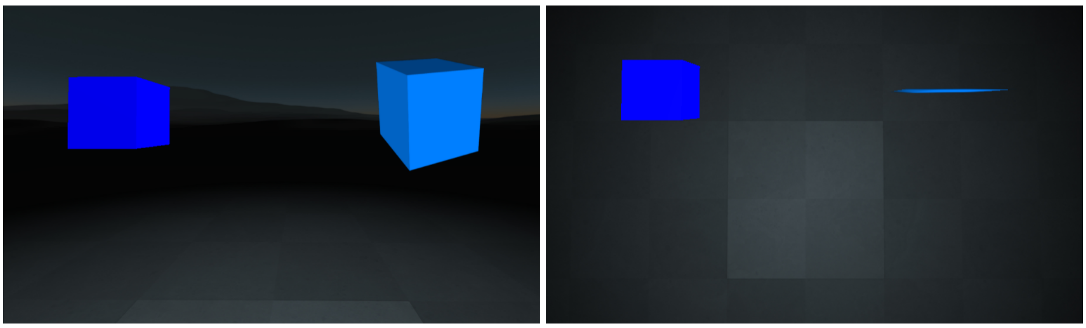


FIGURE 3.2: The scene containing both a 3D model and a 2D perspective image of the cube, seen from the beginning position (left) and from above (right).

(A) The scene containing the 3D example of the firefly, as seen from above.

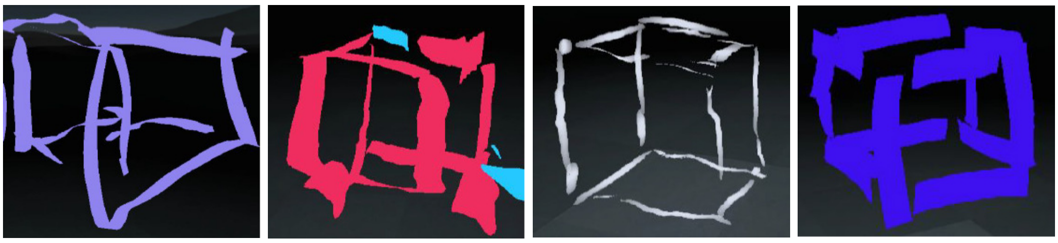
(B) The scene containing the 2D example of the firefly, as seen from above.

3.4 Issues

Originally, it was planned for the children to draw four figures. The examples were divided in such a way that all participants would have received two 2D images and two 3D models. However, the drawing took up a lot more time than anticipated. Thus it was necessary to cut back to only the example figure and one of the more difficult figures.

3.5 Findings

This section gives a structured overview of the main findings. The drawings made by the participants can be found in Figures 3.4 and 3.5.



(A) Participant 1 (B) Participant 2 (C) Participant 3 (D) Participant 4

FIGURE 3.4: Cube drawings. Clicking on them will open a complete view of the drawing in a webbrowser.

(A) Participant 1 (2D example) | (B) Participant 2 (2D example) | (C) Participant 3 (3D example) | (D) Participant 4 (3D example)

FIGURE 3.5: Firefly drawings. Clicking on them will open a complete view of the drawing in a webbrowser.

3.5.1 General observations

- The children that were not drawing were very involved with the child that was drawing.
  - Advantage: they tried to help each other and gave lots of (helpful) advice. Their mutual jokes also created a fun atmosphere.
  - Disadvantage: it seemed to make them (more) self-conscious about their drawings. Especially when something did not succeed, they tended to make a joke about it and seemingly make it worse on purpose as if they were not doing their best anyway (examples are 3.4a and 3.5c). They also distracted each other from time to time.
- Implementing a warning for the 'clear' button proved its value; already during the first figure this button was accidentally selected instead of the 'save' button, which normally would have resulted in completely erasing the entire drawing.
- The participant that performed best on the 3D drawings (participant 4), also answered several MRT questions strikingly quick and almost faultless. No particular observations have been made for the other subjects.

3.5.2 Drawing observations

- The first figure (the cube) went quite well.
  - The children did not really look at the examples but immediately started drawing.
  - Most of them also quickly had an idea on how to do it. Even before trying it one of them already said: "Ohh that is easy, just draw a square, turn, draw another square, turn and so on".
  - Only one participant said that they found this figure really difficult.
- The second figure (the firefly) was found to very difficult.
  - As soon as the children saw the figure they exclaimed things as: "Nooooo. . . " and "How would you even draw this in 3D??".
  - They particularly indicated not knowing where to start.
  - When it was suggested to start with the body, the participants struggled with the oval 3D shape.

  - They did however address it very methodically by first carefully drawing a framework and then filling it in.
  - Three out of four participants experienced the firefly figure as too difficult.

- Conclusions about the difference between 2D and 3D examples cannot be drawn since there was, due to time limitations, only one figure where the participants had either a 2D or 3D example. Differences between these drawings may be the result of differences in the talent of the individual children.

- The first participant with a 2D example also created a 2D drawing, however, later it became apparent that the assignment had not been entirely clear to them. The other participant with a 2D example did make their drawing in 3D.

- Finally, the controls caused quite some problems;

  - Especially selecting colors did not go smoothly. How to point with the other controller was not clear and even when they knew how it worked, they still had trouble pointing and seeing the pointer line.
  - They accidentally teleported quite a number of times.
  - Everyone had a hard time finding the 'undo' button, which is located on the sides of the controller.

  However, the problems with the controls became less over time.

3.5.3 Questions

- The children were asked beforehand whether they thought it would be easier to draw from a 2D or 3D example; they all thought drawing from a 3D example would be easier. Afterwards the children received the same question and they all still agreed to their answer. The main reason they mentioned was that "a 3D example shows how long and round something is".

- When asking what they found the most difficult about drawing in 3D in VR:

  - One participant answered that the VR headset / controls made it (more) difficult.
  - Another participant disagreed, they responded that VR makes 3D drawing easier because "you can look from underneath, from above, the sides etc. and you cannot do that on paper".
  - The shape of the firefly was also mentioned as the most difficult. Since it is some sort of oval shape, drawing the curves to form the shape and making them the same on different sides is really tough, according to the participant. Also the 'closing' of the shape was experienced as difficult and laborious.

- We also asked what sort of exercises they think would help them to learn drawing in 3D.

  - The children all agreed that starting with basic figures, such as cubes, spheres and pyramids, and then steadily going more difficult would be a good idea.

- One of the children also came up with a good solution for the problems with the selecting of the colors.

  - They suggested to display the color circle on the trackpad of the controller that is displayed in the virtual environment. This way you can directly tap on the wanted color.
  - However, this might cause a (great) loss in accuracy. Also, making big changes in the controls is not within the scope of this project.
- They all favored drawing buildings (house, room, city), which was interesting as we suspected animals to be preferred.
  - When asked, the children answered that animals are often probably too difficult due to their 'weird and different shapes'.
  - One participant wished to draw a house which you could enter and then also draw the inside. The other participants reacted very enthusiastically to this idea.
- They also all reacted very enthusiastically on the idea to create point-to-point drawing exercises in the virtual environment and said that they definitely would like to do that in 3D.
- The step-by-step drawing idea was also received positively. It is also in line with their wish to start with basic figures. The children thought it would certainly make it easier to draw more complex figures, since you can just follow the steps and do not have to figure out yourself where to start and how to do it .

3.5.4 Spatial ability exercises

- Both the Spatial Reasoning (SR) and Mental Rotation Test (MRT) exercises were understood by the children, although most of them did not find them easy.
- There appeared to be big differences between the children; where one of them doubted a lot and indicated that they found it incredibly difficult, another one did not seem to have any doubts and answered everything quickly and almost faultless.
- The participants found it difficult to understand how the cubes could be folded in the SR exercises. Explaining this also proved to be challenging without physical aids.
- One of the participants mentioned that the symbols of the SR test confused them several times.

3.6 Conclusions and impact on subsequent experiments

Using a small number of subjects, this pre-study aimed at getting a better understanding of the matter, especially with respect to how children experience it. Another goal was to identify important issues in order to eliminate potential pitfalls and problems for the setup of the main experiment.
It became clear that the children need more time for their drawings than expected, which led to the decision to make the sessions longer and have less exercises. Secondly, we concluded that it is better to have no other children in the room during the main experiment. This way the children can really try their best and do not have to feel ashamed or 'act cool' in front of each other.

Since the controls were found to be troublesome, it was concluded to spend more time on the explanations and practising of the controls. In particular on the actions that caused the most problems.
Furthermore, as all children expressed the wish to start with more basic shapes, the decision was made to add the drawing of five basic shapes to the drawing exercises of the main experiment. Both the involved art teacher and the children unanimously deemed the drawing of the basic shapes to be the most helpful when learning to draw in 3D. Thus the basic shapes were inserted at the expense of the point-to-point drawings, which were deemed fun but less helpful.
One of the main issues observed during this experiment was 'not knowing where to start', especially with the extra dimension that suddenly had to be taken into account. This strengthened our idea that step-by-step drawing exercises are a good way to learn drawing in 3D.
As the children all favored drawing buildings, a number of exercises containing a building were added for the upcoming experiments.
Based on the performance of the participants in this experiment, we assume that both the SRT and MRT questions are suitable for this age group. They did however need more time for the MRT questions, thus in the main experiment we do not adhere to the official strict time limits. Given the participant that got confused by the symbols of the SRT questions and the literature that indicates that adding color can make spatial tests more suitable for young children [36], we decided to test the difference between usage of colors and symbols in the succeeding experiment.
Finally, in order to be able to explain more clearly how the SRT questions should be solved, we decided to use printed folding patterns for the explanations in the succeeding experiments. This way the children could physically fold them, helping them to understand how to mentally fold the other ones.

4. Trial run: testing and improving the implemented exercises

This section contains all information of the second exploratory experiment preceding the main experiment: the trial run. Section 4.1 presents the motivation for this experiment and the implementation and setup are described in Sections 4.2 and 4.3. Encountered issues can be found in Section 4.4. The observations are discussed in Section 4.5 and Section 4.6 closes with conclusions and the impact on the main experiment.

4.1 Motivation

To test our implemented software for usability and bugs, we decided to conduct a user test. This user test took place in the form of a trial run for the main experiment. The main goals were to minimize the chance at problems during the main experiment and to find out what still could be improved. It was also tested whether there was a noticeable difference between using colors and symbols for the SRT. Additionally, time indications for the different drawing exercises and the spatial ability test were gathered.

4.2 Implementation

The used hard- and software was mostly equal to the previous experiment, only A-Painter was further extended.
To enable the experimenter to control the experiment, a menu was added that is visible on the additional screen but not on the HMD. The menu, shown in Figure 4.1, contains buttons for the different drawing exercises/modes, a 2D/3D switch and buttons to save and clear the drawings. By switching the 2D/3D switch to the desired dimension and subsequently clicking a figure, the example of this figure will appear in the corresponding dimension.

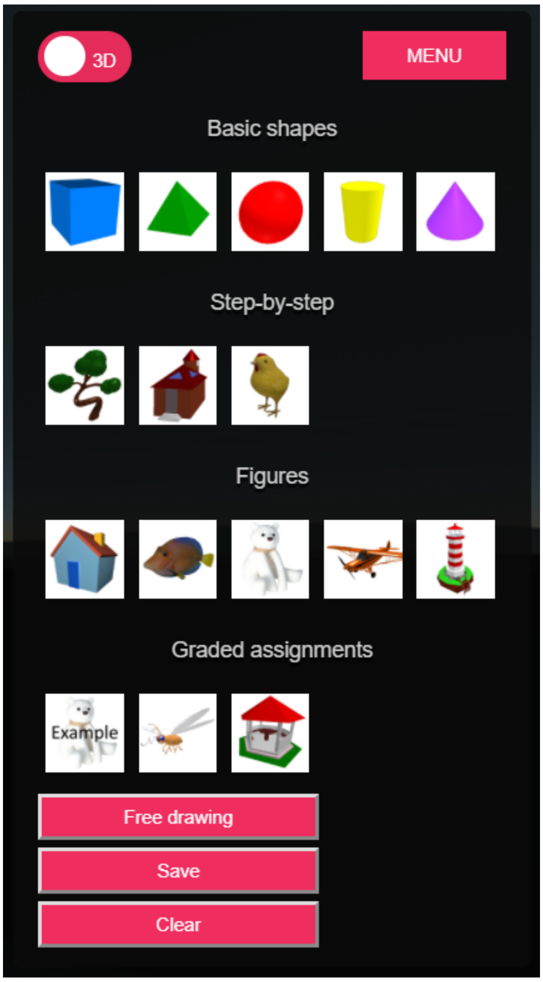


FIGURE 4.1: Menu

For the practising of the basic shapes five shapes were added: a cube, a pyramid, a sphere, a cylinder and a cone (4.2). Three SBS drawing exercises were created and included as well. The intermediate steps of the SBS exercises, shown in Figures 4.3, 4.4 and 4.5, were created with Blender.

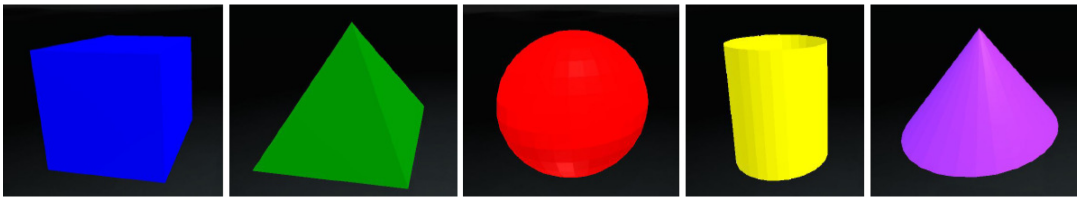


FIGURE 4.2: 3D basic shapes

FIGURE 4.3: Steps of the SBS Tree exercise.

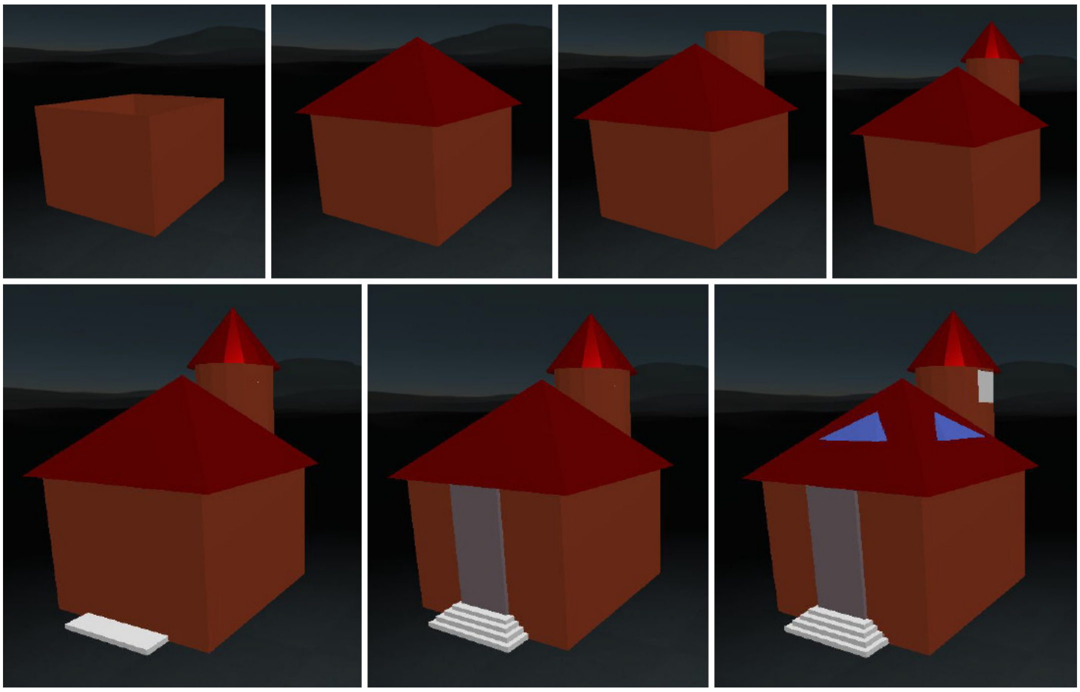


FIGURE 4.4: Steps of the SBS Church exercise.

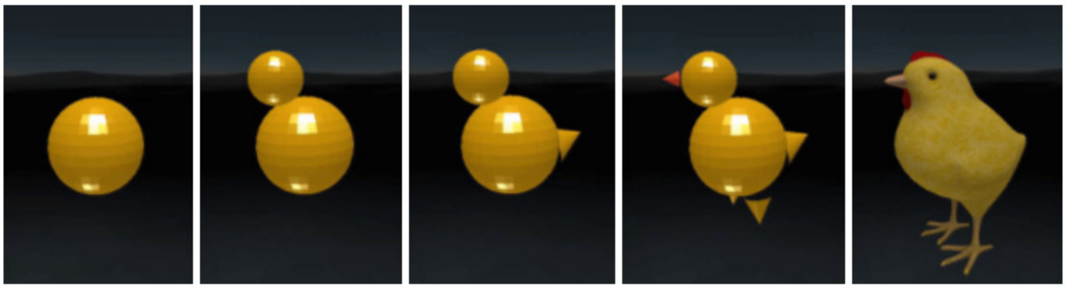


FIGURE 4.5: Steps of the SBS Chicken exercise

To allow the participants to control the steps of the SBS exercises themselves, two buttons were placed inside the virtual environment. By pressing the trigger button while touching one of these buttons with a controller, the example will go one step forward or backward depending on the button. Figure 4.6 shows a screenshot of the

SBS chicken exercise.

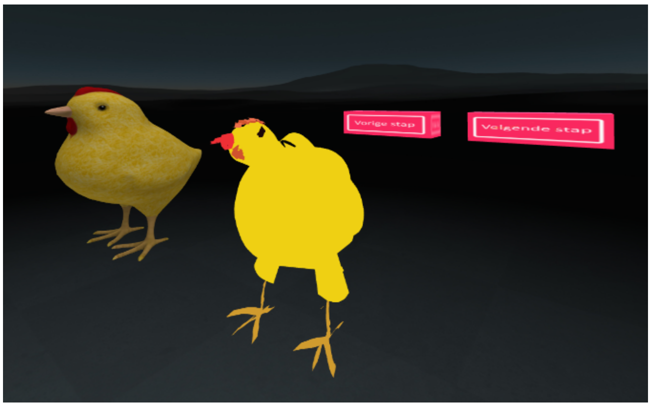


FIGURE 4.6: How the scene looks when doing the SBS chicken exercise.

4.2.1 Spatial Ability Test

A spatial ability test consisting of three parts was created:

- Spatial Reasoning Test with colors (SRT-colors)
- Spatial Reasoning Test with symbols (SRT-symbols)
- Mental Rotations Test (MRT)

Four example questions (1 SRT-colors, 1 SRT-symbols and 2 MRT) were added for the instructions and practice.

SRT

To test the spatial visualization skills in our participants, the Spatial Reasoning Test (SRT) of 123test [64] was used. Spatial visualization ability and spatial reasoning both refer to the ability to visualize three-dimensional objects in your mind and to mentally manipulate them. Figure 4.7 shows one of the questions of the test.

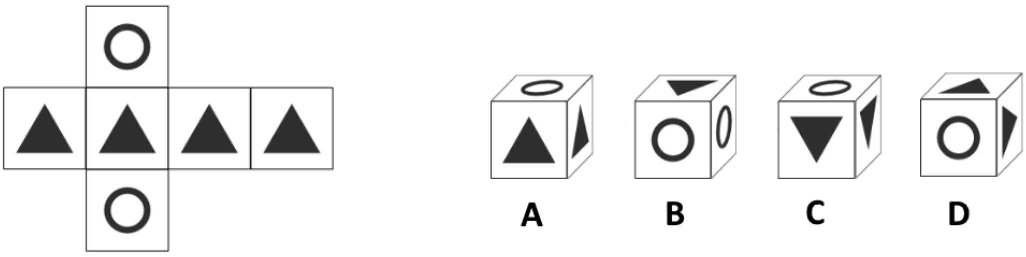


FIGURE 4.7: Example question of the SRT-symbols: Choose the cube that CANNOT be made based on the unfolded cube.

In order to test whether using colors instead of symbols would help the children, it was decided to adjust the test. With the use of Paint.NET, the sides of the cubes were colored. For each question, every symbol was assigned a color, thus maintaining the original questions. In cases where the direction of the symbols were important for solving the question, different colors were used for the different directions. Both the questions and answers in this part were shuffled to make sure that the students would not notice receiving the same test twice. One of the questions of this colored version of the SRT is shown in Figure 4.8.

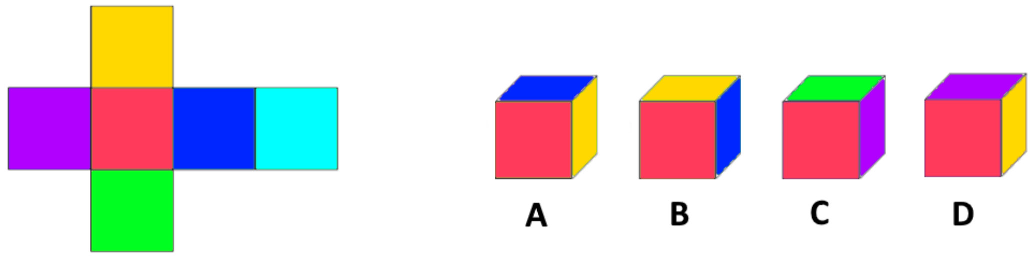


FIGURE 4.8: Example question of the SRT-colors: Choose the cube that CANNOT be made based on the unfolded cube.

4.2.2 MRT

To test our participants mental rotations skills, we used the redrawn Vandenberg and Kuse Mental Rotations Test created by Peters et al. [49]. Figure 4.9 shows one of the MRT example questions.

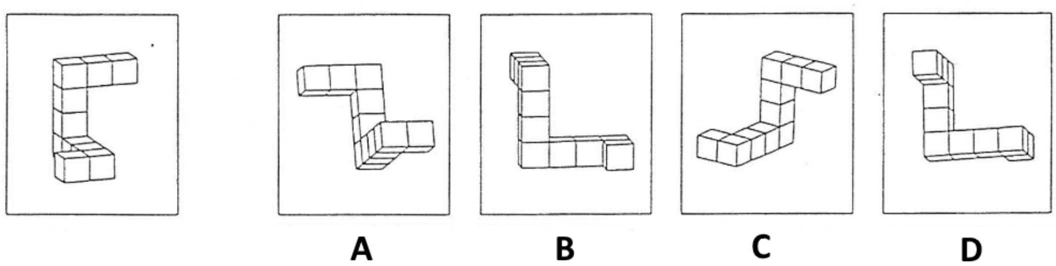


FIGURE 4.9: Example question of the MRT: Choose the 2 figures that can be obtained by rotating the first figure.

4.3 Setup and Procedure

Three participants participated in this trial run. Before starting the experiment, instructions were given and all participants signed a consent form. Then, they made several drawing exercises, completed the spatial ability test and filled in a questionnaire. They all made different drawing exercises, allowing more exercises to be tested. The schedule with the distribution of the drawing exercises can be found in table 4.1.
During the whole experiment, the children were observed closely to see whether things went wrong or were unclear. The time needed for the spatial ability tests and the drawing exercises was measured for each subject.

Time	Participant 1	Participant 2	Participant 3
12:30 - 12:40	General instructions and signing of the consent forms		
12:40 - 13:05	A-Painter - Free drawing - Sphere shape - SBS tree	Spatial ability test	Spatial ability test
13:05 - 13:30	Questionnaire Spatial ability test	A-Painter - Free drawing - Cylinder shape - SBS small church	(Continue spatial ability test)
13:30 - 13:55	(Continue spatial ability test)	Questionnaire (Continue spatial ability test)	A-Painter - Free drawing - Cone shape - SBS chicken Questionnaire
13:55 - 14:00	Wrap up and joint discussion		

TABLE 4.1: Schedule trial run

4.4 Issues

Finding complete and suitable spatial ability tests turned out to be quite challenging. Many well-known tests are incomplete or not available online due to their age. Newer tests often lack confirmations of reliability or are simply not free to use.

4.5 Observations and Results

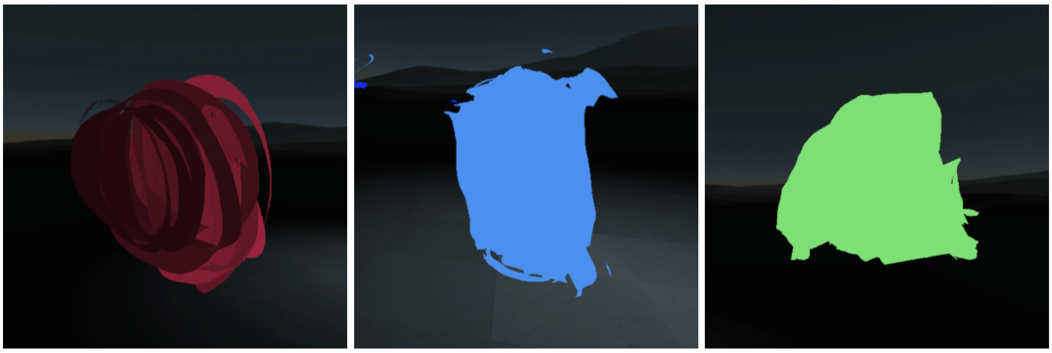
The drawings created during this trial run can be found in Figures 4.10 and 4.11. Tables 4.2 and 4.3 show the time measurements and table 4.4 shows the spatial ability test scores. The translated questionnaire questions are presented in Table 4.5 and the answers in Table 4.6.

A structured overview of the observations made during the experiment:

- The children found the difficulty of the basic figures exactly right, although they would have liked some extra instructions/assistance. They also thought that practising these basic shapes can help them to draw more difficult figures.
- The participants all liked the SBS exercises and thought they were a good way to learn drawing in 3D.
- The exercises are working really well in their current form; no problems were found and everything was clear.
- Participant 3 indicated that they would have liked more steps during their SBS exercise. This participant did the chicken and told us the changes between the last and second-to-last step were too big.
- The children like to chose their own colors for their drawings.
- The process of drawing shows an important part of one's skill and understanding in 3D drawing, something that is not always reflected in the final result. For

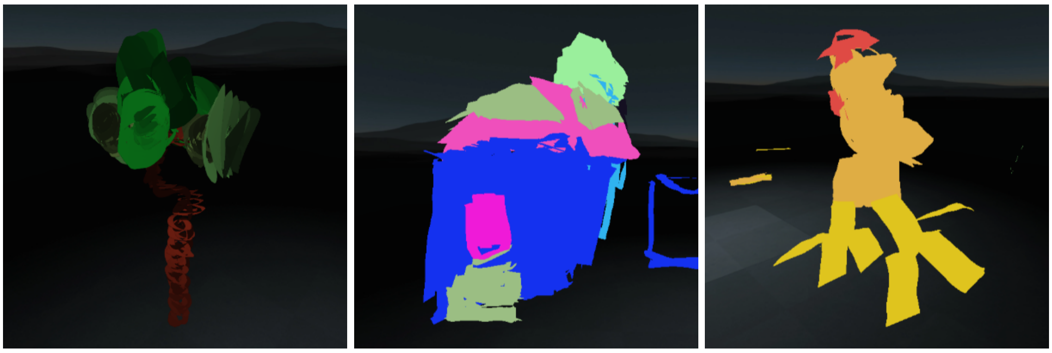
example when a very nice skeleton for a shape is drawn quickly and correctly, but then rough coloring makes the drawing look sloppy and the skeleton invisible.

- Both the spatial ability test and questionnaire proved to be understandable for children of 10/11 years old.
- Two participants found the SRT-colors more difficult than the SRT-symbols, while one found the SRT-colors more simple. Their results however show that they all performed better on the SRT-colors.



(A) Participant 1 Sphere | (B) Participant 2 Cylinder | (C) Participant 3 Cone

FIGURE 4.10: Basic shape drawings. Clicking on them will open a complete view of the drawing in a webbrowser.



(A) Participant 1 Tree | (B) Participant 2 Church | (C) Participant 3 Chicken

FIGURE 4.11: SBS drawings. Clicking on them will open a complete view of the drawing in a webbrowser.

Exercise	**Participant 1**	**Participant 2**	**Participant 3**
Basic shape	1:22 minutes	4:00 minutes	5:19 minutes
SBS drawing	6:04 minutes	16:00 minutes	3:43 minutes

TABLE 4.2: Time measurements for the drawings

Test	Participant 1	Participant 2	Participant 3
SRT-symbols	10 minutes	8 minutes	16 minutes
SRT-colors	17 minutes	11 minutes	9 minutes
MRT	15 minutes	7 minutes	10 minutes

TABLE 4.3: Time measurements for the spatial ability test

Test	Participant 1	Participant 2	Participant 3
SRT-symbols	7/10	3/10	1/10
SRT-colors	10/10	7/10	3/10
MRT	19/20	12/20	13/20

TABLE 4.4: Spatial ability test scores

	Question	Response format	Possible answers
Q1	Did you have any experience with VR before today?	Multiple choice	"No", "Yes, once before", "Yes, a few times or more"
Q2	Have you ever painted in VR before today?	Multiple choice	"No", "Yes, once before", "Yes, a few times or more"
Q3	Are you good at calculating (school subject)	Smiley scale	"Very bad", "Bad", "Not good, not bad", "Good", "Very good"
Q4	Are you good at drawing?	Smiley scale	"Very bad", "Bad", "Not good, not bad", "Good", "Very good"
Q5	Do you like drawing (on paper)?	Smiley scale	"Not at all", "No", "Neutral", "Yes", "Very much"
Q6	How often do you draw?	Open question	-
Q7	Do you like drawing in VR?	Smiley scale	"Not at all", "No", "Neutral", "Yes", "Very much"
Q8	Would you like to get better at drawing in VR?	Smiley scale	"Not at all", "No", "I don't know", "Yes", "Very much"
Q9	What did you think about drawing the basic 3D figures?	Multiple choice	"Very easy", "Easy", "Exactly right", "Difficult", "Very difficult"
Q10	Would you like to have more explanation or help while drawing the basic figures	Multiple choice	"No", "I don't know / Maybe", "Yes"
Q11	If yes, what help would you want to have?	Open question	-
Q12	Do you think practice with these basic figures will help draw more complicated figures?	Smiley scale	"Not at all", "No", "Neutral", "Yes", "Very much"
Q13	Did you like making the 'step-by-step' drawing?	Smiley scale	"Not at all", "No", "Neutral", "Yes", "Very much"
Q14	What did you think about drawing these 'step-by-step' figures?	Multiple choice	"Very easy", "Easy", "Exactly right", "Difficult", "Very difficult"
Q15	Did you think drawing the figure was made easier by these steps?	Smiley scale	"Not at all", "No", "Maybe / I don't know", "Yes", "Very much"
Q16	Would you prefer a different amount of steps?	Multiple choice	"A lot less", "A little less", "Exactly right", "A little more", "A lot more"
Q17	Do you think you can draw a certain figure better after completing the 'step-by-step' assignment?	Smiley scale	"Not at all", "No", "Maybe / I don't know", "Yes", "Very much"
Q18	Do you think 'step-by-step' drawings are a good way to learn 3D drawing?	Smiley scale	"Not at all", "No", "Maybe / I don't know", "Yes", "Very much"
Q19	Anything else you would like to tell us?	Open question	-

TABLE 4.5: Translated questions of the questionnaire used during the trial run.

	Participant 1	Participant 2	Participant 3
Q1	Yes, once before	No	Yes, once before
Q2	No	-	No
Q3	Not good, not bad	Good	Very good
Q4	Good	Not good, not bad	Bad
Q5	Very much	Yes	Neutral
Q6	Every day	Not very often	Not much
Q7	Very much	Very much	Yes
Q8	Very much	Very much	Very much
Q9	Exactly right	Exactly right	Exactly right
Q10	I don't know / Maybe	Yes	Yes
Q11	-	-	By painting in VR more often
Q12	Yes	Very much	Yes
Q13	Very much	Yes	Yes
Q14	Exactly right	Very easy	Exactly right
Q15	Yes	Very much	Yes
Q16	Exactly right	Exactly right	A little more
Q17	Yes	Very much	Yes
Q18	Yes	Very much	Yes
Q19	It was super fun	I really liked this assignment!	No

TABLE 4.6: Translated answers of the questionnaire.

4.6 Conclusions and impact on the main experiment

The main goals of this experiment were testing everything for the main experiment and seeing what could be improved. No problems were found, but some interesting insights were gained. Based on these, some valuable improvements were made.
First of all, the participants indicated that more instructions for the basic shapes were desirable. Therefore, step-by-step instructions have been implemented for these figures as well. Secondly, the SBS chicken was found to have too little steps. Hence, these were extended.
Since the children liked choosing their own colors for their drawings, they are encouraged to do so during the assignments. Only for the graded drawings they are asked to use similar colors in order to facilitate the grading process.
Due to the observation that the drawing process is of importance when assessing one's ability to draw in VR, it was decided to include this process in the grading in the form of bonus points. Screen recordings were made of every session, enabling looking back on everyone's drawing process.
Furthermore, it was tested whether there was a noticeable difference between using colors and symbols for the SRT. The participants scored better when colors were used, however, they already scored well on the SRT-symbols. Since using colors was a solution in case the test was still too difficult for children of this age, which is clearly not the case, there is no need for using the colorized version. Also, the high scores on the SRT-colors leave less room for improvement.
The children also scored quite well on the MRT test. Therefore, it was decided to use the official way of checking their answers during the main experiment: subtracting an incorrect choice from a correct one. This is clearly communicated beforehand so that they can consciously decide whether or not to write down an answer.

Finally, the time measurements were used for creating the schedules of the main experiment. Since steps will be added, 6/7 minutes are assigned per basic shape. For the SBS exercises; 8 minutes are reserved for the tree, 15 minutes for the church and 10 minutes for the chicken. The chicken also got some extra time, since steps will be added.
The participants spent on average 22 minutes on the MRT and SRT-symbols. They were, however, somewhat distracted at times, since one of them was drawing in VR in the same room. This will not be the case during the next experiment; then they will all make the test together in a classroom without distractions. Therefore, it was decided to schedule 25 minutes for the spatial ability test.

5. Main experiment: answering the research questions

The main experiment and its findings have been summarized in the scientific paper. Additional data and background information not included in the paper, can be found in this section. Section 5.1 starts with additional information on the implementation and setup. Encountered issues are discussed in Section 5.2 and Section 5.3 contains all relevant data produced in our experiment.

5.1 Implementation & setup

Based on the new insights gained from the trial run, A-Painter has been improved for the main experiment. The basic shapes now come with a 'Help-button', shown in Figure 5.1. By pressing this button, an exercise similar to the SBS exercises will start; showing possible steps to create the shape one by one. The steps provided for the various shapes can be seen in Figures 5.2 to 5.6.

FIGURE 5.1: The help button

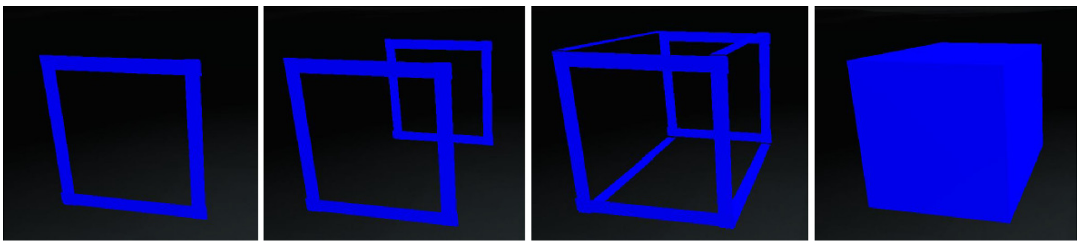


FIGURE 5.2: Possible steps to construct a cube.

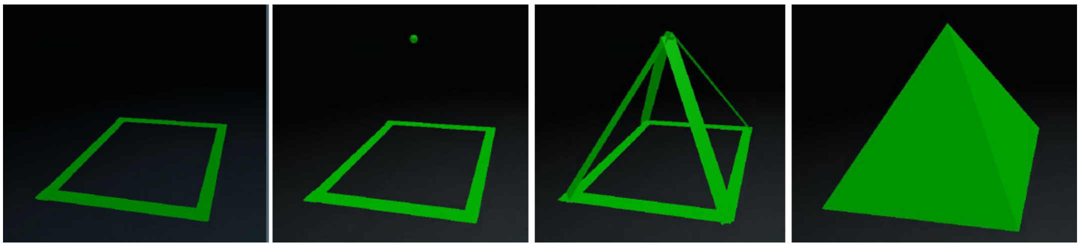


FIGURE 5.3: Possible steps to construct a pyramid.

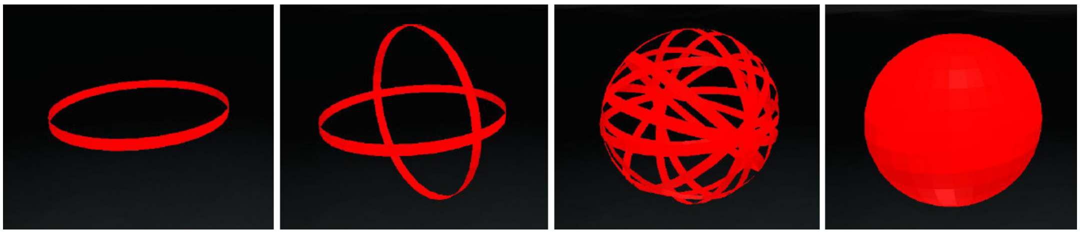


FIGURE 5.4: Possible steps to construct a sphere.

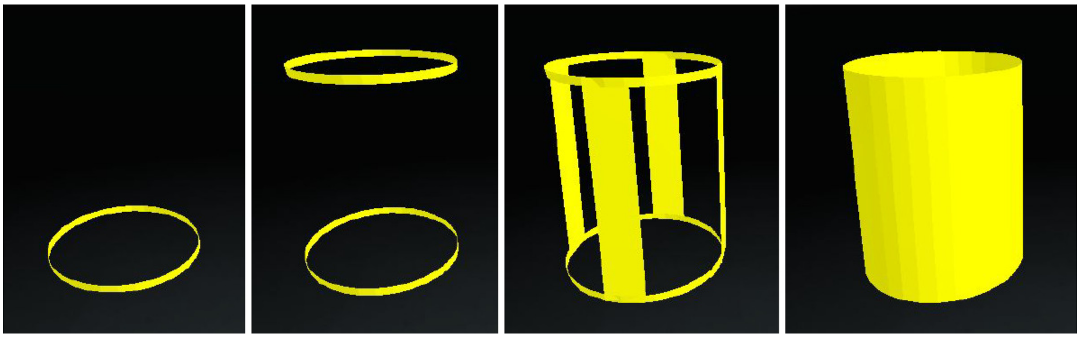


FIGURE 5.5: Possible steps to construct a cylinder.

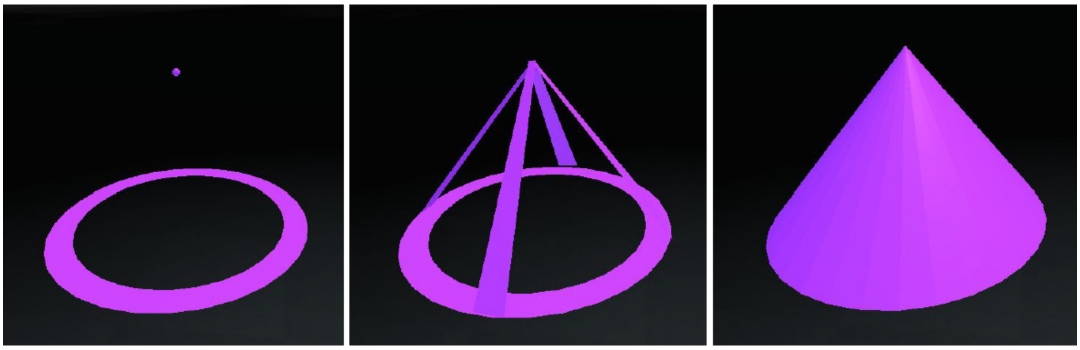
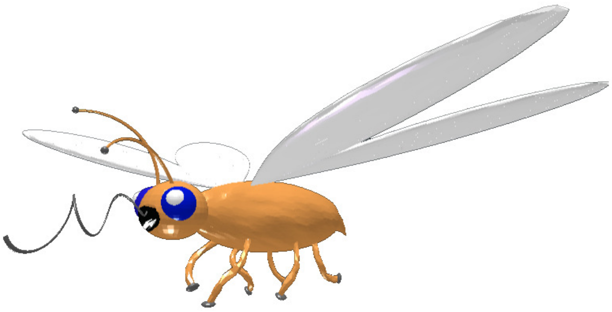


FIGURE 5.6: Possible steps to construct a cone.

During the previous experiment, it was indicated that the SBS chicken exercise had too little steps, with especially a big gap between the last and one-to-last step. Therefore, three more steps have been added. The 3D models of the intermediate steps have also been improved, the new SBS chicken exercise can be found in Figure 5.7.



(A) Firefly

(B) Garden House

FIGURE 5.8: Example figures for the graded drawings. (Click to open the 3D models in a webbrowser)

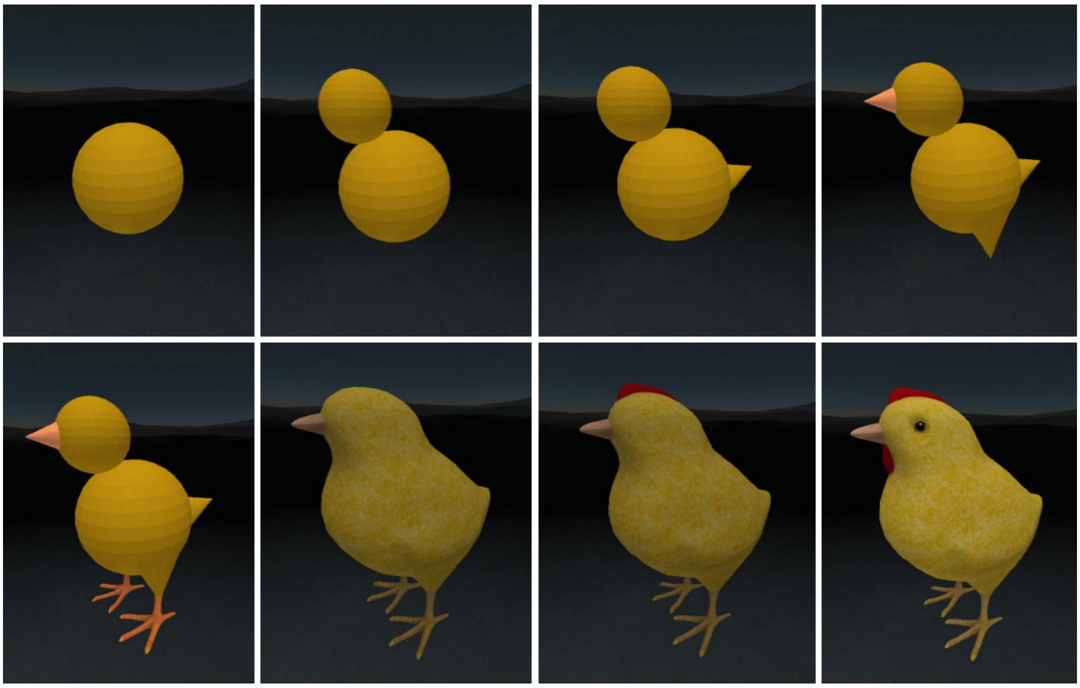


FIGURE 5.7: Steps of the SBS Chicken exercise.

Furthermore, 2D images and 3D models for the graded drawing examples were included. The 2D images are shown in Figure 5.8, clicking them references to the 3D models.

Participant	Pre-test version	Post-test version	Pre GD1	Pre GD2	Post GD1	Post GD2
A1	1	2	A-2D	B-3D	B-3D	A-2D
A2	2	1	B-3D	A-2D	A-2D	B-3D
A3	1	2	A-2D	B-3D	A-2D	B-3D
A4	2	1	A-3D	B-2D	B-2D	A-3D
A5	1	2	B-2D	A-3D	B-2D	A-3D
A6	2	1	A-3D	B-2D	A-3D	B-2D
B1	1	2	B-3D	A-2D	B-3D	A-2D
B2	2	1	A-2D	B-3D	B-3D	A-2D
B3	1	2	B-3D	A-2D	A-2D	B-3D
B4	2	1	B-2D	A-3D	B-2D	A-3D
B5	1	2	A-3D	B-2D	A-3D	B-2D
B6	2	1	B-2D	A-3D	A-3D	B-2D
C1	1	2	-	-	-	-
C2	2	1	-	-	-	-
C3	1	2	-	-	-	-
C4	2	1	-	-	-	-
C5	1	2	-	-	-	-
C6	2	1	-	-	-	-

TABLE 5.1: Participant overview

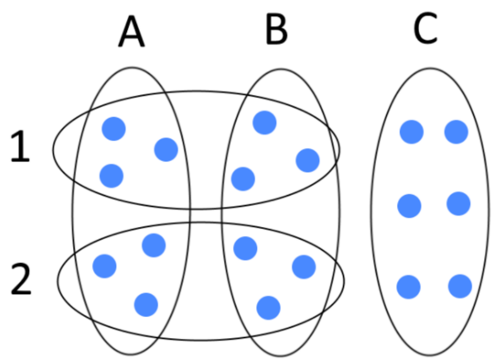


FIGURE 5.9: This figure shows how the groups were created for the division of the 2D/3D examples for the graded drawings. Half of the participants in group A (exercise group) with half of the participants in group B (free drawing group) formed group 1, the other halves of both groups formed group 2.

5.2 Issues

Although most children could not get enough of it, some children wanted to stop painting before the ending of their session. They did not really give a reason, besides that "it was really difficult" and that they "just did not want to do it anymore". As a result participants A6 and B6 have spent considerably less time painting in VR than the other participants. Participant A6 has however finished all their exercises. Furthermore, participant A6 had so much trouble with the controls that it influenced their pre graded drawings.

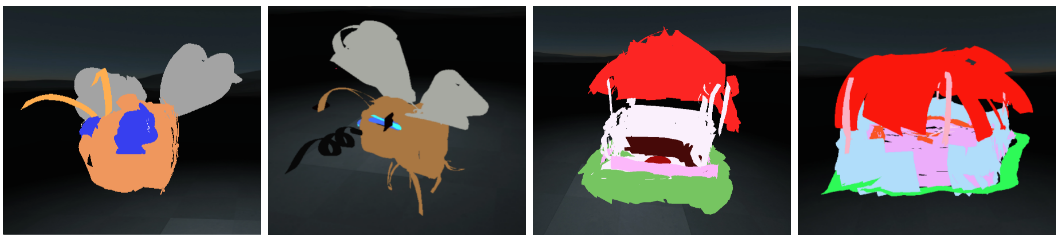
	Group A	**Group B**
Session 1	Instruction + practise - 10 minutes Graded drawing 1 - 12 minutes 2 minute break Graded drawing 2 - 12 minutes	Instruction + practise - 10 minutes Graded drawing 1 - 12 minutes 2 minute break Graded drawing 2 - 12 minutes
Session 2	Cube - 7 minutes Pyramid - 7 minutes Sphere - 6 minutes 2 minute break Cylinder - 6 minutes Cone - 7 minutes	Free drawing - 17 minutes 2 minute break Free drawing - 16 minutes
Session 3	SBS tree - 8 minutes SBS church - 15 minutes 2 minute break SBS chicken - 10 minutes	Free drawing - 17 minutes 2 minute break Free drawing - 16 minutes
Session 4	Final practise - 5 minutes Graded drawing 1 - 12 minutes 2 minute break Graded drawing 2 - 12 minutes	Final practise - 5 minutes Graded drawing 1 - 12 minutes 2 minute break Graded drawing 2 - 12 minutes

TABLE 5.2: Schedules of the individual VR painting sessions.

5.3 Data & Results

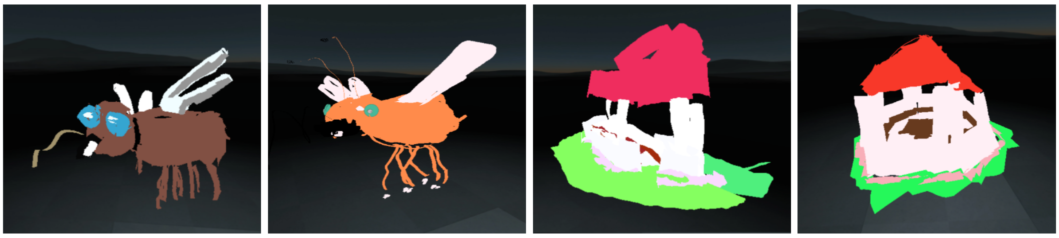
- The graded drawings of the participants can be found in Figures 5.10 through 5.21. Clicking on them will open a complete view of the drawing in a web-browser.
- All final grades can be found in Table 5.3.
- The scores for the spatial ability tests, separately for SRT and MRT, are listed in Table 5.4.
- The translated questions and answers of the pre-questionnaire can be found in Tables 5.5 to 5.8.
- Tables 5.9 to 5.15 contain the translated questions and answers on the post-questionnaires.

FIGURE 5.10: Participant A1



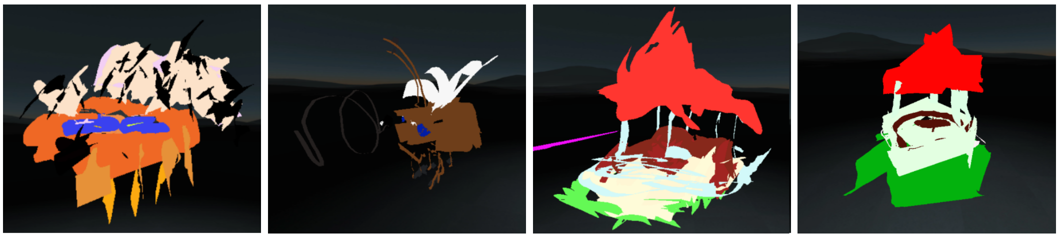
(A) Pre A-2D (B) Post A-2D (C) Pre B-3D (D) Post B-3D

FIGURE 5.11: Participant A2



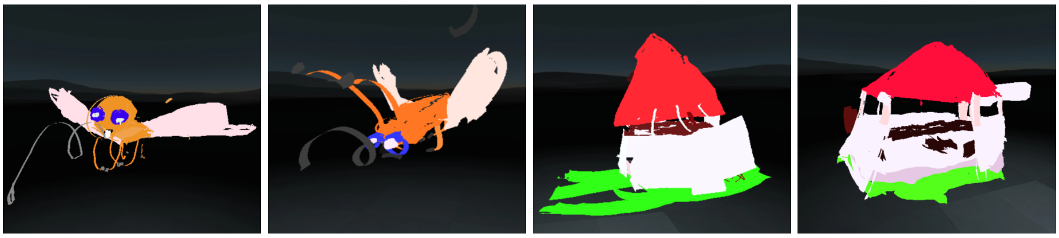
(A) Pre A-2D (B) Post A-2D (C) Pre B-3D (D) Post B-3D

FIGURE 5.12: Participant A3



(A) Pre A-2D (B) Post A-2D (C) Pre B-3D (D) Post B-3D

FIGURE 5.13: Participant A4

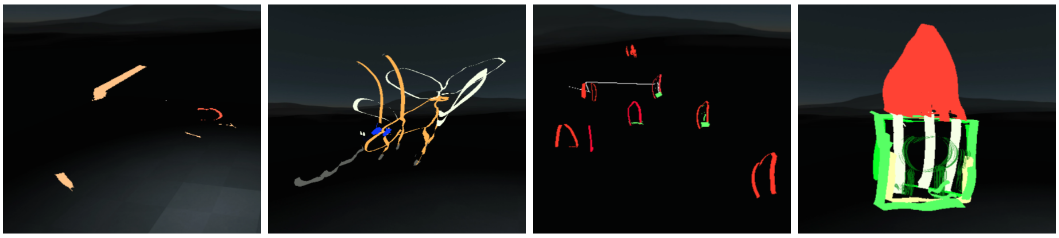


(A) Pre A-3D (B) Post A-3D (C) Pre B-2D (D) Post B-2D

FIGURE 5.14: Participant A5

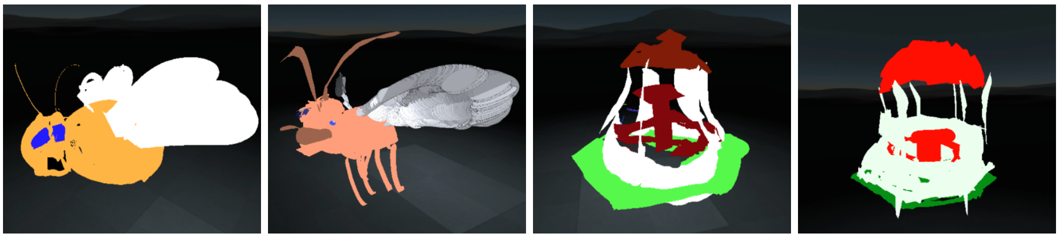
(A) Pre A-3D (B) Post A-3D (C) Pre B-2D (D) Post B-2D

FIGURE 5.15: Participant A6



(A) Pre A-3D (B) Post A-3D (C) Pre B-2D (D) Post B-2D

FIGURE 5.16: Participant B1

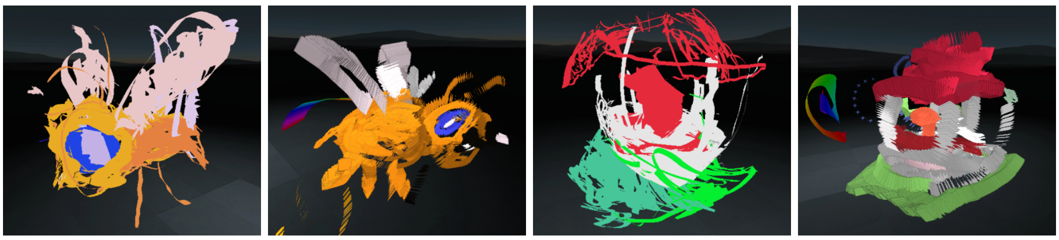


(A) Pre A-2D (B) Post A-2D (C) Pre B-3D (D) Post B-3D

FIGURE 5.17: Participant B2

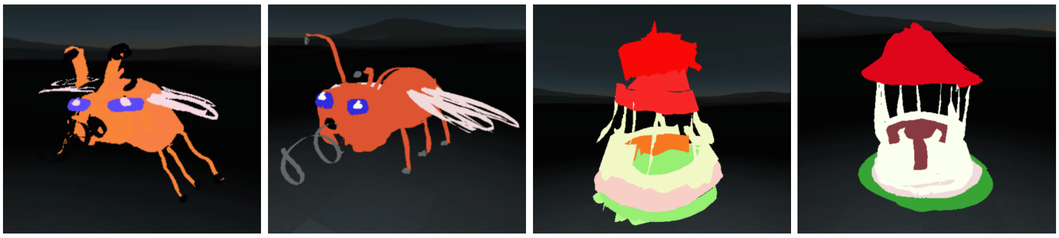
(A) Pre A-2D (B) Post A-2D (C) Pre B-3D (D) Post B-3D

FIGURE 5.18: Participant B3



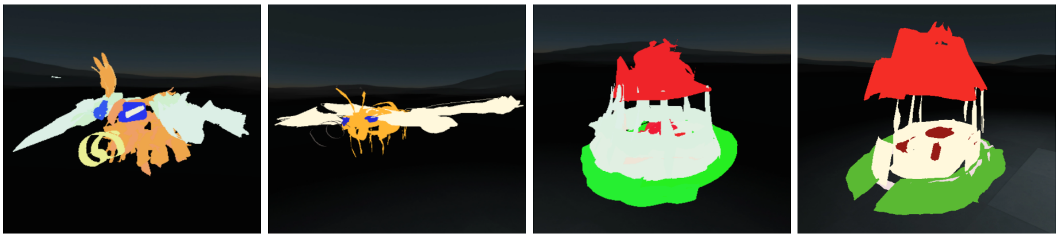
(A) Pre A-2D (B) Post A-2D (C) Pre B-3D (D) Post B-3D

FIGURE 5.19: Participant B4



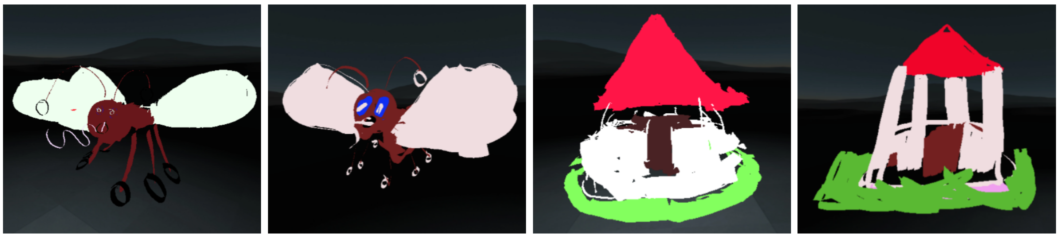
(A) Pre A-3D (B) Post A-3D (C) Pre B-2D (D) Post B-2D

FIGURE 5.20: Participant B5



(A) Pre A-3D (B) Post A-3D (C) Pre B-2D (D) Post B-2D

FIGURE 5.21: Participant B6



(A) Pre A-3D (B) Post A-3D (C) Pre B-2D (D) Post B-2D

		Pre drawings													**Post drawings**													
		Graded by the art teacher					Graded by the experimenter					Combined			Graded by the art teacher					Graded by the experimenter					Combined		
P	Ex.	A	B	C	D	T	A	B	C	D	T	C	E	C+	A	B	C	D	T	A	B	C	D	T	C	E	C+
A1	2D	4	3	4	3	7	4	2	4	3	6,5	6,8	0	**6,8**	5	4	4	4	8.5	4	3	4	3	7	7.8	0	**7.8**
	3D	5	4	5	5	9,5	5	5	5	4	9,5	9,5	0,5	**10**	4	3	4	4	7.5	4	3	3	3	6.5	7	0.5	**7.5**
A2	2D	4	3	1	3	5,5	2	2	2	3	4,5	5	0	**5**	5	4	4	4	8.5	5	4	4	4	8.5	8.5	1.5	**10**
	3D	3	2	3	3	5,5	2	2	1	2	3,5	4,5	0	**4,5**	5	5	4	4	9	5	5	4	4	9	9	0.5	**9.5**
A3	2D	0	1	1	0	1	0	1	0	0	0,5	0,8	0	**0,8**	5	3	4	4	8	5	3	4	3	7.5	7.8	0	**7.8**
	3D	4	2	2	3	5,5	5	2	4	1	6	5,8	0	**5,8**	4	2	3	3	6	4	3	3	3	6.5	6.3	1	**7.3**
A4	2D	3	1	2	2	4	3	2	2	2	4,5	4,3	0	**4,3**	4	3	3	3	6.5	4	4	3	4	7.5	7	1	**8**
	3D	5	4	4	4	8,5	4	4	4	4	8	8,3	0,5	**8,8**	4	4	2	3	6.5	3	4	4	4	7.5	7	0	**7**
A5	2D	3	2	2	3	5	4	3	3	3	6,5	5,8	1,5	**7,3**	5	3	3	4	7.5	5	3	3	3	7	7.3	0.5	**7.8**
	3D	5	3	3	4	7,5	5	3	4	4	8	7,8	1,5	**9,3**	5	5	5	4	9.5	5	4	5	3	8.5	9	0.5	**9.5**
A6	2D	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0	0	1	0	0	0	0.5	0.3	0	**0.3**
	3D	0	0	0	0	0	0	0	0	0	0	0	0	**0**	2	2	1	1	3	3	2	2	2	4.5	3.8	0	**3.8**
B1	2D	3	1	1	2	3,5	0	2	0	1	1,5	2,5	0	**2,5**	5	2	2	2	5.5	2	2	2	2	4	4.8	0	**4.8**
	3D	3	2	2	2	4,5	4	2	3	2	5,5	5	1	**6**	5	4	4	4	8.5	5	4	4	4	8.5	8.5	0	**8.5**
B2	2D	0	3	0	2	2,5	0	3	0	4	3,5	3	0	**3**	3	2	2	2	4.5	2	2	1	2	3.5	4	0	**4**
	3D	4	3	3	3	6,5	5	3	5	3	8	7,3	1	**8,3**	5	4	4	4	8.5	5	4	4	4	8.5	8.5	0	**8.5**
B3	2D	3	1	1	1	3	3	2	2	2	4,5	3,8	0	**3,8**	2	2	2	3	4.5	1	2	1	2	3	3.8	0	**3.8**
	3D	3	1	1	1	3	4	3	1	0	4	3,5	0	**3,5**	4	2	2	3	5.5	5	4	4	3	8	6.8	0	**6.8**
B4	2D	4	2	2	3	5,5	4	2	4	3	6,5	6	1,5	**7,5**	5	5	5	5	10	5	4	5	4	9	9.5	1.5	**10**
	3D	4	4	5	4	8,5	5	3	5	4	8,5	8,5	1,5	**10**	5	4	5	4	9	5	4	5	5	9.5	9.3	1.5	**10**
B5	2D	4	4	4	4	8	4	4	3	3	7	7,5	1	**8,5**	5	3	3	3	7	4	3	3	3	6.5	6.8	1	**7.8**
	3D	4	3	2	3	6	4	3	2	3	6	6	0	**6**	4	5	5	5	9.5	5	4	4	3	8	8.8	1	**9.8**
B6	2D	3	3	2	3	5,5	3	3	2	3	5,5	5,5	0	**5,5**	3	2	2	2	4.5	2	2	1	1	3	3.8	0	**3.8**
	3D	5	4	5	5	9,5	5	4	5	4	9	9,3	0,5	**9,8**	5	4	5	5	9.5	4	4	5	5	9	9.3	0	**9.3**

TABLE 5.3: The grades and how they are constructed, separately for both graders. The combined grades can be found under C, the drawing process bonuses under E and the combined grades including the bonus under C+.

	Pre-SRT	Post-SRT	Pre-MRT	Post-MRT
A1	4	3	6	3
A2	10	9	20	20
A3	8	7	19	18
A4	7	7	5	14
A5	6	4	11	13
A6	4	6	7	5
B1	6	9	20	16
B2	9	5	8	12
B3	5	4	16	10
B4	5	8	15	14
B5	7	6	18	17
B6	8	9	11	13
C1	3	9	5	10
C2	10	6	18	18
C3	4	5	8	10
C4	8	9	10	20
C5	5	5	12	18
C6	6	4	14	18

TABLE 5.4: The scores of the spatial ability tests

	Question	Response format	Possible answers
Q1	Do you have experience with Virtual Reality?	Multiple choice	"No", "Yes, tried it once", "Yes, tried it multiple times"
Q2	Have you ever drawn or painted in Virtual Reality? (for example with Tilt Brush)	Multiple choice	"No", "Yes, once", "Yes, multiple times"
Q3	Do you play computergames? This means all digital games, so for example on the Playstation or on your mobile phone as well.	Multiple choice	"No", "Yes, sometimes", "Yes, regularly", "Yes, a lot"
Q4	Can you describe 1) What kind of games you like to play, 2) On what platform (computer, Playstation, tablet etc.) and 3) How often?	Open question	-
Q5	Are you good at math?	Smiley scale	"Very bad", "Bad", "Not good, not bad", "Good", "Very good"
Q6	Are you good at drawing?	Smiley scale	"Very bad", "Bad", "Not good, not bad", "Good", "Very good"
Q7	Do you like drawing/painting?	Smiley scale	"Not at all", "No", "Neutral", "Yes", "Yes, very much"
Q8	Approximately how often do you draw/paint?	Open question	-
Q9	What way of drawing do you like best? (For example with paint on paper, or on the computer with Paint)	Open question	-
Q10	Can you explain why you like this way of drawing/painting best?	Open question	-
Q11	Would you like to learn to draw/paint better?	Smiley scale	"Not at all", "Not really", "I don't know", "Yes", "Love to"
Q12	Would you like to learn to draw better in Virtual Reality?	Smiley scale	"Not at all", "Not really", "I don't know", "Yes", "Love to"
Q13	Is there anything else you want to tell us?	Open question	-

TABLE 5.5: The translated questions of the pre-questionnaire.

	Q1	Q2	Q3	Q4
A1	Yes, tried it once	Yes, once	Yes, a lot	Minecraft, Pixelgun, Kami
A2	Yes, tried it once	No	Yes, a lot	I play Call of Duty on the Playstation often, almost every day.
A3	Yes, tried it multiple times	No	Yes, regularly	1. I like to play games such as Crossy Road, Minion Rush and Subway Surfers. I also like to play Angry Birds. 2. I always play on my iPad, sometimes at the Wii and DS and rarely at the PS. 3) Mostly in my spare time. I also often read a comic, magazine or book, but I mostly play games.
A4	Yes, tried it once	Yes, once	Yes, regularly	Playstation once a week
A5	No	No	Yes, regularly	I play Musical.ly, Minecraft on my phone and iPad.
A6	No	No	Yes, a lot	Computer, tablet
B1	Yes, tried it once	No	Yes, sometimes	1) Mario Kart 8 deluxe 2) Nintendo Switch 3) 5 times a week
B2	No	No	Yes, a lot	1) Horror 2) Playstation, iPad and computer
B3	Yes, tried it once	No	Yes, sometimes	1) I prefer to play Minecraft 2) Xbox One 3) 10 minutes a day
B4	Yes, tried it once	No	Yes, regularly	Roblox on the iPad, Mario Kart on the Wii, Skylanders on the Wii, Kamie2 on the iPad, Mario Tennis on the Wii, Pianotils on the iPad and internet games, for example A10.
B5	Yes, tried it once	No	Yes, regularly	I don't play games very often but mostly Musical.ly and Tigerball on my iPad and phone.
B6	No	No	Yes, a lot	Computer, tablet
C1	Yes, tried it multiple times	No	Yes, sometimes	Call of Duty, Playstation 4
C2	Yes, tried it multiple times	No	Yes, a lot	1) Adventure, Action 2) DS, iPad 3) One hour a day
C3	Yes, tried it once	Yes, once	Yes, a lot	1) Pixelgun, Kami, Minecraft 2) iPad 3) Every day
C4	No	No	Yes, sometimes	I almost never play games
C5	No	No	Yes, regularly	Minecraft (iPad, computer, Xbox 360), Starstable (computer), Roblox (iPad, computer), Fortza (Xbox)
C6	Yes, tried it once	No	Yes, regularly	I play sometimes GTA on the Playstation and on the iPad: Minecraft, Roblox, Pixelfun.

TABLE 5.6: The translated answers on pre-questionnaire questions 1-4.

	Q5	Q6	Q7	Q8	Q9
A1	Good	Very good	Yes, very much	I draw every day and paint once per week	Paper
A2	Very good	Not good, not bad	Yes	Every day at school	With pencil
A3	Not good, not bad	Good	Yes	A few times a month, but not very often.	I mostly prefer a pen or pencil on a paper sheet.
A4	Very good	Not good, not bad	Yes, very much	3 or 4 times a week	Everything
A5	Not good, not bad	Bad	Neutral	Once a week	On paper
A6	Not good, not bad	Bad	Neutral	Not often, sometimes	With paint and on the computer
B1	Good	Good	Yes, very much	10 times a week	On the Ipad Pro
B2	Good	Very good	Yes, very much	Often	Computer and in real life
B3	Good	Not good, not bad	Yes	I mostly draw 15 minutes	Paint on paper
B4	Good	Very good	Yes, very much	Quite often	On paper
B5	Good	Bad	Neutral	Sometimes I try to copy things	Just normal drawing
B6	Good	Very good	Yes, very much	Not often but a lot	On the computer or paper
C1	Good	Not good, not bad	Yes, very much	10 times	Paper
C2	Very good	Good	Neutral	Now and then	Paper and pencil
C3	Not good, not bad	Not good, not bad	Yes, very much	Quite often	Color pencils on paper
C4	Very good	Good	Yes	I almost never paint, I draw quite often	With paint on paper
C5	Not good, not bad	Very good	Yes, very much	Almost every day	Paint, paper
C6	Not good, not bad	Not good, not bad	Yes, very much	Two times a month	With pencil on paper

TABLE 5.7: The translated answers on pre-questionnaire questions 5-9.

	Q10	Q11	Q12	Q13
A1	Because I can draw cartoons and find that awesome and on the computer difficult	Love to	Love to	No
A2	Because it is not difficult to do.	Yes	I don't know	No
A3	Well, I am not very good with computers.	Yes	Yes	No
A4	No	Love to	Love to	No
A5	Because I find it the most enjoyable to just draw on paper.	Yes	Yes	No
A6	-	Yes	Yes	No
B1	No, not really	Yes	Love to	No
B2	I want to try something new.	Love to	Love to	No
B3	I find it easier on paper	I don't know	I don't know	Virtual Reality can be very scary and cool
B4	Because you can use so many colors and ways.	Love to	Love to	-
B5	Because you can still erase which is not the case with paint and with the iPad you didn't completely do it yourself and is it more difficult.	Yes	Yes	No
B6	On paper with pencil is easy, with paint things don't become very beautiful and it will be a mess.	Love to	Yes	No
C1	No	Love to	Love to	No
C2	Because pencils do not leak	I don't know	I don't know	Not really
C3	I can draw very beautiful with those.	I don't know	Yes	No
C4	I just like that better	Yes	Not really	No
C5	No idea!	Love to	Love to	No
C6	Because you can erase it then	Love to	Love to	No

TABLE 5.8: The translated answers on pre-questionnaire questions 10-13.

	Question	Response format	Possible answers
Q1	What did you think about the past weeks' Virtual Reality drawing sessions?	Smiley scale	"Not fun at all", "Not fun", "Neutral", "Fun", "A lot of fun"
Q2	What did you like most?	Multiple choice	"To copy the figures", "Basic 3D shapes", "Step-by-step assignments", "Freestyle drawing"
Q3	What did you like least?	Multiple choice	"To copy the figures", "Basic 3D shapes", "Step-by-step assignments", "Freestyle drawing"
Q4	Do you think the sessions helped you become better at drawing in VR?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q5	What do you think is the best way to improve at VR drawing?	Multiple choice	"To copy the figures", "Basic 3D shapes", "Step-by-step assignments", "Freestyle drawing"
Q6	What was the hardest part of drawing in VR for you?	Open question	-
Q7	Would you like to get (even) better at drawing in VR?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q8	What is now your favorite method of drawing/painting? (For example with paint on paper, on the computer with Paint or in Virtual Reality)	Open question	-
Q9	Can you explain why this is your favorite method? (You can skip this question if you gave the same answer above as in the previous questionnaire)	Open question	-
Q10	Did you use the 'Help' button?	Multiple choice	"Never", "One or two times", "A few times", "With (almost) every shape"
Q11	Did you think this function was useful?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q12	What shape was hardest to draw?	Multiple choice (with images)	"Cube", "Pyramid", "Sphere", "Cylinder", "Cone"
Q13	Do you think any other shape(s) should be added? (You may draw them if you want)	Open question	-
Q14	Do you think practice with these basic shapes will help you draw harder to draw shapes?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q15	Do you think drawing figures was easier with the use of steps?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"

	Question	**Response format**	**Possible answers**
Q16	Would you rather have more or less steps?	Multiple choice	"A lot less", "A little less", "This was exactly right", "A little more", "A lot more"
Q17	Do you think your ability to draw a certain figure increases after completing a 'step-by-step' drawing of this figure?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q18	Do you think 'step-by-step' drawings are a good way to learn drawing in 3D?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q19	Do you think copying a figure is a good way to learn drawing in 3D?	Smiley scale	"Not at all", "No", "Maybe/I don't know", "Yes", "Yes, very much"
Q20	Do you think you will draw more often using other methods (for example on paper) after drawing in VR?	Multiple choice	"No", "Maybe", "I think so", "Yes, definitely"
Q21	What did you think about the length of the practice sessions?	Multiple choice	"Much too long", "Too long", "Exactly right", "Too short", "Much too short"
Q22	If you could draw in VR more often at school, how often would you want to?	Multiple choice	"Never", "Maybe once or twice ever", "Every month", "Every week", "Every day"
Q23	Do you have anything else you want to tell us?	Open question	-

TABLE 5.9: Translated post-questionnaire questions for group A.

	Question	**Response format**	**Possible answers**
Q1	What did you think about the past weeks' Virtual Reality drawing sessions?	Smiley scale	"Not fun at all", "Not fun", "Neutral", "Fun", "A lot of fun"
Q2	What did you like most?	Multiple choice	"To copy the figures", "Freestyle drawing"
Q3	Do you think the sessions helped you become better at drawing in VR?	Smiley scale	"Not at all", "No", "Maybe /I don't know","Yes", "Yes, very much"
Q4	What do you think is the best way to improve at VR drawing?	Multiple choice	"To copy the figures", "Freestyle drawing"
Q5	What was the hardest part of drawing in VR for you?	Open question	-
Q6	Would you like to get (even) better at drawing in VR?	Smiley scale	"Not at all", "Not really", "I don't know","Yes", "Love to!"
Q7	What is now your favorite method of drawing/painting? (For example with paint on paper, on the computer with Paint or in Virtual Reality)	Open question	-
Q8	Can you explain why this is your favorite method? (You may skip this question if you gave the same answer above as in the previous questionnaire)	Open question	-
Q9	Do you think copying a figure is a good way to learn drawing in 3D?	Smiley scale	"Not at all", "No", "Maybe /I don't know", "Yes", "Yes, very much"
Q10	Do you think you will draw more often using other methods (for example on paper) after drawing in VR?	Multiple choice	"No", "Maybe", "I think so" , "Yes, definitely"
Q11	What did you think about the length of the practice sessions?	Multiple choice	"Much too long", "Too long" , "Exactly right", "Too short", "Much too short"
Q12	If you could draw in VR more often at school, how often would you want to?	Multiple choice	"Never", "Maybe once or twice ever", "Every month", "Every week", "Every day"
Q13	Do you have anything else you want to tell us?	Open question	-

TABLE 5.10: Translated post-questionnaire questions for group B.

	Q1	Q2	Q3	Q4	Q5	Q6
A1	A lot of fun	Freestyle drawing	To copy the figures	Yes	Basic 3D shapes	Drawing uniformly
A2	Fun	Freestyle drawing	To copy the figures	Yes	Step-by-step assignments	Picking the colors
A3	A lot of fun	Freestyle drawing	Basic 3D shapes	Yes	Step-by-step assignments	I only had trouble at the start, because I did not know how anything worked
A4	Fun	Freestyle drawing		Yes	Step-by-step assignments	The café
A5	Fun	Freestyle drawing	Step-by-step assignments	Yes	Basic 3D shapes	Drawing the fly
A6	Neutral	Freestyle drawing	To copy the figures	Maybe /I don't know	Basic 3D shapes	The circle a house

TABLE 5.11: Translated answers on post questionnaire A, questions 1-6.

	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
A1	Yes	Paper and paint	Because you can draw uniformly	A few times	Yes	Sphere and Cone	?	Yes
A2	I don't know	Paper	Because I like it more	Never	Maybe/ I don't know	Cone	No	Yes
A3	Yes, very much	Before drawing in VR I liked drawing on paper the most, but now I definitely like drawing in VR the most	I really like that you can walk around and draw in 3D	Never	Yes	Cone	No	Yes, very much
A4	Yes, very much	Paint and VR		One or two times	Yes	Cone	No	Yes
A5	I don't know	In VR	It is fun to decorate something from the inside	One or two times	Yes	Cone	No, not really	Yes
A6	I don't know	Paper		With (almost) every shape	Yes	Cylinder		Yes

TABLE 5.12: Translated answers on post questionnaire A, questions 7-14.

	Q15	Q16	Q17	Q18	Q19	Q21	Q22	Q23	Q24
A1	Yes	A little more	Yes	Yes	Yes	Yes, definitely	Too short	Every week	No
A2	Maybe /I don't know	This was exactly right	No	Maybe /I don't know	Maybe /I don't know	Maybe	Exactly right	Every week	No
A3	Yes, very much	This was exactly right	Maybe /I don't know	Yes, very much	Yes	Maybe	Too short	Every day	No
A4	Maybe /I don't know	This was exactly right	Maybe /I don't know	Yes	Maybe /I don't know	Maybe	Exactly right	Every day	
A5	Yes	A little less	Maybe /I don't know	Yes	Yes, very much	Maybe	Exactly right	Every month	It was super fun!!!
A6	Yes	A little more	Yes	Yes, very much	Yes	Maybe	Too long	Maybe once or twice ever	No

TABLE 5.13: Translated answers on post questionnaire A, questions 15-24.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
B1	Fun	To copy the figures	Yes	To copy the figures	3D	Love to!	Computer
B2	A lot of fun	Freestyle drawing	Yes	Freestyle drawing	Remembering the buttons		VR and paper
B3	Fun	Freestyle drawing	Yes, much better	To copy the figures	Copying a drawing	Yes	VR
B4	A lot of fun	Both	Yes, much better	To copy the figures	Copying the polar bear	Love to!	VR
B5	A lot of fun	Freestyle drawing	Yes	To copy the figures	The fact it is 3D and a lot different from drawing normally	Love to!	VR
B6	Neutral	Freestyle drawing	Maybe/I don't know	To copy the figures	Drawing the farmhouse	I don't know	On paper and the computer

TABLE 5.14: Translated answers on post questionnaire B, questions 1-7.

	Q8	Q9	Q10	Q11	Q12	Q13
B1	No	Yes, very much	Yes, definitely	Exactly right	Every week	No
B2	VR because it is not real, you're in another world for a little while. Paper because you can draw everything in different styles.	Yes	No	Exactly right	Every day	It was super fun!
B3	I think it's a pleasure	Yes	I think so	Exactly right	Every week	VR is cool
B4	Because it is new to me	Yes, very much	I think so	Exactly right	Every week	It was super fun. I hope you will come again and have fun
B5	Because it is different from normal	Yes	Maybe	Exactly right	Every day	It was a lot of fun
B6		Yes	I think so	Exactly right	Every month	No

TABLE 5.15: Translated answers on post questionnaire B, questions 8-13.

Bibliography

[1] *A-Painter*. https://blog.mozvr.com/a-painter/. Accessed: 2017-03-07.

[2] Kiyofumi Abe, Hideo Saito, and Shinji Ozawa. "3-D drawing system via hand motion recognition from two cameras". In: *Systems, Man, and Cybernetics, 2000 IEEE International Conference on*. Vol. 2. IEEE. 2000, pp. 840–845.

[3] Maizam Alias, Thomas R Black, and David E Gray. "Effect of instruction on spatial visualization ability in civil engineering students". In: *International Education Journal* 3.1 (2002).

[4] Maizam Alias, David E Gray, and Thomas R Black. "Attitudes towards sketching and drawing and the relationship with spatial visualisation ability in engineering students". In: *International Education Journal* 3.3 (2002), pp. 165–175.

[5] Lisa Avila and Mike Bailey. "Art in the Digital Age". In: *IEEE Computer Graphics and Applications* 36.4 (2016), pp. 6–7.

[6] Sasha A Barab et al. "Virtual solar system project: Building understanding through model building". In: *Journal of research in science teaching* 37.7 (2000), pp. 719–756.

[7] David Ben-Chaim, Glenda Lappan, and Richard T Houang. "Adolescents' ability to communicate spatial information: Analyzing and effecting students' performance". In: *Educational Studies in Mathematics* 20.2 (1989), pp. 121–146.

[8] George K Bennett, Harold G Seashore, and Alexander G Wesman. "The differential aptitude tests: An overview". In: *Journal of Counseling & Development* 35.2 (1956), pp. 81–91.

[9] Meredith Bricken. "Virtual reality learning environments: potentials and challenges". In: *ACM SIGGRAPH Computer Graphics* 25.3 (1991), pp. 178–184.

[10] William Bricken. "Learning in Virtual Reality." In: (1990).

[11] Arthur W Brody and Chris Hartman. "Painting in space". In: *Photonics West 2001-Electronic Imaging*. International Society for Optics and Photonics. 2001, pp. 602–614.

[12] John Seely Brown, Allan Collins, and Paul Duguid. "Situated cognition and the culture of learning". In: *Educational researcher* 18.1 (1989), pp. 32–42.

[13] Jeff Butterworth et al. "3DM: A three dimensional modeler using a head-mounted display". In: *Proceedings of the 1992 symposium on Interactive 3D graphics*. ACM. 1992, pp. 135–138.

[14] James J Cummings and Jeremy N Bailenson. "How immersive is enough? A meta-analysis of the effect of immersive technology on user presence". In: *Media Psychology* 19.2 (2016), pp. 272–309.

[15] Richard De Lisi and Jennifer L Wolford. "Improving children's mental rotation accuracy with computer game playing". In: *The Journal of genetic psychology* 163.3 (2002), pp. 272–282.

[16] Michael F Deering. "HoloSketch: a virtual reality sketching/animation tool". In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 2.3 (1995), pp. 220–238.

[17] Michele D Dickey. "Teaching in 3D: Pedagogical affordances and constraints of 3D virtual worlds for synchronous distance learning". In: *Distance education* 24.1 (2003), pp. 105–121.

[18] Andreas Dünser et al. "Virtual and augmented reality as spatial ability training tools". In: *Proceedings of the 7th ACM SIGCHI New Zealand chapter's international conference on Computer-human interaction: design centered HCI*. ACM. 2006, pp. 125–132.

[19] Joseph Flaherty. *3Doodler Lets You Hand-Draw 3-D Objects*. https://www.wired.com/2013/02/3doodler/. Accessed: 2017-04-09. 2013.

[20] Chris Fowler. "Virtual reality and learning: Where is the pedagogy?" In: *British journal of educational technology* 46.2 (2015), pp. 412–422.

[21] Georg Gittler and Judith Glück. "Differential transfer of learning: Effects of instruction in descriptive geometry on spatial test performance". In: *Journal of Geometry and Graphics* 2.1 (1998), pp. 71–84.

[22] JORGE MARTÍN GUTIERREZ and MELCHOR GARCÍA DOMÍNGUEZ. "Using 3D Virtual Technologies to Train Spatial Skills in Engineering". In: ().

[23] Kristan Harris and Denise Reid. "The influence of virtual reality play on children's motivation". In: *Canadian Journal of Occupational Therapy* 72.1 (2005), pp. 21–29.

[24] Franklin Houser. *Best 3D Pen 2017 – Guide to 95 3D Pens + 3Doodler Review*. https://all3dp.com/best-3d-pen-buyers-guide-3d-printing-pens/. Accessed: 2017-04-09. 2017.

[25] Nady Hoyek et al. "The use of the Vandenberg and Kuse mental rotation test in children". In: *Journal of Individual Differences* (2011).

[26] Hsiu-Mei Huang, Ulrich Rauch, and Shu-Sheng Liaw. "Investigating learners' attitudes toward virtual reality learning environments: Based on a constructivist approach". In: *Computers & Education* 55.3 (2010), pp. 1171–1182.

[27] Randolph L Jackson, Wayne Taylor, and William Winn. "Peer collaboration and virtual environments: a preliminary investigation of multi-participant virtual reality applied in science education". In: *Proceedings of the 1999 ACM symposium on Applied computing*. ACM. 1999, pp. 121–125.

[28] Hannes Kaufmann, Dieter Schmalstieg, and Michael Wagner. "Construct3D: a virtual reality application for mathematics and geometry education". In: *Education and information technologies* 5.4 (2000), pp. 263–276.

[29] Daniel F Keefe et al. "CavePainting: a fully immersive 3D artistic medium and interactive experience". In: *Proceedings of the 2001 symposium on Interactive 3D graphics*. ACM. 2001, pp. 85–93.

[30] *Keep Talking and Nobody Explodes*. http://www.keeptalkinggame.com/. Accessed: 2017-03-15.

[31] Muhammad Sikandar Lal Khan, Haibo Li, and Shafiq Ur Réhman. "Tele-Immersion: Virtual Reality Based Collaboration". In: *International Conference on Human-Computer Interaction*. Springer. 2016, pp. 352–357.

[32] Bo Kim et al. "Virtual Reality as an Artistic Medium: A Study on Creative Projects Using Contemporary Head-Mounted Displays". In: (2016).

[33] Marjan Laal and Seyed Mohammad Ghodsi. "Benefits of collaborative learning". In: *Procedia-Social and Behavioral Sciences* 31 (2012), pp. 486–490.

[34] Cornelie Leopold, Renata A Gorska, and Sheryl A Sorby. "International experiences in developing the spatial visualization abilities of engineering students". In: *Journal for Geometry and Graphics* 5.1 (2001), pp. 81–91.

[35] Marcia C Linn and Anne C Petersen. "Emergence and characterization of sex differences in spatial ability: A meta-analysis". In: *Child development* (1985), pp. 1479–1498.

[36] Nikolay Lütke and Christiane Lange-Küttner. "Keeping it in three dimensions: Measuring the development of mental rotation in children with the Rotated Colour Cube Test (RCCT)". In: *International Journal of Developmental Science* 9.2 (2015), pp. 95–114.

[37] Sam Machkovech. *Learning how to VR with Tilt Brush, HTC Vive's killer app*. https://arstechnica.com/gaming/2016/04/learning-how-to-vr-with-tilt-brush-htc-vives-killer-app/. Accessed: 2017-03-21. 2016.

[38] Wille Mäkelä and Tommi Ilmonen. "Drawing, painting and sculpting in the air: Development studies about an immersive free-hand interface for artists". In: *Beyond Wand and Glove Based Interaction Workshop, IEEE Virtual Reality Conference*. 2004, pp. 89–92.

[39] Jorge Martín-Gutiérrez et al. "Virtual Technologies Trends in Education". In: (2016).

[40] Mark L Merickel. "A Study of the Relationship between Virtual Reality (Perceived Realism) and the Ability of Children To Create, Manipulate and Utilize Mental Images for Spatially Related Problem Solving." In: (1992).

[41] Tassos A Mikropoulos et al. "Students' attitudes towards educational virtual environments". In: *Education and Information Technologies* 3.2 (1998), pp. 137–148.

[42] James L Mohler and Craig L Miller. "Improving spatial ability with mentored sketching". In: *Engineering Design Graphics Journal* 72.1 (2009).

[43] David Moreau. "Differentiating two-from three-dimensional mental rotation training effects". In: *The Quarterly Journal of Experimental Psychology* 66.7 (2013), pp. 1399–1413.

[44] Michael Narayan et al. "Quantifying the benefits of immersion for collaboration in virtual environments". In: *Proceedings of the ACM symposium on Virtual reality software and technology*. ACM. 2005, pp. 78–81.

[45] Lynn Okagaki and Peter A Frensch. "Effects of video game playing on measures of spatial performance: Gender effects in late adolescence". In: *Journal of applied developmental psychology* 15.1 (1994), pp. 33–58.

[46] Kimberley Osberg. "Spatial cognition in the virtual environment". In: (1997).

[47] Veronica S Pantelidis. “Reasons to use virtual reality in education and training courses and a model to determine when to use virtual reality”. In: *Themes in Science and Technology Education* 2.1-2 (2010), pp. 59–70.

[48] David Passig and Sigal Eden. “Virtual reality as a tool for improving spatial rotation among deaf and hard-of-hearing children”. In: *CyberPsychology & Behavior* 4.6 (2001), pp. 681–686.

[49] Michael Peters et al. “A redrawn Vandenberg and Kuse mental rotations test-different versions and factors that affect performance”. In: *Brain and cognition* 28.1 (1995), pp. 39–58.

[50] *Quill*. https://www.oculus.com/experiences/rift/1118609381580656/. Accessed: 2017-03-07.

[51] Ahmad Rafi, Khairul Anuar Samsudin, and Azniah Ismail. “On improving spatial ability through computer-mediated engineering drawing instruction”. In: *Journal of educational technologyand society* 9.3 (2006), p. 149.

[52] Ahmad Rafi et al. “Improving spatial ability using a Web-based Virtual Environment (WbVE)”. In: *Automation in construction* 14.6 (2005), pp. 707–715.

[53] Albert A Rizzo et al. “The virtual reality mental rotation spatial skills project”. In: *CyberPsychology & Behavior* 1.2 (1998), pp. 113–119.

[54] David Roberts et al. “Constructing a Gazebo: supporting teamwork in a tightly coupled, distributed task in virtual reality”. In: *Presence* 12.6 (2003), pp. 644–657.

[55] Cristina Roca-González et al. “Virtual Technologies to Develop Visual-Spatial Ability in Engineering Students.” In: *Eurasia Journal of Mathematics, Science & Technology Education* 13.2 (2017).

[56] Ralph Schroeder. *The social life of avatars: Presence and interaction in shared virtual environments*. Springer Science & Business Media, 2012.

[57] Roger N. Shepard and Jacqueline Metzler. “Mental Rotation of Three-Dimensional Objects”. In: *Science* 171.3972 (Feb. 1971), pp. 701–703. URL: http://dx.doi.org/10.1126/science.171.3972.701.

[58] Bryan Sinclair. “The Promise of Virtual Reality in Higher Education”. In: *EDUCAUSE Review* (2016).

[59] Mel Slater and Sylvia Wilbur. “A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments”. In: *Presence: Teleoperators and virtual environments* 6.6 (1997), pp. 603–616.

[60] Mel Slater et al. “Small-group behavior in a virtual and real environment: A comparative study”. In: *Presence: Teleoperators and virtual environments* 9.1 (2000), pp. 37–51.

[61] Sheryl A Sorby. “Developing 3-D spatial visualization skills”. In: (1999).

[62] Sheryl A Sorby and Beverly J Baartmans. “The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students”. In: *Journal of Engineering Education* 89.3 (2000), pp. 301–307.

[63] Sheryl A Sorby, Thomas Drummer, and Raymond Molzon. “Experiences in using spatial skills testing instruments with younger audiences”. In: *Journal for Geometry and Graphics* 10.2 (2006), pp. 225–235.

[64] *Spatial reasoning test*. https://www.123test.com/spatial-reasoning-test/. Accessed: 2017-06-25. 2017.

[65] Jonathan Steuer. "Defining virtual reality: Dimensions determining telepresence". In: *Journal of communication* 42.4 (1992), pp. 73–93.

[66] Víctor Theoktisto and Marta Fairén. "Enhancing collaboration in virtual reality applications". In: *Computers & Graphics* 29.5 (2005), pp. 704–718.

[67] Gisli Thorsteinsson and Tom Page. "Computer Supported Collaborative Learning in Technology Education Through Virtual Reality Learning Environments". In: (2007).

[68] *Tilt Brush*. https://www.tiltbrush.com/. Accessed: 2017-03-07.

[69] Neal Ungerleider. *Google's Tilt Brush Is The First Great VR App*. https://www.fastcompany.com/3056668/googles-tilt-brush-is-the-first-great-vr-app. Accessed: 2017-03-21. 2016.

[70] Steven G Vandenberg and Allan R Kuse. "Mental rotations, a group test of three-dimensional spatial visualization". In: *Perceptual and motor skills* 47.2 (1978), pp. 599–604.

[71] Maria Virvou and George Katsionis. "On the usability and likeability of virtual reality games for education: The case of VR-ENGAGE". In: *Computers & Education* 50.1 (2008), pp. 154–178.

[72] William Winn. "Research into practice: Current trends in educational technology research: The study of learning environments". In: *Educational Psychology Review* 14.3 (2002), pp. 331–351.