# Aalborg University Copenhagen

**Semester: 10th**

**Title: An Immersive Geometry Environment (IGE): exploring the design of gesture-based interactions with dynamic geometry in Immersive Virtual Reality**

Aalborg University Copenhagen

Frederikskaj 12,

DK-2450 Copenhagen SV

Semester Coordinator:

Secretary: Lisbeth Nykjær

**Project Period: February 2021 – August 2021**

**Semester Theme: Master's Thesis**

**Supervisor(s): Lui A. Thomsen**
**Rolf Nordahl**

**Members:**
**Kevin Baars**
**Christoffer Bendig Mundbjerg-Sunne**

**Abstract:**

Teaching and learning mathematics are challenges that have echoed through our history. It is notoriously hard to convey knowledge on mathematics and it is because of this yearning for improvement that in recent years, we have been able to witness an increase in the use of dynamic geometry environments (DGEs) in schools and educational institutions. XR technologies show a statistically significant improvement in the student's learning outcome over traditional methods, such as printed media and desktop applications, regarding spatial domains like geometry. When introducing XR in education, the immersive spectrum is added to the realm of environments in which teachers can plan learning activities.
In this report, we present a VR implementation for a DGE, using embodied interaction inside an immersive virtual environment (IVE). In this thesis, we present the design, implementation and evaluation of this new type of virtual learning environment: an Immersive Geometry Environment.

A UX experiment and heuristic evaluation have shown that the IGE suggested by this thesis could facilitate a new and possibly enhanced method for teaching geometry at a lower-secondary education level, based on positive responses regarding usability, presence, agency and cognitive load. 10 design guidelines for developing an IGE were synthesized from the experimental data.

AALBORG UNIVERSITY COPENHAGEN

MASTER THESIS

# An Immersive Geometry Environment (IGE): exploring the design of gesture-based interactions with dynamic geometry in Immersive Virtual Reality

*Authors:*
Kevin Baars & Christoffer Bendig Mundbjerg-Sunne

*Supervisors:*
Lui A. Thomsen & Rolf Nordahl

Department of Architecture, Design, and Media Technology

June 25, 2021

AALBORG UNIVERSITY COPENHAGEN

# *Abstract*

Faculty of IT and Design
Department of Architecture, Design, and Media Technology

MSc Medialogy

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by Kevin Baars & Christoffer Bendig Mundbjerg-Sunne

Teaching and learning mathematics are challenges that have echoed through our history. It is notoriously hard to convey knowledge on mathematics and it is because of this yearning for improvement that in recent years, we have been able to witness an increase in the use of dynamic geometry environments (DGEs) in schools and educational institutions. XR technologies show a statistically significant improvement in the student's learning outcome over traditional methods, such as printed media and desktop applications, regarding spatial domains like geometry. When introducing XR in education, the immersive spectrum is added to the realm of environments in which teachers can plan learning activities. In this report, we present a VR implementation for a DGE, using embodied interaction inside an immersive virtual environment (IVE). In this thesis, we present the design, implementation and evaluation of this new type of virtual learning environment: an Immersive Geometry Environment.

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# *Acknowledgements*

First and foremost, we want to thank our supervisor Lui A. Thomsen for supporting us in writing this thesis over the past year and a half. His work and knowledge on Virtual Reality in Mathematics Education (VRiME) has provided us with a treasure of information and guidance. He is currently finishing his Industrial Phd on the topic of VRiME.
We also would like to thank Rolf Nordahl, Phd, co-ordinator of the Multi-sensory Experience lab, for his input early on in the project and connecting us with Lui. A special appreciation goes to the friends and family members that helped populating our UX experiments.
Acknowledgements go out to Niels Christian Nilsson, Cumhur Erkut, Ali Adjorlu and Cecilie Carlsen Bach for providing us with their expertise.

I would personally like to thank my wife, Nanna Marie Baars Støvelbæk, for her incredible support with the experiments and mental support throughout the past year and a half.

I would like to thank my wife, Kathrine Bendig Mundbjerg-Sunne, for taking care of our newborn son so I had time to work on this project.

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# List of Abbreviations

| | |
|---|---|
| **ACT** | **A**ction-**C**ognition **T**ransduction |
| **AR** | **A**ugmented **R**eality |
| **CLT** | **C**ognitive **L**oad **T**heory |
| **CLQ** | **C**ognitive **L**oad **Q**uestionnaire |
| **DGE** | **D**ynamic **G**eometry **E**nvironment |
| **DGS** | **D**ynamic **G**eometry **S**ystems |
| **DMS** | **D**ynamic **M**athematics **S**oftware |
| **EC** | **E**mbodied **C**ognition |
| **ELM** | **E**xploratory **L**earning **M**odel |
| **HMD** | **H**ead **M**ounted **D**isplay |
| **IGE** | **I**mmersive **G**eometry **E**nvironment |
| **IPQ** | **I**mmersion **P**resence **Q**uestionnaire |
| **IVE** | **I**mmersive **V**irtual **E**nvironment |
| **IVR** | **I**mmersive **V**irtual **R**eality |
| **RC** | **R**easoning **C**ompetency |
| **STEM** | **S**cience, **T**echnology, **E**ngineering and **M**athematics |
| **SUS** | **S**ystem **U**sability **S**cale |
| **UI** | **U**ser **I**nterface |
| **UX** | **U**ser e**X**perience |
| **VEQ** | **V**irtual **E**mbodiment **Q**uestionnaire |
| **VR** | **V**irtual **R**eality |
| **XR** | e**X**tended **R**eality |

# Chapter 1

# Introduction

Teaching and learning mathematics are challenges that have echoed through our history. It is notoriously hard to convey knowledge on mathematics and it is due to this yearning for improvement that in recent years, we have been able to witness an increase in the use of Dynamic Geometry Environments (DGEs) in schools and educational institutions (Kjeldsen, Kristensen, and Christensen, 2019). A DGE is a mathematics software for creating and manipulating geometric constructions interactively[1]. DGEs have been implemented in Danish primary and lower secondary schools and become standard for teaching mathematics across all educational levels in Denmark (Højsted, 2020).
However, introducing new technologies does not come easy. In a meta-review by Radu, 2013 on the topic of AR in education, both the most prominent issues and affordances with implementing a form of eXtended Reality (XR) into the educational sector were outlined. Although XR brings affordances such as engagement, collaboration and immersion, the writer reports that the main issues include topics such as usability and accessibility. XR technologies show a statistically significant improvement in the student's learning outcome over traditional methods, such as printed media and desktop applications, regarding spatial domains like geometry. Radu, 2013 argues that XR technologies advocate several crucial contributions to enhance learning outcome in Science, Technology, Engineering and Mathematics (STEM) topics: visualizing abstract concepts, as is inherent for STEM topics, and an active didactic approach such as constructivism (Nawaz, Kundu, and Sattar, 2017, Abdoli-Sejzi, 2015 and Gardner and Elliott, 2014), more on didactic approaches is found in section 2.1.4.

The range of geometry learning activities reaches from analogous, such as pen and paper assignments, to digital, like using a DGE. When introducing XR in education, the immersive spectrum is added to the realm of environments in which teachers can plan learning activities.
In this report, we present a VR implementation for a DGE, using embodied interaction inside an Immersive Virtual Environment (IVE). In the following report, this new type of virtual learning environment will be referred to as an Immersive Geometry Environment (IGE).

## 1.1 Previous work

During the last year and a half, we have investigated digital technologies in mathematics education, with a focus on affordances and limitations inherent for DGEs, for

[1] http://www.math.bas.bg/bantchev/misc/dgs.pdf

the purpose of designing an IVE, and developed the first iteration of the prototype IGE (see figure 1.1).

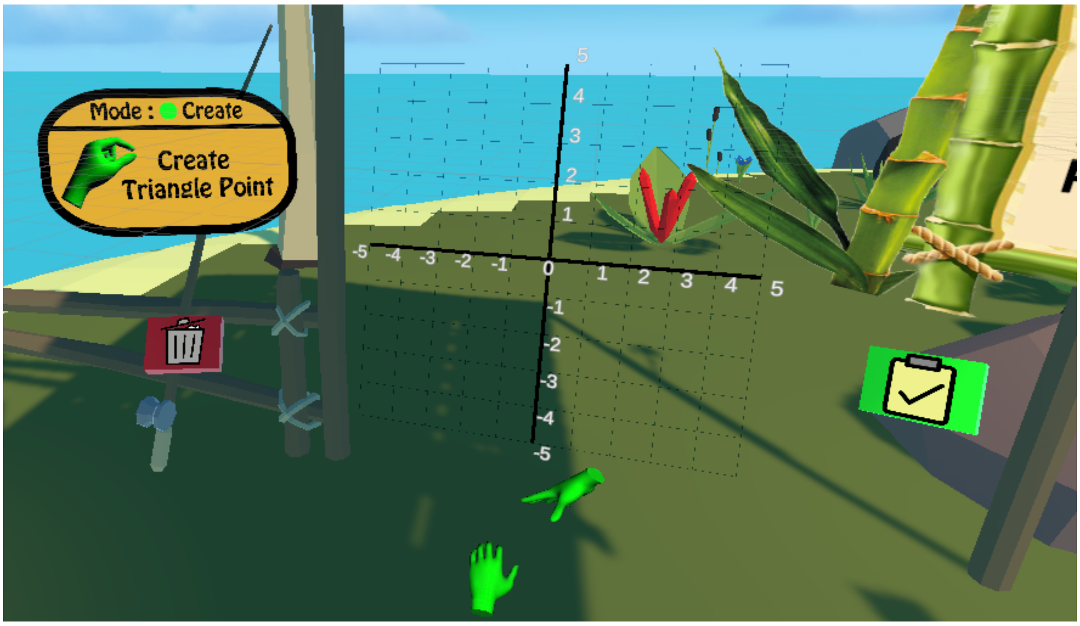



FIGURE 1.1: First prototype of the immersive geometry environment.

For this environment, we designed an embodied experience utilizing teachings from constructivism and exploratory learning. A gesture-based interface was implemented, eliminating the need for physical controllers and using only a VR Head-mounted Display (HMD).

We performed a user-experience experiment, investigating categories such as immersion, presence, simulation sickness and interaction design. Using convenience sampling (Bjørner, 2016), 7 users were tasked to enter our environment for the first time and explore the functionality of the project. The results showed positive prospects, seemingly due to the factors of immersion and presence, overall satisfaction and usability (see appendix B).

However, the users gave a varied result when asked about their confidence inside the virtual environment, as seen in figure 1.2.

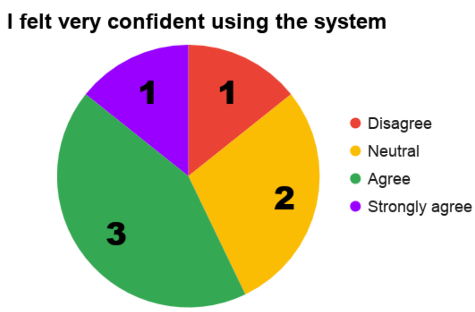



FIGURE 1.2: User confidence.

Based on user feedback, the reason for this disparity in confidence came from 2 gesture interactions: "tape measure" and "protractor". In the prototype, we had the following gesture-based interactions:

- Pinching - for constructing a triangle.
- Grabbing - for manipulating an existing triangle.
- Protractor - measuring angles of the triangle.
- Tape Measure - for measuring triangle sides.

Besides gesture-based interactions, there was also an interactive grid for placing the triangle and 2 interactive buttons; a red button to delete the triangle and a green button to submit your triangle for an assignment.

Our first-time users provided feedback on each interaction technique and element. Based on this feedback, we implemented new features and interactions in the prototype. New features include:

- Area gesture - for measuring triangle area.
- Modes - 3 modes were introduced: create, manipulate and tools. We created these modes to segment the possible gestures over different situations and give the user more control over the gestures.
- Multiple triangles - we improved the core geometry engine of our prototype to support the construction of multiple triangles.
- Menu gesture - this gesture opens up the controls for the user and keeps the interactive buttons and modes in one place.

We also reworked the "tape measure" and "protractor" gesture. Details of this procedure will be revealed in section 4.2.

This paper aims to present the rationale behind these new changes and investigate their impact on user experience and cognitive load. Additionally, we investigate a popular DGE named GeoGebra and its interactions and affordances in mathematics education. This leads to the initial problem statement:

> "*How can the affordances from Dynamic Geometry Environments and embodied exploratory learning be utilized to create an Immersive Geometry Environment with a gesture-based interface?*"

In the following chapter, we shed light on relevant research and converge on a method for designing, implementing and evaluating an IGE using a gesture-based interface congruent with the user's hands.

# Chapter 2

# Analysis

The theoretical underpinnings form the scientific background of the design decisions for the IGE and are presented in this chapter. How does embodiment connect with cognition and apply to developing competencies in mathematics? The didactic approaches for immersive virtual learning and the popular DGE GeoGebra are investigated and become the foundation of our designs. The analysis narrows the scope of this thesis and synthesizes design requirements based on the findings of related research.

## 2.1 Theoretical underpinnings

This section ties together the different scientific theories involved in developing the IGE. These theories are regarding the expected competency development in lower-secondary geometry education, the link between embodiment and cognition and how they apply to mathematics education. We introduce gesturing as a form of embodiment and the idea that when enacting mathematics, one is becoming mathematical and thus developing important mathematical competencies. We guide the user through our IGE using a task design inspired by the didactic approach of *constructivism* and the *exploratory learning model*.

### 2.1.1 Competencies and mathematical learning

After 6th-grade (lower-secondary education), there are certain learning goals that students are assessed on, as dictated by the Danish Ministry of Children and Education (Undervisningsministeriet, 2019). These goals are listed in table 2.1.

Moyer-Packenham and Bolyard, 2016 gives an update on the notions regarding mathematical competence and competencies introduced by Undervisningsministeriet, 2019. Moyer-Packenham and Bolyard, 2016 maintains the view that mathematical competencies are cognitive constructs. They asses the educational use of competencies in 5 ways.
Competencies can be used a normative method for designing curricula in mathematics education. They put emphasis on the enactment of mathematics and speculate that a competency-oriented curriculum design allows for an improved balance between performing and having knowledge in mathematics.
Competencies can also be used analytically to describe the pursued competencies in e.g. geometry.
Diagnostically using competencies is deemed a crucial move by the authors when attempting to improve key elements of students' learning of mathematics, which is manifested in the development and possession of competency.

Teachers can use competencies to reflect and evaluator upon their own work, e.g. when planning student assignments.
Lastly, the authors write that competencies can be used by the students themselves as a metacognitive support for self-reflection learning activities and their outcome.

Thus, for an IVE to facilitate geometry education means to facilitate competency development.
The IGE narrows the focus on the competencies of "Geometry and measuring". Beside the learning goals students are assessed on, the Danish Ministry of Children and Education also lists a guide for skills- and knowledge-goals (see table 2.2).

Ideally, any application aimed at teaching geometry in lower-secondary education should facilitate the established competence goals set forward by the ministry. Incorporating the skills- and knowledge-goals is crucial for the IGE.

For example, to facilitate the goal of "Placement and moving", one can look at its guided skills- and knowledge-goal: "The student has knowledge about the entire coordinate-system", thus the IGE should have a representation of a coordinate-system.

### 2.1.2 Embodied cognition

Embodied Cognition (EC) refers to the theory that cognition is rooted in bodily activities (Wilson, 2002, Barsalou, 2010). It is argued that because the action system and cognition have reciprocity; cognitive states can lead to actions and actions can induce cognitive states (Walkington et al., 2014 Abrahamson et al., 2020). The notion that actions can induce cognitive processes is the basis for Action-Cognition Transduction (ACT). For mathematics education, ACT may extend to mathematical objects such as shapes and symbols. This is because we treat these mathematical objects as physical objects, we perceive and manipulate algebraic symbols as though they were objects (Abrahamson et al., 2020). An important example of this is the *virtual manipulative*.

(Moyer-Packenham and Bolyard, 2016) defines the virtual manipulative as:

> *"an interactive, technology-enabled visual representation of a dynamic mathematical object, including all of the programmable features that allow it to be manipulated, that represent opportunities for constructing mathematical knowledge."*

Common environments where virtual manipulatives appear are: single-representation, multi-representation, tutorial, gaming and simulation.

A single-representation virtual manipulative environment contains only a visual representation of the dynamic mathematical object (i.e. images). These environments and the use of gesturing among paired students are the most discussed.

| **Competencies areas** | **Competencies goal** | **Skills- and knowledge-areas and -goal** |
|---|---|---|
| Mathematical competencies | The student can act appropriate in situations with mathematics | Problem solving |
| | | Modeling |
| | | Reasoning and thinking |
| | | Representation and symbol processing |
| | | Communication |
| | | Assistive devices |
| Numbers and algebra | The student can apply rational numbers and variable in descriptions and calculations | Numbers |
| | | Calculation Strategies |
| | | Algebra |
| Geometry and measuring | The student can apply geometric methods and calculate simple measurements | Geometric properties and coherence |
| | | Geometric drawing |
| | | Placement and moving |
| | | Measurement |
| Statistics and Probability | The student can perform own statistical studies and determine statistical probabilities | Statistics |
| | | Probability |

TABLE 2.1: Competencies and mathematical learning for danish 6th. grader.

However, these discussions were not at a level that could lead to mathematical generalization. The environments also lead to more creative variations during problem solving.

A multi-representation virtual manipulative environment relies on two or more forms of representation, often pictorial and numerical. The simultaneous linking of representations has a positive impact on students' mathematical achievement. Student don't have to remember or recount information and can see the result of their action as they interact with the virtual manipulative. Students working in pairs in these environments showed discussions of higher levels of mathematical generalization, justification and collaboration. Multi-representation encourages students to make connections, comparisons and see patterns more easily.

The tutorial virtual manipulative environment functions like the multi-representation, but with the addition of some form of guidance through a mathematical process. This format discourages communication in student pairs and allows for little exploration. However, it is better suited for individual work as the guidance serves as a

| Geometric properties and coherence | Geometric drawing | Placement and moving | Measurement |
|---|---|---|---|
| The student can categorize polygons based on side-length and angles | The student can reproduce traits from the outside world by drawing as well as drawing out from given conditions | The student can describe placement in the coordinate-systems first quadrant | The student can estimate and determine the perimeter and area |
| The student has knowledge about angle types and sides in simple polygons | The student has knowledge of geometric drawing shapes that can reproduce features from the outside world, including drawing shapes in digital tools | The student has knowledge about the coordinate-systems first quadrant | The student has knowledge about different methods to estimate and determine circumference and are, including methods with digital tools |
| The student can investigate geometric properties by plane figures | The student can use sketches and precise drawings | The student can describe placement in the entire coordinate-system | The student can estimate decide volume |
| The student has knowledge about angles measurements, lines reciprocal location and methods for the study of figures, including with dynamic geometry program | The student has knowledge of sketches and precise drawings | The student has knowledge about the entire coordinate-system | The student has knowledge of methods for estimating and determining volume |
| The student can examine geometric properties of spatial figures | The student can draw spatially figures with different methods | The student can produce patterns with mirrors, parallel displacements and turns | The student can determine circumference and are of circles |
| The student has knowledge of polyhedra and cylinders | The student has knowledge of geometric drawing shapes for reproduction of spaciousness | The student has knowledge about methods to make patterns with mirrors, parallel displacements and rotations, including with digital tools | The student has knowledge about methods for determining perimeter and area of circles |

TABLE 2.2: Geometric competencies and mathematical learning for the 6th grade in Denmark.

personal tutor. Low achievers benefit from the step-by-step format of the tutorial environment.

The gaming virtual manipulative environment functions similar to a multi-representation embedded in some form of game. This environment has shown positive effects on the development of mathematical learning.

The simulation virtual manipulative environment is similar to a multi-representation that is embedded in a format which allows users to run simulations that represent or draw attention to embedded mathematical concepts. This environment helps students link symbolic and visual representations, demanded greater precision in geometric thinking from students and encouraged them to perform and explore geometric conjectures.

The potential of virtual manipulatives to support the student in developing mathematical competencies, relies on judicious, appropriate, and effective use. Learners must experience the virtual manipulative and interact with its characteristics and features in ways that represent the relevant mathematics. Virtual manipulatives do not develop mathematical competencies on their own; it is the quality of the engagement with the technology that presents opportunities for developing competencies (Moyer-Packenham and Bolyard, 2016).

Radu, 2013, Akćayır and Akćayır, 2017 and Bacca et al., 2014 reports on the affordance of embodied learning in XR. These affordances include; increased content understanding, better learning of spatial structures and functions, long-term memory retention, increased student motivation, improved collaboration and improved physical task performance.
Nicolas and Trgalova, 2019 presents an implementation of asymmetric virtual learning, where a student in an immersive environment is guided by another student in a non-immersive environment to solve tasks related to spatial geometry. Their implementation includes a gesture-based interface inside a DGE using Immersive Virtual Reality (IVR). They demonstrated the transfer of dimensional construction to 2D supporting the development of the student's heuristic understanding of drawings in a cavalier perspective. This demonstration coupled with the presence students perceived leads to a permeability at the cognitive level between virtual and real world experiences, thus developing mathematical competency.

Georgiou, Ioannou, and Kosmas, 2021 investigated the potential of motion-based technologies in the context of geometry elementary education, by comparing digital and non-digital embodied intervention. While the study supports the positive effects of embodiment on students' conceptual understanding, the study goes further and demonstrated that the students in the digital embodied learning intervention outperformed the students in the non-digital embodied learning intervention. This gives empirical substantiation on the added value of motion-based technologies for embodied learning.

### 2.1.3 Gestures

This section ties together the development of mathematical competency with embodiment through the conjecturing of meaningful gestures.

One important type of gesture is the *iconic gesture* (sometimes referred to as *depictive gestures*) (McNeill, 1992). Iconic gestures are used to convey information about the object of discourse with the body - e.g. the speaker can convey the notion of *"barrelling"* by doing a rotational barrelling motion with the hands.

Expanding on this, Walkington et al., 2014 describe the distinction between *static* and *dynamic iconic gestures*. A static iconic gesture shows a static representation of an object. In dynamic iconic gestures, the person first represents an object and then manipulates the object, using their body – e.g. the person might make a rectangle with their hands and then move their hands outward, signalling that the rectangle "grows". They argue that dynamic gestures are an important component of formulating and communicating valid proofs in geometry, thus being crucial in developing mathematical competencies.

Learners can enact mathematical relations using gestures, thereby *becoming* the relation, thus *knowing* the relation (Walkington et al., 2014, Price, Yiannoutsou, and Vezzoli, 2020). People who enact the key mathematical relations, and thus *"become"* mathematical relations, of a task in dynamic body-based form, can better assess the validity of mathematical conjectures and are more likely to generate valid mathematical proofs to warrant their judgments. More so, participants who were directed to perform relevant gestures constructed valid proof and correctly judged conjectures more often than participants who were directed to perform irrelevant gestures. However, these directed relevant gestures may only be effective when the learner is explicitly made aware of their relevance (Walkington et al., 2014).

Meaningful learning might only take place if the gestures made, relate to what they are meant to represent (Lindgren and Johnson-Glenberg, 2013, Skulmowski and Rey, 2018a), rather than performing unrelated gestures (Abrahamson et al., 2020). This is also referred to as *gestural congruency* (Lindgren and Johnson-Glenberg, 2013, Skulmowski and Rey, 2018a).

We've established that learning through embodiment and gestural congruency improves the student's mathematical competency development. There is another important angle to look at: the didactic approach.

### 2.1.4 Didactic approaches in virtual immersive learning

Knowing that learning mathematics through gestural congruency aids in developing mathematical competency, there is still an important aspect to investigate. How do we didactically approach the design of tasks for an IGE? This section discusses the didactic approach of constructivism and the Exploratory Learning Model (ELM).

Constructivism (sometimes referred to as student-centered or learner-centred learning (Abrahamson et al., 2020, Nawaz, Kundu, and Sattar, 2017)) has no agreed-upon definition, but the unifying theme shows that learners develop their competencies where learning is achieved through the learner's perspective and previous experiences, through observations, processing and interpretation (Abrahamson et al., 2020, Nawaz, Kundu, and Sattar, 2017). The constructivist approach is recognized as a valuable technique to increase a deep understanding of scientific ideas (Nawaz, Kundu, and Sattar, 2017). XR technology can effectively align with constructivist ideas of education through active interactions, exploration, collaborative behaviour, exploratory behaviour and personalized experiences (Abdoli-Sejzi, 2015). Embodiment also overlaps with constructivism, because the action of moving simultaneously, the gestures that emerge through student-student/teacher-student interactions, epitomize constructivism (Abrahamson et al., 2020).

Extending the constructivist practice into an IVE, the ELM (Exploratory Learning Model)(De Freitas and Neumann, 2009) introduces the notion of "explorations" as being a key learning construct, usually through collaborative activities, communication and social interactions. Exploration of virtual and/or physical environments aids the learners to:

> *"find new boundaries, to push back on what they know and to help them to engage socially and conceptually with others."*

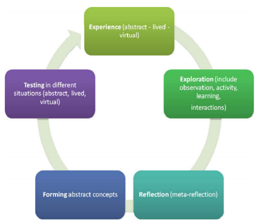



FIGURE 2.1: The exploratory learning model.

The ELM states that the experiences from which knowledge emerges, is not only limited to lived reality, but also include virtual and mixed reality (VR and MR).

In the van Heile model of thinking in geometry, learners progress through a series of levels (Jones, 1998).
Level 0: the student identifies, names, compares and operates on geometric figures.
Level 1: the student analyses figures in terms of their components and relationships between components and discovers properties empirically.
Level 2: the student logically inter-relates previously discovered properties by giving or following informal arguments.
Level 3: the student proves theorems deductively and establishes inter-relationships between networks of theorems.
Level 4: the student establishes theorems in different postulation systems and analyses/compares these systems (Jones, 1998).

The van Heile model of thinking in geometry could also be described using the ELM.
Level 0 could be argued to require previous experience to identify, name, compare

and operate on geometric figures.
Level 1 has an exploration part in order to discover properties.
Level 2 has the student reflect to relate the properties to the figures.
Level 3 has the forming of abstract concepts.
level 4 contains self-reflection and analysis.

Yet another way of describing geometrical reasoning is Duval's cognitive model of geometrical reasoning (Jones, 1998). In this model there are three kinds of cognitive processes: visualisation processes, construction processes and reasoning processes. These processes can be performed separately, but Duval argues that these processes are "closely connected" .

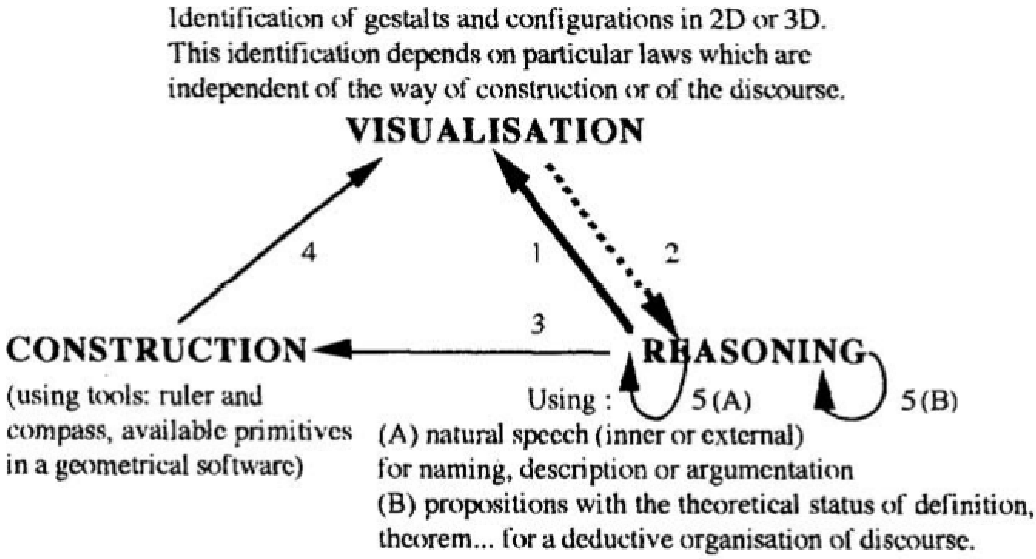



FIGURE 2.2: Cognitive interaction involved in geometrical activities.

We have established a didactic approach through the ELM and constructivist theory. We can now apply this knowledge to a task design for our IGE. The following section covers the theory of task design involved in developing the IGE.

## 2.2 Task design

Task design for embodied learning faces two challenges; the embodied part of the experience and the tasks to be completed.

We have looked at embodied cognition theory and the positive effects on developing competencies using embodied learning and gestural congruency. Using the taxonomy suggested by Skulmowski and Rey, 2018b, we can convert our findings into task design guidelines.

Embodied learning can be divided into two dimensions: bodily engagement and task integration. Bodily engagement is an expression of how much bodily activity is involved and ranges from Low (i.e., observing movement, animated interactions with desktop simulations and seated experiences) to High (i.e., bodily movements and locomotion).

Task integration is whether bodily activities are related to a learning task in a meaningful way. Task integration bears some resemblance to gestural congruency, although task integration is more general (i.e., not only applicable to gestures) (Skulmowski and Rey, 2018b). Task integration ranges from incidental to integrated forms of embodiment. Incidental forms of embodiment involves cognitive processes using incidental cues, like making information appear more important by presenting it on a heavy object instead of a light one. Integrated forms of embodiment are bodily activities that are integrated into the learning task itself. This has some resemblance to gestural congruence, but can be applied more generally and not just to gestures.

Skulmowski and Rey, 2018b echoes the findings in section 2.1.2, namely that high bodily engagement has been linked to both developing mathematical competencies and the risk of cognitive overload (more on this in section 2.3), and that task integration is important. Tasks in embodied learning should have both moderate to high bodily engagement and integrated activities.

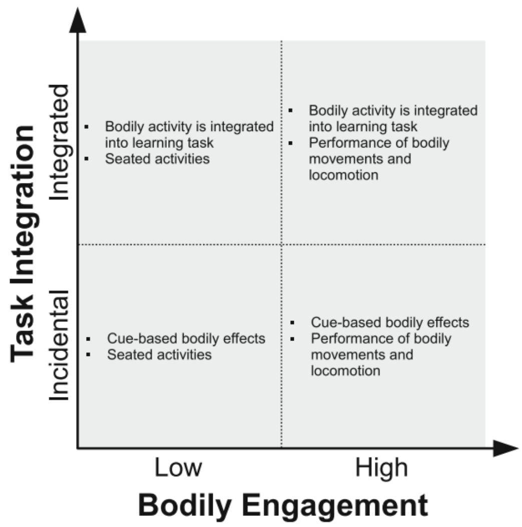



FIGURE 2.3: Skulmowski and Rey, 2018b's two-dimensional taxonomy of embodied cognition. They note that while the borders appear sharply defined, it should be regarded as continuous and the case may be made for regarding the boundaries as fuzzy.

A pedagogical reasoning for using technology is to empower the ability of students to acquire knowledge. E.g. students can do and see things that they could not without the technology (Leung, 2011). Based on this, Leung, 2011 propose a model of task design that is situated in a technology-rich pedagogical environment.

Three epistemic modes that characterize mathematics knowledge acquisition process are put forward as the foundation of the techno-pedagogic task design model:

- Establishing Practices Mode (PM)
  - PM1: Construct mathematical objects or manipulate pre-design mathematical objects using tools embedded in a technology-rich environment.

  - PM2: Interact with the tools in a technology-rich environment to develop (a) skill-based routines (b) modalities of behaviour (c) mode of situated dialogue.

- Critical Discernment Mode (CDM)
  - Observe, record, re-present (re-construct) patterns of variation and invariant.

- Establishing Situated Discourses Mode (SDM)
  - SD1: Develop inductive reasoning leading to making generalized conjecture.
  - SD2 Develop discourse and modes of reasoning to explain or prove.

This structure is understood as a nested expanding space the student moves through. Practice evolves into discernment, which evolves into reasoning. Students have to learn how to use new mathematical tools and in doing so, gradually realize the knowledge potential that is embedded in it. These practices could be established via construction or manipulative tasks. Constructing or manipulating virtual mathematical objects is a meaningful way to learn to turn virtual tools into pedagogical instruments. PM is where a tool turns into an instrument by associating it with a utility scheme, a systematic procedure on how to use the tool to achieve a certain purpose. CDM is when the focus shifts from routine tool usage to meaningful construction. A shift of attention happens in the transition between PM and CDM, where utilization schemes become schemes for discernment. The learner can discern variance or invariance and can make conjectures about the mathematical object. Lastly comes explanation, or proof, of the conjecturing.

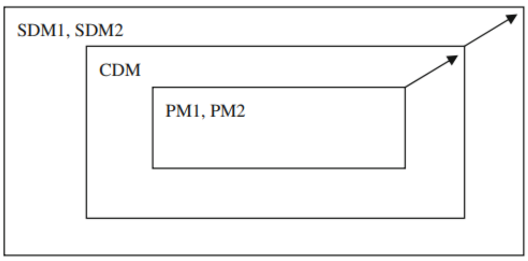



FIGURE 2.4: An illustration of the nested structure sequenced by the three epistemic modes, Leung, 2011

Trocki and Hollebrands, 2018 analysed tasks submitted by lower-secondary mathematics teachers to produce the Dynamic Geometry Task Analysis Framework (DGTA Framework). The DGTA Framework is meant to indicate the quality of Dynamic Geometry Systems (DGS) and as a guide when writing tasks. The Framework consists of two parts: mathematical depths and technological affordances. Each of the two categories have different levels, used to indicate the quality of the task.

The DGTA Framework suggests that tasks in an IGE should have integrated tasks (gestural congruence) and a moderate to high level of bodily engagement. Although not at the expense of the student's cognitive load (see section 2.3). Tasks should also allow students to construct and manipulate mathematical objects, have activities where students observe, re-construct or record, as well as including tasks which involve conjecturing, explanation and encourage discourse.

Now that we have established a framework for task design, let's take a look at cognitive load theory and how it relates to the design of an IGE.

## 2.3 Cognitive load theory

Cognitive Load Theory (CLT) Sweller, Van Merrienboer, and Paas, 1998 has been considered to be a strong influence in embodied learning and thus research in education has concerned itself more with the relationship between EC and CLT (Shapiro, 2019 and Skulmowski et al., 2016). CLT was created on the idea that cognitive capacity is limited by the resources of our working memory (Sweller, Van Merrienboer, and Paas, 1998 and Baddeley, 1992). To use all the resources to their full extend, CLT suggests to investigate and manipulate the 3 types of cognitive load: *instrinsic load*, *extraneous load*, and *germane load*.

*Intrinsic load* refers to the inherent difficulty of the contents that are to be learned by the user (Sweller, Van Merrienboer, and Paas, 1998). How the learning contents are designed and represented towards the user is affecting the *extraneous load*. The third type of load, *germane load*, is related to the process of generating knowledge structures in the user's long-term memory (Sweller, Van Merrienboer, and Paas, 1998).

Skulmowski and Rey, 2017 suggests several methods for measuring cognitive load inside embodied learning environments. For subjective methods, several questionnaires were designed to elaborate to what degree the user is experiencing the different types of cognitive load. One of those methods is the NASA Task Load Index, or NASA-TLX (Harris, Wilson, and Vine, 2020. The NASA-TLX aims to investigate 6 items: mental demand, physical demand, temporal demand, performance, effort and frustration. According to the findings of several studies, Skulmowski and Rey, 2017 found that there were no significant differences in the cognitive variables presented in the NASA-TLX. Skulmowski and Rey, 2017 instead recommends the question items presented by Eysink et al., 2009 and be seen in figure 2.5.

Makransky and Petersen, 2021 investigate what constitutes as learning outcome in digital applications. The Cognitive Affective Model of Immersive Learning (CAMIL, see figure 2.6) shows several factors contributing to gaining knowledge.

CAMIL is a research-based theoretical framework that describes how IVR can lead to knowledge acquisition as well as the transfer of learning. Makransky and Petersen, 2021 identify presence and agency as the two general affordances of IVR and described how it is not the medium of IVR that causes more or less learning, but rather that the instructional methods used in an IVR lesson will be specifically effective if it facilitates the unique affordances of the medium. The instructional methods that enrich learning through higher presence or agency will specifically increase learning through immersive technology.

Presence and agency influence six affective and cognitive factors and through these factors different learning outcomes can occur. Those learning outcomes are

**Overview of Cognitive Load Items Used in the Learning Environments**

| Type of Cognitive Load | Corresponding Item |
|---|---|
| Intrinsic load | How easy or difficult do you consider probability theory at this moment? |
| Extraneous load: navigation | How easy or difficult is it for you to work with the learning environment? |
| Extraneous load: design of the learning task | How easy or difficult is it for you to distinguish important and unimportant information in the learning environment? |
| Extraneous load: accessibility of information | How easy or difficult is it for you to collect all the information that you need in the learning environment? |
| Germane load | How easy or difficult was it to understand the simulation?[a] |
| Overall load | Indicate on the scale the amount of effort you had to invest to follow the last simulation.[a] |

[a]This item was taken from the inquiry learning environment. The other environments used similar wordings depending on their particular instructional approach.

FIGURE 2.5: Questionnaire items for investigating cognitive load (Skulmowski and Rey, 2017).

factual, conceptual and procedural knowledge and transfer of learning. Factual knowledge are rather specific things like terminology, specific details and elements, whereas conceptual knowledge is more comprehensive, like principles, theories and structures. IVR might, however, not necessarily be the ideal medium for these two learning outcomes and the effectiveness of IVR for developing factual and conceptual knowledge depends on how the IVR lesson is designed (Makransky and Petersen, 2021).

Procedural knowledge is regarding *how* to do something and is seen in behaviour (e.g. like how to drive a car) rather than conscious recollection. IVR is frequently used for teaching procedural-practical knowledge, since IVR provides optimal conditions for rehearsing procedure. Transfer of learning is learning that took place in one context impacting performance on another. Such transfer can be either procedural or conceptual (Makransky and Petersen, 2021).

The six affective and cognitive factors that can lead to these learning outcomes are: situational interest, intrinsic motivation, self-efficacy, embodiment, cognitive load and self-regulation.
Situational interest promotes learning by increasing the learners attention and engagement.

Intrinsic motivation can influence learning by exciting persistence and curiosity. Keeping the learner's focus on the task and inciting awareness of one's learning process, these processes can promote factual, conceptual and procedural knowledge and transfer of learning.

Self-efficacy is a determinant of setting goals, activity choices, willingness to spend effort and persistence and all have a positive effect on academic performance and learning.

Makransky and Petersen, 2021 argue that embodiment is important for learning, with some of the same reasoning as explored in section 2.1.2. They highlight the connection between motor and visual processes, the more explicit the connection the better the learning and that, when physical activities are meaningful for the learning, learning outcome improves.

Cognitive load provides an understanding to the complexity that occurs when designing IVR learning experiences. While higher degrees of presence and agency are a positive, it can create a virtual environment with a higher extraneous load. This is especially true when the information and details presented are not relevant for learning. The cognitive load is therefore a negative influence on learning.

Self-regulation is another complicated factor. Students who successfully self-regulate generate thought, feeling and action to attain their learning goals. However, IVRs are highly engaging, so learning can suffer if lessons are not scaffolded. Self-regulation can be increased through meaningful interaction with peer avatars or pedagogical agents. Self-regulation can therefore be both a negative and a positive factor. IVR learning tools should be developed with a focus on their affordances, while also considering cognitive load and self-regulationMakransky and Petersen, 2021.

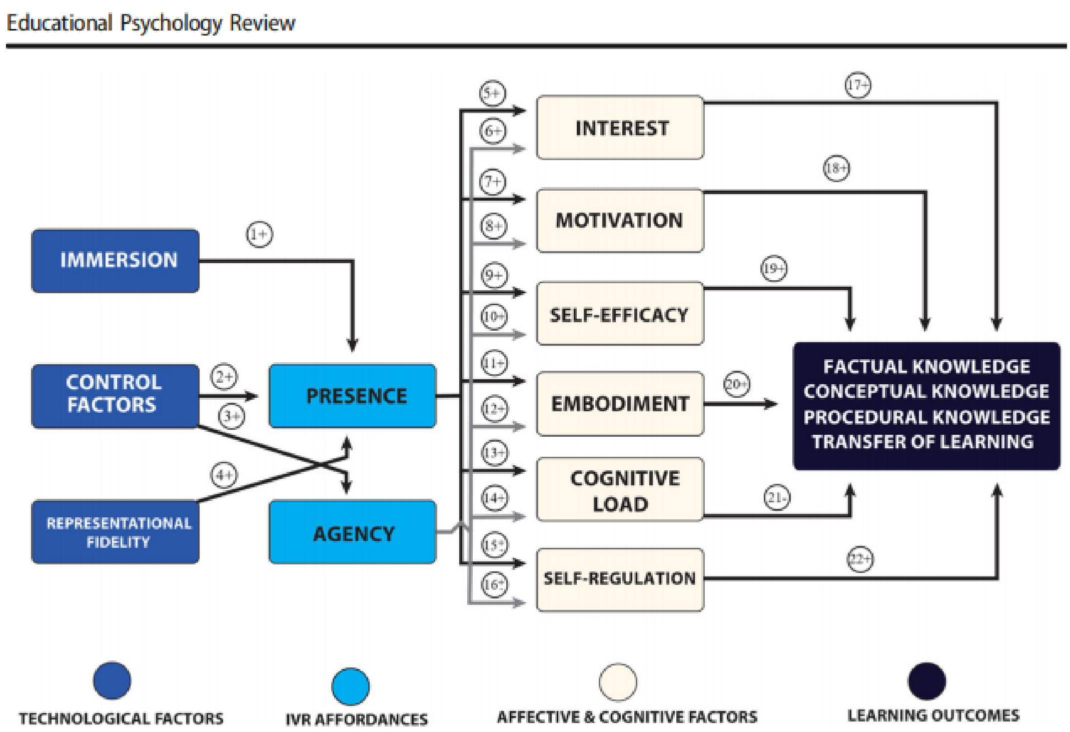



FIGURE 2.6: The Cognitive Affective Model of Immersive Learning, by Makransky and Petersen, 2021.

The following section will look at the most popularly used DGE in Denmark today: GeoGebra.

## 2.4 GeoGebra

In this section, we investigate the most used DGE for mathematics education in Denmark today: GeoGebra (Højsted, 2020). How does this popular DGE affect student's learning achievement and what can we learn from it?

GeoGebra[1] is an open-source mathematics software that is globally used in and outside of classrooms. It is the leading software for supporting STEM education and teaching innovation, known mostly for its easy-to-use interface.

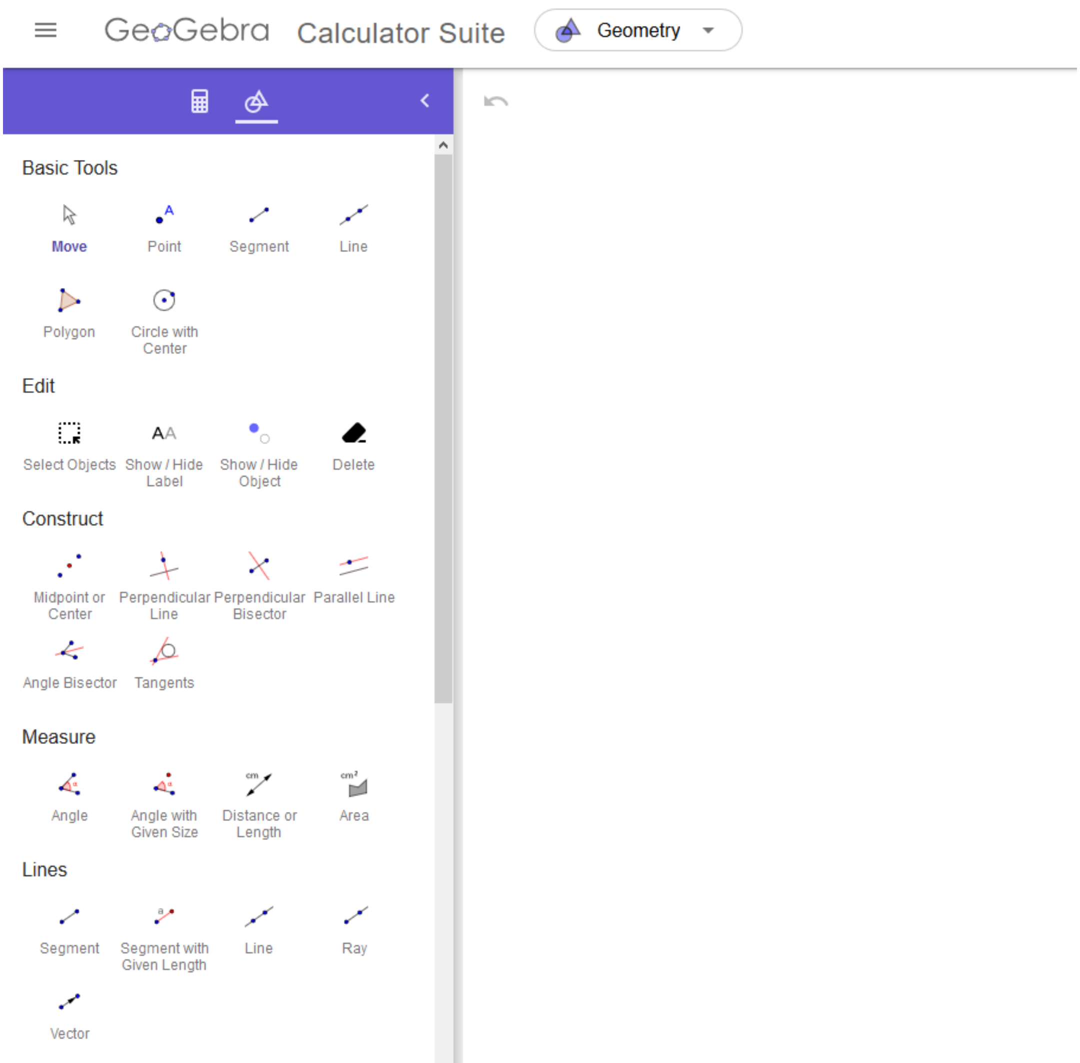



FIGURE 2.7: The GeoGebra Geometry User Interface.

In a study by Arbain and Shukor, 2015, the effects on learning achievement on students in Malaysia was investigated. A control group was to be taught mathematics without a DGE and the experimental group was taught classes using GeoGebra.

[1]https://www.geogebra.org

Their results showed that students have a positive perception towards learning and show a better learning achievement when being taught classes using GeoGebra.
However, are we using the potentials that GeoGebra can bring to a classroom to its full extend? Højsted, 2020 wrote an article with a quantitative study investigating DGEs in the Danish lower-secondary mathematics education, in relation to reasoning competency. A questionnaire aimed towards mathematics teachers was developed based on an extensive review by Niss and Højgaard, 2019, where four reasoning potentials of DGEs are uncovered: feedback, dragging, measuring and tracing. Højsted, 2020 reports that in the current state, DGEs might largely be used in lower-secondary education as a digital substitute for paper-and-pencil assignments. Therefore, DGEs might not be fully utilized to their potential in improving the Reasoning Competency (RC) of the young students.
For example, in one of the questions in Højsted, 2020, the teachers are asked about locked and free objects and whether they are an important aspect of the DGEs used today. Arzarello et al., 2002 describes that the distinction between locked and free objects potentially link spatio-graphical and theoretical properties of figures, which is an important aspect of developing reasoning competency (as previously established in section 2.1.4). Højsted, 2020 reports that this aspect of DGEs is not sufficiently utilized in the current state. Rather, teachers use DGEs for improving the efficiency and precision of existing pencil-and-paper tasks.
Højsted, 2020 writes suggestions for future DGE tasks. Højsted, 2020 suggests that teachers need guidelines for creating tasks in DGEs, as it cannot be expected for a teacher to adapt pencil-and-paper tasks to specialized tasks utilizing the full potential of a DGE. Højsted, 2020 refers to Trocki and Hollebrands, 2018 for task quality. Additionally, it is suggested to implement *"construction"* tasks, as they may support the theoretical underpinnings of locked and free objects, so that a student may interpret the theory behind mathematical figures and how the figures react to the user's manipulation. This construction task should take into account the affordance of constructing a mathematical figure and cannot expect a teacher or student to do this without prior knowledge. Therefore, the task must be clearly instructed for novice-level users (Højsted, 2020).

### 2.4.1 Summary

We have presented the theoretical underpinnings for creating an IGE. We have looked at the formal definitions for geometry related competencies that students are expected to possess, how they can be obtained through embodied cognition and gestural congruency, using moderate to high bodily engagement with integrated tasks. Dynamic gestures form an important component in formulating and communicating valid proofs in geometry education. Students that perform meaningful and relevant gestures are shown to have an improved understanding of mathematical concepts.

Constructing and/or manipulating mathematical objects and letting learners observe, record and/or reconstruct patterns of variance/invariance is likewise important for conjecturing, explanation and proof. Digital embodied learning increases the learning potential of embodied learning. Additionally, digital embodied learning can improve the student's content understanding, motivation and mathematical competency development.

The two main affordances of IVR are presence and agency. These two affordances, in turn, influence six affective and cognitive factors through which learning can occur. Of these six, cognitive load is a negative impacting factor and is highlighted as a potential problem for an IGE. This was also found to be the case in our previous work. Design of an IGE should therefore also focus on minimizing the cognitive load as well as how to implement high level of bodily relevant activities.

The following chapter synthesizes design requirements for an IGE from the theoretical underpinnings presented in this chapter.

# Chapter 3

# Final Problem Statement & Design Requirements

## 3.1 Design requirements

Based on the analysis of relevant literature and user testing from our previous work, we can establish a set of design requirements, presented in table 3.1.

From chapter 2, we have narrowed the scope of this thesis down to the following final problem statement:

> *"How can an immersive virtual environment with a gesture-based interface facilitate geometry education at a lower-secondary level?"*

Where, as mentioned in section 2.1.1, by "facilitate geometry education" we imply the development of mathematical competency in geometry.

| **Functional Requirements** | | | |
|---|---|---|---|
| No. | | | Section |
| 1 | | The application should have three modes | |
| 2 | | Create mode should have a gesture for constructing a point. | 2.2, 2.4 |
| 3 | | Manipulation mode should have a gesture for manipulating a point. | 2.2, 2.4 |
| 4 | | Manipulation mode should have a gesture for manipulating the entire triangle at once. | 2.2, 2.4, 2.1.1 |
| 5 | | Conjecture mode should have a gesture for measuring angles. | 2.2, 2.4, 2.1.1 |
| 6 | | Conjecture mode should have a gesture for measuring side length. | 2.2, 2.4, 2.1.1 |
| 7 | | Conjecture mode should have a gesture for measuring area. | 2.2, 2.4, 2.1.1 |
| 8 | | The environment should contain a 2D coordinate system | 2.1.1 |
| 9 | | The environment should contain a task board. | 2.1.1, 2.2 |
| 10 | | The environment should contain a hint board | 2.1.1 |
| 11 | | The environment should contain a submit action | 2.1.1 |
| **Non-functional Requirements** | | | |
| 1 | | Gestures should be Iconic – preferably dynamic gestures. | 2.1 |
| 2 | | Gestures should have gestural congruence. Learners should be aware of the gesture's relevance to the mathematical concept. | 2.1, 2.2 |
| | a) | The gesture for measuring angles should have relevance to existing tools like a protractor or a goniometer. | |
| | a) | The gesture for measuring side length should have relevance to existing tools like a ruler or a measuring tape. | |
| | a) | The gesture for measuring angles should have relevance to the concept of area, like representing or illustrating an area. | |
| 3 | | The embodied activity should let learners enact mathematical relationships. | 2.1 |
| 4 | | The application should allow for active interaction, exploration, and exploratory behaviour. | 2.1 |
| 5 | | The application should provide tools so learners can use geometric methods and calculate simple measurements. | 2.1.1 |
| 6 | | The application should have high levels of presence and agency. | 2.3 |
| 7 | | The application should have a low cognitive load. | 2.3, 2.2 |
| | a) | Reduce unnecessary process (extraneous load). | 2.3 |

TABLE 3.1: Functional and non-functional design requirements.

# Chapter 4

# Design and implementation

The design and implementation of an IGE is presented in this chapter. We will run through the hardware and software specifications, their designed elements and limiting factors. This implementation, as mentioned in the introduction, is a second iteration. The first iteration was implemented and tested by 7 User eXperience (UX) testers. The results of this UX experiment were converted into developmental tasks which were performed and presented in the current second iteration.

## 4.1 Hand-tracking enabled HMD

For the implementation of the IGE, the Oculus Quest 2[1] was utilized (see figure 4.1). It is a VR headset capable of running as a standalone headset with an internal android-based operating system. When connected to a computer, it can also function as VR for PC, using the computer's power and virtual content. We chose this hardware because of the mobility it provides and built-in native hand-tracking.

FIGURE 4.1:
The Oculus Quest 2.

Hand-tracking allows the users to utilize their hands directly, instead of conventional controllers to navigate through virtual applications. The feature is optional and currently still experimental. It works through image processing technology; the HMD uses 4 monochromatic sensors to estimate the transform of certain points on the hands, like fingertips, joints, knuckles and bones. The image processing analysis is done during real-time. The software estimates the size of hands, position of the hands in the real space and gets translated to the VR environment, as seen in figure 4.2.

In our previous work, UX test results showed positive user feedback on the topics of immersion and presence, primarily due to the hand-tracking feature. Because of the ability to use embodied interaction, the relatively low pricing (compared to other existing VR headsets) and the standalone feature, we chose to use the Oculus Quest 2. For a classroom implementation, it is crucial to be able to deliver hardware that is self-sufficient and compact to be considered a viable option for institutions.

[1] https://www.oculus.com/quest-2/

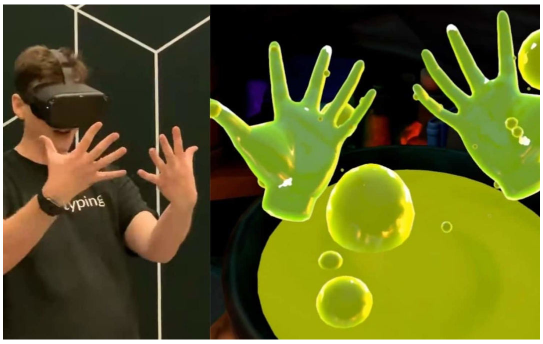


FIGURE 4.2: The user can see and use their own hands in virtual space.

## 4.2 Previous iteration

This section will give an overview of the first iteration of the IGE implementation.

### 4.2.1 System Overview

There were four different gestures available for the user to do, "Create" gesture, pinch with one hand, "Grab" gesture, making a fist, "Measuring" gesture, pinch with both hands and a "Protractor" gesture, an L-shape using their index and thumb (see figure 4.3). The gestures were designed to have gestural congruence (see section 2.1, 2.2). For example, the L-shape gesture was used to measure angles and believed to have a strong resemblance to two sides of a triangle that would make an angle.

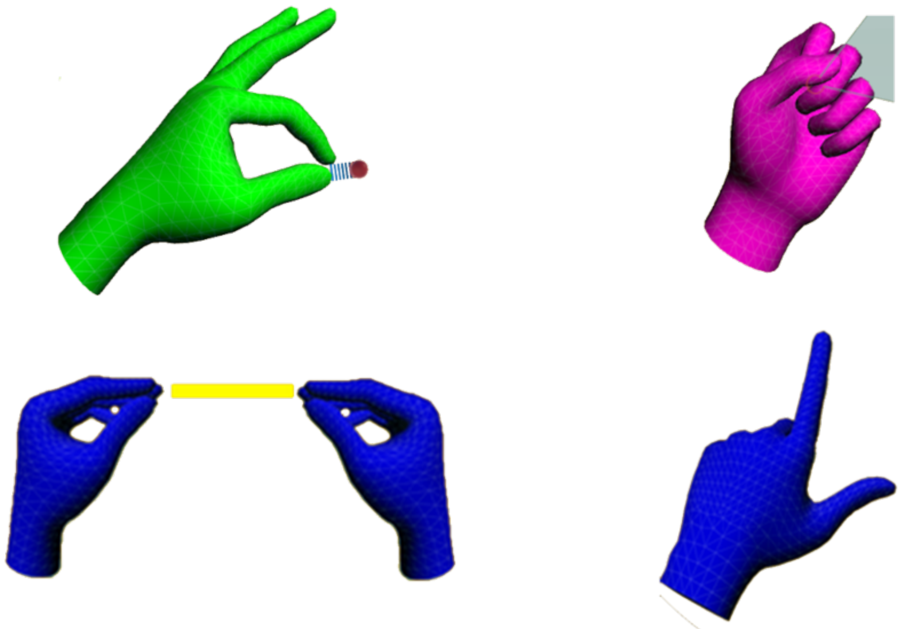


FIGURE 4.3: Previous iterations gestures. Upper left "Create", upper right "Grab", bottom left "Measuring", bottom right "Protractor".

At the start of the application, the user would be in construction mode. To visualize this to the user, their hands would be coloured green. Here the user could use the one-handed pinch gesture to construct a point in 3D space. The point would be represented as a small coloured sphere. When a point/two points were constructed, a dotted line appeared between the point(s) and the user's thumb of the hand in focus (see figure 4.4). When the third point was constructed, the dotted line would disappear, a solid triangle would appear between the points and the user would now be in manipulation mode. To indicate this their hands would now be coloured blue.

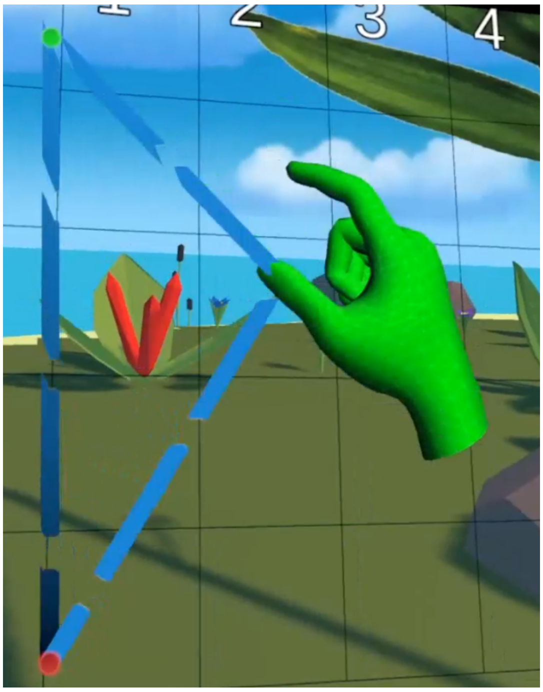



FIGURE 4.4: Dotted preview line.

In this mode, the user could grab one of the points to move them around in 3D space. They could also grab the triangle's centroid to move and rotate the entire triangle at once. The user could also place the point(s) on a coordinate system one by one or place all the points at once by placing the centroid first. Once the triangle was on the coordinate system the user could use the angle- and side measuring tool by performing the gesture in proximity to the desired corner for angles or corners for side lengths.

In the IVE, besides the coordinate system, a "Hint" board would display the current mode and what gestures were available in that mode. There was also an assignment board with a list of tasks the user should try to solve. Lastly, there were two buttons. A red "Delete" button would delete the triangle and a green "Submit" button that would check if the user has solved any of the tasks on the assignment board. An overview of the environment is presented in figure 4.5.

Lastly, a warning sign would appear in the centre of the field of view if the user's hands for any reason would stop rendering.

### 4.2.2 Technical Implementation

"Oculus Integration for Unity" provides rendering, social, platform, audio, and Avatars development support for Oculus VR devices and some Open VR supported devices[2]. From this package, the "OVRHandPrefab" was used to render the user's hands in the application. The "OVRHandPrefab" also contains a hierarchy of the

[2]https://assetstore.unity.com/packages/tools/integration/oculus-integration-82022

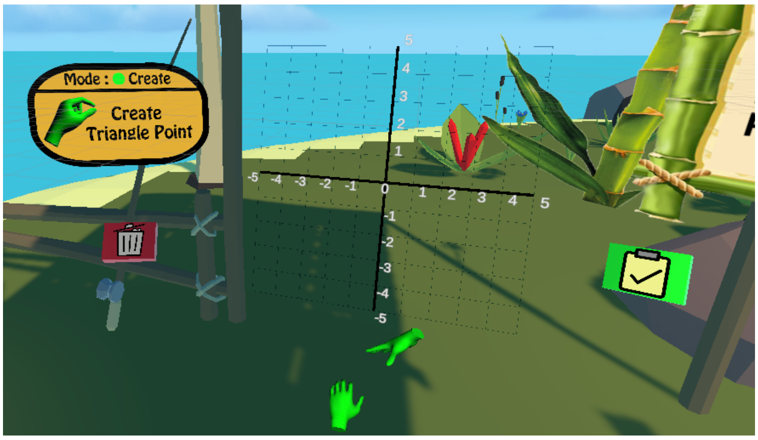



FIGURE 4.5: Previous iteration's environment.

prefab's "bones". The "bones" are empty game objects located at each of the rendered hand's joints and fingertips (see figure 4.6).

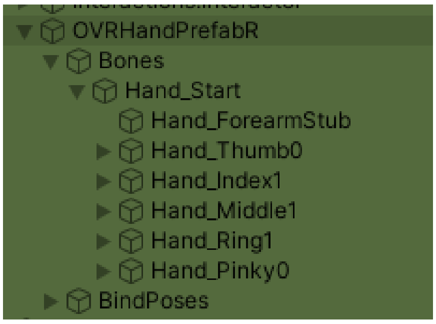



FIGURE 4.6: Hierarchy of the bones in an OVRHandPrefab for the right hand.

A gesture would then be made by a team member and the "bones" relative transform would be saved to a custom "Gesture" game object. Starting at line 12 in listing 1, the function loops through the "fingerIndex" array. In line 14, the inverse transform positions of the "bone" with the index number i is added to a Vector3 list called "position". The inverse transform is used to transform the "bone's" position from world space to object space. This is to save the "bone's" relative position to each other and not their position in the 3D world space. If this is not done the gesture would only work if the user performed the gesture at the same place in space every time.

Next, in line 18 there is a nested for-loop of the same "fingerIndex" array. Then at line 20-21, there is a check to make sure that the two for-loops are not at the same "bone". At line 22-26 the distance from the "bone" i and "bone" j is calculated and added in a float list called distances. When the nested for-loop has finished, each "bone" in this gesture would have calculated and saved its distance to all other "bones" in this gesture. The check at line 20-21 is to avoid having to calculate and add a distance for the current "bone" itself.
Lastly, line 30 and 31 saves the two lists to two publicly accessible lists.

During run-time, the application can then check the position and distance to the user's "bones" and compare it to the different gestures that are saved.
Listing 2 shows the part of the "gesture detection" function that compares the saved

```
public void Save()
{
    Debug.Log("Saveing...");

    List<float> distance = new List<float>();
    List<Vector3> position = new List<Vector3>();

    nameOfHand = GetComponentInParent<GestureDetector>().nameOfHand;
    fingerBones = handData.Bons(nameOfHand);
    skeleton = handData.Skellington(nameOfHand);

    for (int i = 0; i < fingerIndex.Length; i++)
    {
        position.Add(skeleton.transform.InverseTransformPoint(
        fingerBones[fingerIndex[i]].Transform.position)
        );

        for (int j = 0; j < fingerIndex.Length; j++)
        {
            if (i == j)
                break;
            distance.Add(Vector3.Distance(
            skeleton.transform.InverseTransformPoint(
            fingerBones[fingerIndex[i]].Transform.position),
            skeleton.transform.InverseTransformPoint(
            fingerBones[fingerIndex[j]].Transform.position)));
        }
    }

    fingerDistances = distance;
    fingerPositions = position;
    Debug.Log("Saved!");
}
```

LISTING 1: Save function for the "Gesture" game object.

gesture's "bones" to the "bones" of the user's hand. This code snippet is within a for-each loop that loops through all the saved "Gesture" game objects.

In line 1, a for-loop loops through the gestures "fingerIndex". Then at line 5-8, the gesture's "bone" position and the current "bone" position of the user's hand are used to calculate the distance between them. The distances between the two positions are added to a Vector3 list, called "currentPositions". The distance between the position is used to tell how "similar "the user's hands are to the gesture. If the position distance is small, the user's hands aligns well with the gesture, if the position distance is large, the user's hands are not aligning with the gesture.

Then in line 18-22, all the positions distances are summed together and divided by the number of position distances.

In line 28, an if-statement checks whether the summed position distances are less than the current minimum, and that the summed position distances is equal to or less than the gesture's acceptance threshold. Each gesture has their own threshold for how similar the user's hand has to be to the gesture before it is accepted. If this is the case, the position the user's hand is in is close to the gesture it is being compared to and the current minimum position distance is updated. The gesture that is being compared is set to the temporal current gesture, in line 32 and 33.

If the next gesture's position distance is even smaller, then the user's hand is

```
for (int i = 0; i < gesture.fingerIndex.Length; i++)
    {
        try
            {
                currentPositions.Add(Vector3.Distance(
                skeleton.transform.InverseTransformPoint(
                fingerBons[gesture.fingerIndex[i]].Transform.position),
                gesture.fingerPositions[i])
                );
            }
        catch (System.Exception)
            {
                Debug.Log($"Failed to load finger positions on:
                {gesture.myName}");
            }
    }

                foreach (float position in currentPositions)
                {
                    sumDistPos += position;
                }
                sumDistPos /= currentPositions.Count;
                gesture.pos = sumDistPos;
                // Check if the gesture is not discarded and that
                the sum distance is less then current minimum
                // currentMin is initially set to Infinity so we
                don't accidentally exclude any first gestures
                if (sumDistPos < currentMinPosDist)
                {
                    // Set the current minimum to this gestures sum
                    distance and this gesture as the current gesture
                    currentMinPosDist = sumDistPos;
                    tempCurrentGesture = gesture;
                }
            }
```

LISTING 2: Part of the "Gesture Detection" function.

closer to this gesture and the current minimum position distance and temporal current gesture are updated again. If this is not the case nothing will be updated.

A similar function is in use for the distances between "bones". The gesture with which position distance and distance between "bone" that are the most similar to the user's hands, end up being the one gesture that the function returns.

Listing 3 shows the gesture detection method being called in line 1. At line 5 there is a check to see if the returned gesture is a saved gesture or an empty gesture (a gesture without any saved data) and the result is saved in a boolean called "hasDetect".

The if-statement in line 7 checks if "hasDetect" is true (meaning the gesture returned by the function is one of the saved ones) and checks if the returned gesture is not the previous gesture. Line 11 and 12 invokes the gesture's "onRecognized" Unity event and sets its boolean action to true. These two methods are used to invoke the functions tied to the detected gesture.

```
currentGesture = DetectTest();
        Debug.Log($"Current Gesture: {currentGesture.myName}");

        // Make sure that it is not a new-never-seen-before gesture
        hasDetect = !currentGesture.Equals(new GestureData());

        if(hasDetect && !currentGesture.Equals(prevGesture))
        {
            // When a gestures is detected, we will have to set a coresponding
            // boolean action and invoke a function
            currentGesture.onRecognized.Invoke();
            currentGesture.GetComponent<BooleanAction>().Receive(true);

            if (prevGesture != null)
            prevGesture.GetComponent<BooleanAction>().Receive(false);

            prevGesture = currentGesture;
            Debug.Log($" Gesture: Accepted {currentGesture.myName}, {nameOfHand}");
        }
```

LISTING 3: Detecting a gesture and invoking its method.

### 4.2.3 User feedback

Based on feedback from the UX test performed for the previous iteration a number of changes were implemented. The biggest changes to come out from the user testing were the wish for the possibility to make more then one triangle, gestures for measuring area and scaling, User Interface (UI) options for switching modes manually and removal of the warning label. During testing, it also became apparent that the gesture detection algorithm needed to be more robust.

## 4.3 Current iteration

This section goes over how the second iteration differs from the previous one, based on the feedback from our 7 UX testers.

### 4.3.1 System overview

The application now has three modes. "Create mode" where the user can construct triangles, "Manipulation mode" where the user can interact with triangles and "Tools mode" where the user can measure angles, side lengths and area of the triangles.

The user can, in any mode, bring up the menu to switch modes, delete triangle or submit at triangle to solve assignments. To bring up the menu the user can point either of their palms towards their face. This will bring a floating menu near the hand performing the gesture.

At all times a coordinate system, assignment board and a hint board is present in the application.
The coordinate system is a 10 by 10 2D coordinate system placed in front of the user. Here the user can place points of the triangle on the board at whole integer intervals.

The assignment board is to the right of the coordinate system. The assignment board contains a list of assignments the user can try to solve. If the user thinks they have solved an assignment they can bring up the menu and press the green "submit" button. This will cross out any assignment correctly solved on the assignment board.

The hint board is located to the left of the coordinate system. This board shows what mode the user is in and what gestures are available to use in the current mode.

At the start of the application the user is in "Create mode". Here the user can perform a one-handed pinch gesture to construct one corner point of a triangle. Constructing three corner points will instantiate a triangle and automatically switch the application to "Manipulation mode". The user can at any time open the menu to manually switch modes.

In "Manipulation mode" the user can use the grab gesture on any of the three corner points and on the triangle's centroid. When the user is grabbing a point they can freely move it around in the 3D space. If the user is grabbing the centroid they can move the entire triangle in one movement and rotate it. The user can place the points individually on the coordinate system or all at once by placing the centroid on the coordinate system first. When a point is snapped on to the coordinate system, the coordinate will be shown next to it and a snapping sound is played.

The user can also grab scalar points to either upscale or downscale the triangle uniformly. This is done by first grabbing two scalars and then moving them outwards from the triangle to upscale it uniformly. Moving them inwards will downscale the triangle uniformly.

The user can again bring up the menu and manually switch modes. In this mode, the user can also bring up the menu and move the triangle to the "delete" icon to delete the triangle.

The user can manually switch to the "Tools mode". In this mode, the user will be able to measure angles, side lengths and area of the triangle.

To measure angles the user can make the "protractor" gesture with either one of their hands, or both at the same time, in the proximity of the angle they want to measure. When performing the "protractor" gesture the angle will be displayed next to the user's hand and a yellow line will go from the user's hands to the angle they are measuring.

To measure side lengths, the user can do a pinch gesture with both hands. This will instantiate a line between the pinched fingers on each hand and display the distance in the middle of the line. The user can then move their hands further or closer apart to measure distances.

To measure the area of a triangle, users can hold up both their hands in front of them with both thumbs pointing towards each other to silhouette a triangle. Pointing this gesture towards a triangle will display the area of that triangle between the hands and create a yellow line that goes from the hands to the triangle they are measuring. The user can at any time open the menu to switch modes.

A full system overview can be seen in appendix A.

### 4.3.2 Gesture improvements

A gesture for measuring the area and for scaling the triangle was implemented. The method of making a gesture was the same as the last iteration of having a team member performing the gesture and having the hand's "bones" data saved in a game object. Since both of these gestures require two hands, the approach to gesture detection needs to be changed.

```
1  void Update()
2      {
3          // Making sure the list of bons is actually is populated and exist,
4          // if no we try grabbing it again
5          if (fingerBons == null || fingerBons.Count == 0)
6          {
7              fingerBons = handData.Bons(nameOfHand);
8          }
9          //________________________________________________//
10         currentGesture = DetectTest();
11         //Debug.Log($"Current Gesture: {currentGesture.myName}");
12
13         // Make sure that it is not a new-never-seen-before gesture
14         hasDetect = !currentGesture.Equals(new GestureData());
15
16         if (currentGesture.is2Handed || currentGesture.myName == "Neutral")
17         {
18             //Debug.Log($"2 Hand: {currentGesture.is2Handed}, {currentGesture.myName}");
19             if (hasDetect && !currentGesture.Equals(prevGesture))
20             {
21                 // When a gestures is detected, we will have to set a corresponding
22                 // boolean action and invoke a function
23                 currentGesture.onRecognized.Invoke(fingerBons[19].Transform.position);
24                 currentGesture.GetComponent<BooleanAction>().Receive(true);
25
26                 if (prevGesture != null) prevGesture.GetComponent<BooleanAction>().Receive(false);
27
28                 prevGesture = currentGesture;
29                 Debug.Log($" Gesture: Accepted {currentGesture.myName}, {nameOfHand}");
30             }
31         }
32         else
33         {
34             if (hasDetect && !currentGesture.Equals(prevGesture) &&
35             nameOfHand == handData.ClosestHand())
36             {
37                 currentGesture.onRecognized.Invoke(fingerBons[19].Transform.position);
38                 currentGesture.GetComponent<BooleanAction>().Receive(true);
39
40                 if (prevGesture != null) prevGesture.GetComponent<BooleanAction>().Receive(false);
41
42                 prevGesture = currentGesture;
43                 Debug.Log($" Gesture: Accepted {currentGesture.myName}, {nameOfHand}");
44             }
45         }
46     }
```

LISTING 4: Current iteration's gesture detection function.

Listing 4 shows the current way detected gestures are handled based on whether they are one- or two-handed. In line 16, the gesture returned by the gesture detection function, is checked to see if its "is2Handed" boolean is true (this boolean was added to the gesture game object) or if the gesture is the "Neutral" gesture. The neutral gesture has no hand data and was added for the purpose of being able to switch to a neutral state where no gesture is being detected. If either one is true, the code for determining if the gesture's action should happen was unchanged.

If none of the checks in line 16 return true, the code jumps to line 32. Here the code functions much like the previous iteration. There was a check added to see if the hand in focus is the one closest to the center of the user's current view. This check was added to reduce the frequency of unintentional gestures, making the algorithm more robust.
If the user's hand is indeed at the center *and* the same hand is performing a gesture, it is very likely to be on purpose.

Another way of making the gesture detection algorithm more robust was the implementation of a "breakout threshold". The "breakout threshold" was implemented to make it harder for the gesture to be discarded after it had been registered.

To recall; the user's "bones" are compared to the gesture's saved "bones" positions. The gesture with the smallest difference in positions and under the "break in" threshold will be accepted as the gesture the user is making. However, if the user is just at the "border" of this threshold, the detection will accept the gesture in one frame, while refusing it in the next, and accept in the third frame. In practice, this could mean that the user would accidentally make two triangle points in one pinch. Therefore the user, after having made a gesture, now has to "break out" of that gesture instead.

```
1  // same check for positions
2              prevSumPos = 0;
3              foreach (float position in currentPositions)
4              {
5                  prevSumPos += position;
6              }
7              prevSumPos /= currentPositions.Count;
8              prevGesture.pos = prevSumPos; // since we only do this for editor visibility,
9              //we don't actually need to do this
10
11             if (prevSumPos > prevGesture.breakPosThresh) isDiscarded = true;
12             // so now neither the dist and pos breakout thresh is exceeded,
13             //we're going to continue with our prev gesture as the current gesture.
14             else if (prevSumPos <= prevGesture.breakPosThresh)
15             {
16                 if (prevGesture.myName == "Menu" &&
17                 !controllerAlias.GetComponent<Raycaster>().menuHit)
18                     isDiscarded = true;
19                 else {isDiscarded = false;}
20             }
```

LISTING 5: "Break out" threshold.

Lines 3-8 in listing 5 calculate the gesture position distance. Then, in line 11, there is a check to see if the current gesture the user is making is exceeding the last gesture's "breakout threshold". A gesture's "breakout threshold" is larger than its threshold for detection. If the position of the "bones" exceeds the previous gesture's, it can be discarded as the same gesture and continue checking other gestures. If not, the user is making the same gesture and the function can simply return it again.

### 4.3.3 Procedural mesh geometry

In order to to make it possible to construct multiple triangles, a queue of "polygon" game objects is required (see figure 4.7). Each of these game objects contain a centroid, three triangle points, and three scalars.


FIGURE 4.7: Queue of "polygon" game object in the scene.

When a "pinch" gesture is made, its "onRecognized" unity event is invoked. Now, this event takes in the Vector3 of the user's fingertip positions in 3D space. This event then calls the "HandlePinch" function (see listing 6).

```
1      public void HandelePinch(Vector3 v)
2      {
3          switch (pinchCount)
4          {
5              case 0:
6                  currentPolygon = inactivePolygon.Peek();
7                  currentPolygon.GetComponent<PolygonGizmoManager>().GeneratePoint(v);
8                  sm.PlayPop();
9                  pinchCount++;
10                 break;
11             case 1:
12                 currentPolygon.GetComponent<PolygonGizmoManager>().GeneratePoint(v);
13                 sm.PlayPop();
14                 pinchCount++;
15                 break;
16             case 2:
17                 currentPolygon.GetComponent<PolygonGizmoManager>().GeneratePoint(v);
18                 sm.PlayPop();
19                 inactivePolygon.Dequeue();
20                 activePolygon.Add(currentPolygon);
21                 pinchCount = 0;
22                 modeManager.ModeState = ModeManager.Mode.Manipulation;
23                 break;
24             default:
25                 break;
26         }
27     }
```

LISTING 6: The "HandlePinch" function.

The functions have a switch-statement with three cases. At the user's first pinch, the first "polygon" game object in the queue of inactive game objects is retrieved at line 6. Then, that game object's "GeneratePoint" function is called, with the position of the user's fingertip. The "GeneratePoint" function places a triangle point at the fingertip of the pinching hand. At line 9 the "pinchCounter" is increased by one.

When the user has pinched three times, the last triangle point has been constructed and this "polygon" game object is dequeued from the inactive polygon queue (line 19) and added to the active polygon queue (line 20). The "pinchCounter" is set to zero (line 21) and the mode is changed to "Manipulation" in line 22.

### 4.3.4 User interface improvements

The warning sign informing the users that their hands are outside the tracking space, was removed. Users found it annoying, did not know what it meant or were confused. Based on interviews with participants, it was found to be an unnecessary feature. The hands disappearing from the scene was enough of an indication towards the user.

The addition of manually selecting modes led to the "menu" gesture. This gesture had the added condition, that the palm of the hand doing the gesture should point towards the user's head. This was implemented by casting a ray from the user's hand (line 1 in listing 7), check if the ray hit the "Headset" game object (line 4) and set a corresponding boolean to true if it does (line 7).

```
1  if(Physics.Raycast(origin, dir, out hit, 5, LayerMask.GetMask("Menu")))
2          {
3              //Debug.Log($"Hit {hit.collider.gameObject.name}");
4              if(hit.collider.gameObject.CompareTag("Headset"))
5              {
6                  Debug.Log("Hit");
7                  menuHit = true;
8              }
9          }
```

LISTING 7: Cast a ray to check if the hand is oriented towards the HMD.

The gesture detection function then checks if the raycast is not hitting the "Headset" when it is about to compare the user's gesture to the "menu" gesture. If the raycast did not return a hit, it continues to the next gesture, as there is no need to calculate whether the user is performing this gesture (see listing 8).

```
if (gesture.myName == "Menu" && !controllerAlias.GetComponent<Raycaster>().menuHit)
                    continue;
```

LISTING 8: Check if the menu raycast is hitting the "Headset" game object.

## 4.4 Island environment

The environment in which the user is immersed in the IGE is a small, low-fidelity island (see figure 4.8). The environment was designed for a young audience. The idea of using an island was with the intent to cause an isolated, yet focused feeling for the user. The graphics are of a low fidelity, due to the fact that this application has to be able to run smoothly on a mobile device (such as the Quest 2) and not distract the user from the tasks. Therefore, we are not expecting a high level of experienced realism from our users.

FIGURE 4.8: The island environment for the IGE.

# Chapter 5

# Methodology

This chapter presents the experimental design for testing our hypothesis. Two experiments were planned: a UX test with 13 participants and a heuristic evaluation performed by 4 experts. The experiments were run following the COVID-19 guidelines[1]:

- Each participant is required to show a negative PCR test no older than 72 hours.
- Every person involved in the experiment is to wear a facemask. An exception is made while the participant is wearing a VR HMD.
- Everyone is to sanitize their hands before, after and between every stage of the experiment.
- A 1.5m distance is to be kept between all persons involved in the experiment.
- The VR HMD is to be cleaned using the Cleanbox[2] after every participant.

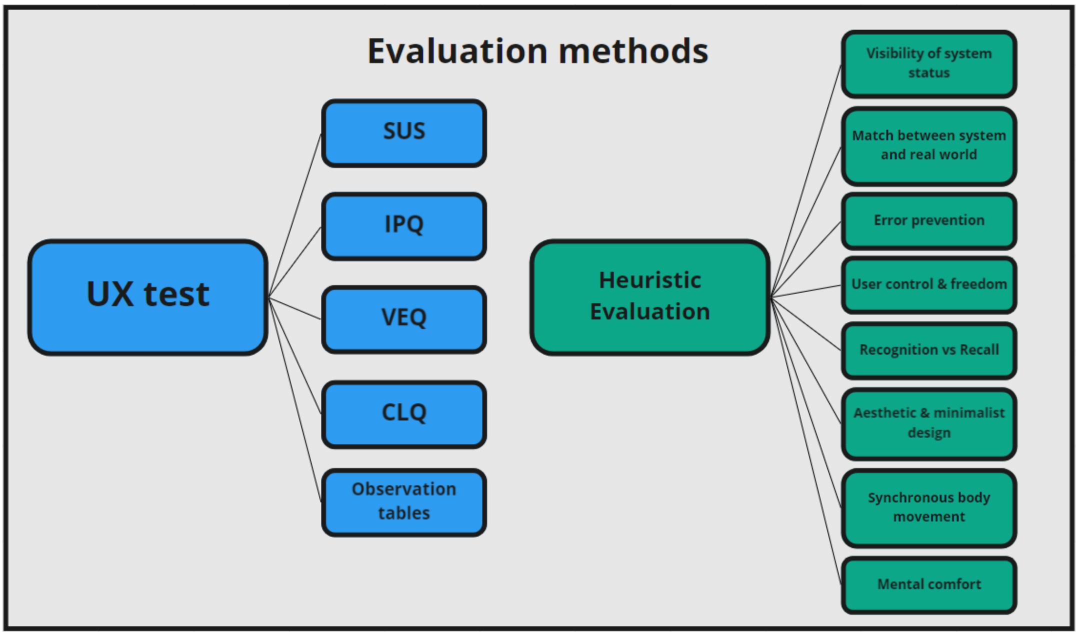



FIGURE 5.1: The evaluation methods.

[1] https://www.aau.dk/coronavirus/
[2] https://www.klaran.com/case-study-cleanbox-disinfection-device-klaran-uvc-leds

These methods are aimed at collecting qualitative data, where participants were gathered using convenience sampling (Bjørner, 2016). We were interested in collecting in-depth feedback from our UX participants and heuristic evaluators. The UX test involved an in-depth questionnaire to retrieve data regarding usability, immersion, presence, embodiment, cognitive load and perceived mental effort. Furthermore, the questionnaire asks the user to be specific about each interaction, how they experienced them and to provide additional feedback regarding interactions or other elements the user felt were missing from the application.

The heuristic evaluation was performed similarly to the UX test, however instead of a questionnaire, a semi-structured interview (Bjørner, 2016) was planned.

## 5.1 UX test

This section covers the target group and experiment procedure for the UX test.

### 5.1.1 Target Group

The target group for our application is 6th-grade students in Denmark learning about geometry. The test participants were selected using *convenience sampling* (Bjørner, 2016). It is not guaranteed that the results from convenient participants would reflect the results of 6th-grade students, however, we were still able to get valuable insight from these participants regarding usability, immersion and cognitive load.
We had 2 different groups of participants for this test: the first group were participants who attended our UX test from our previous iteration (as mentioned in section 1.1). These were now second-time users and were labelled as the "A-group". The second group consisted of participants that were conveniently selected, based on the proximity of the test location and were all considered first-time users of our application. They were labelled as the "B-group".

### 5.1.2 Procedure

The experiment was identical for both test groups. The participant was read a script (found in appendix B), instructing the experiment procedure. A pre-test questionnaire was then filled in by the participant. This pre-test questionnaire contained items regarding demographics and previous experience in VR. Following the pre-test, the participant was guided to the experiment area. The participant was then allowed to spend time in our application and tasked to think out loud during their experience. The experience was, with the participant's consent, filmed and timed (see figure 5.2). After the experience, the participant was asked to fill out the post-test questionnaire, which consisted of 4 main elements:

- The System Usability Scale (SUS) (Brooke, 1996).
- The Immersion-Presence Questionnaire (IPQ) (Schubert, Friedmann, and Regenbrecht, 2001).
- The Virtual Embodiment Questionnaire (VEQ) (Roth and Latoschik, 2020).
- The Cognitive Load Questionnaire (CLQ). This was inspired by the questionnaire suggested by Skulmowski and Rey, 2017 which was a variant of the questionnaire made by Eysink et al., 2009.

FIGURE 5.2: A test participant during the experiment.

The SUS was scored on a 1-5 point scale, where for each participant "Strongly Disagree" was 1 point and "Strongly Agree" was 5 points (Will, 2021). The calculation works as follows:

- X = Sum of points for odd-numbered questions - 5
- Y = 25 - Sum of points for even-numbered questions
- SUS score = (X+Y) * 2.5

The total score has a maximum of 100, each question weighing in at a maximum of 10 points.
Odd-numbered questions were all in a positive statement, therefore if the response was "Strongly Agree", the maximum score of 10 was granted. For "Strongly Disagree", 0 points were granted. For the even-numbered questions, the opposite logic was used, where "Strongly Agree" was 0 points and "Strongly Disagree" 10 points.

For interpreting the SUS score, the guidelines in figure 5.3 are presented by Will, 2021:

| SUS Score | Grade | Adjective Rating |
|---|---|---|
| > 80.3 | A | Excellent |
| 68 – 80.3 | B | Good |
| 68 | C | Okay |
| 51 – 68 | D | Poor |
| < 51 | F | Awful |

FIGURE 5.3: SUS score guidelines Will, 2021.

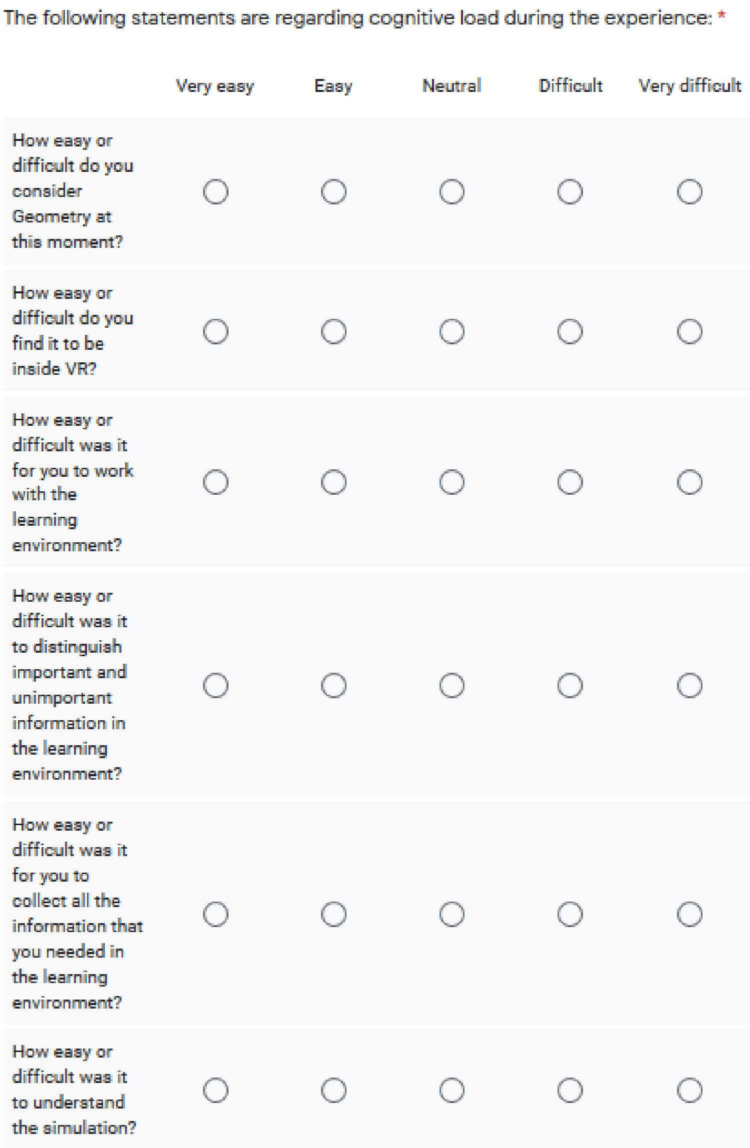
The IPQ has 4 categories (Schubert, Friedmann, and Regenbrecht, 2001):

- General Presence (GP): relating to the general feeling of being present in the virtual environment.
- Spatial Presence (SP): the feeling of presence in the virtual space.
- Involvement (INV): feeling involved in the virtual environment.
- Experienced Realism (REAL): how realistic the simulation feels.

For each category and participant, a score between 1 (Strongly Disagree) and 5 (Strongly Agree) was given depending on their response. For items with a negatively posted statement, reverse scoring was used. With this scoring, a 3 would be the balance point between positive and negatively received, where higher than 3 is positive and lower than 3 is negative, with a maximum of 5 and a minimum of 1.

The VEQ has 3 item categories: acceptance of ownership (ACC), control & agency (CTRL) and perceived change in body scheme (CHNG). For each item, a score between 1 (Strongly Disagree) and 7 (Strongly Agree) was given. A score higher than 4 indicates the user accepting the virtual body as their own, lower than 4 meaning a poor or no acceptance of the virtual body.

The CLQ has 4 categories, as explained in section 2.3. The scoring was done using a 1 - 5 scale, where 1 indicated a high load and 5 a low load.
The CLQ has 2 items regarding intrinsic load, 2 items for extraneous load, 1 item for germane load and 1 item for overall load. The CLQ is presented in figure 5.4.



The following statements are regarding cognitive load during the experience: *

| | Very easy | Easy | Neutral | Difficult | Very difficult |
|---|---|---|---|---|---|
| How easy or difficult do you consider Geometry at this moment? | ○ | ○ | ○ | ○ | ○ |
| How easy or difficult do you find it to be inside VR? | ○ | ○ | ○ | ○ | ○ |
| How easy or difficult was it for you to work with the learning environment? | ○ | ○ | ○ | ○ | ○ |
| How easy or difficult was it to distinguish important and unimportant information in the learning environment? | ○ | ○ | ○ | ○ | ○ |
| How easy or difficult was it for you to collect all the information that you needed in the learning environment? | ○ | ○ | ○ | ○ | ○ |
| How easy or difficult was it to understand the simulation? | ○ | ○ | ○ | ○ | ○ |

FIGURE 5.4: The questionnaire on Cognitive Load in the UX test.

During the experiment, an observer kept track of items on an *observation table* (see figure 5.5). These observation tables were double-checked after the experiment, using both video and screen recordings of each participant. The observation tables can be found in appendix B.

## 5.2 Heuristic evaluation

This section covers the experiment procedure for the heuristic evaluation test.

### 5.2.1 Participants, objectives, and heuristics

The heuristics evaluation took place at the Multisensory Lab at Aalborg University Copenhagen and was comprised of 4 evaluators. Two with experience in UX and interaction design, one in teaching and embodiment and one expert in the field of building mathematical competencies with digital technology. The evaluators would

| Participant #: | Total time spent: | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Menu | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Measure Angle | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Measure Side | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Measure Area | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Grabbing Point | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Grabbing Centroid | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |
| Scaling Triangle | Attempted exploration | | |
| | Used with intent | | |
| | Used with intent more than once | | |
| | Used without intent | | |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | | |
| | Used to conduct tasks | | |
| Hint GUI | User clearly noticed this element | | |
| | Used to conduct tasks | | |
| | Consulted this element for guidance | | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | | |
| | Used with intent | | |
| | Used without intent | | |
| Create Mode Button | Attempted exploration | | |
| | Used with intent | | |
| | Used without intent | | |
| Tools Mode Button | Attempted exploration | | |
| | Used with intent | | |
| | Used without intent | | |
| Manipulation Mode Button | Attempted exploration | | |
| | Used with intent | | |
| | Used without intent | | |
| Trash can | Attempted exploration | | |
| | Used with intent | | |
| | Used without intent | | |
| | Tried to click | | |
| Grid | Snapped triangle point with intent | | |
| | Snapped triangle centroid with intent | | |
| | Snapped object without intent | | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | | |
| | Submitted any completed task with intent | | |
| | Submitted all tasks with intent | | |
| Time elapsed for task completion with intent: | | | |
| Observer notes | | | |

FIGURE 5.5: The template of the observation tables used during the experiment.

evaluate interactions in the application from start to finish. "Finish" being when they have completed the 5 tasks listed in the application. Specifically, the interactions they evaluated were:

- Creating, moving, and scaling the triangle(s).
- Measuring triangle(s) side length, angles, and area.
- Manually switching modes. Create, Tools, Manipulation.
- Deleting triangles.
- Submitting assignments.

There were 8 heuristics the evaluators would work from, based on what can be considered an industry standard and what has been used for similar applications:

- Visibility of system status.
- Match between system and the real world.
- Error prevention.
- User control and freedom.
- Recognition rather than recall.
- Aesthetic and minimalist design.
- Synchronous body movement.
- Mental Comfort

The evaluators would place the usability issues on a severity scale, red, orange, yellow and green. Red, being most critical and green being least critical.

### 5.2.2 Procedure

The evaluator was read a script introducing them to the experiment and the procedure. The scripts can be found in appendix C. The evaluator would then begin the first of two walkthroughs (see figure 5.6). In the first walkthrough, the evaluator could freely interact with the application, familiarize themselves with it and try to solve the tasks in the application. In the second walkthrough, the evaluator would be tasked to go in-depth on application specifics, such as gestures, sounds and graphical elements. After the two walkthroughs, the team and evaluator would summarize the experience and ask more in-depth questions. The results would then be aggregated by the team. These can found in appendix C.

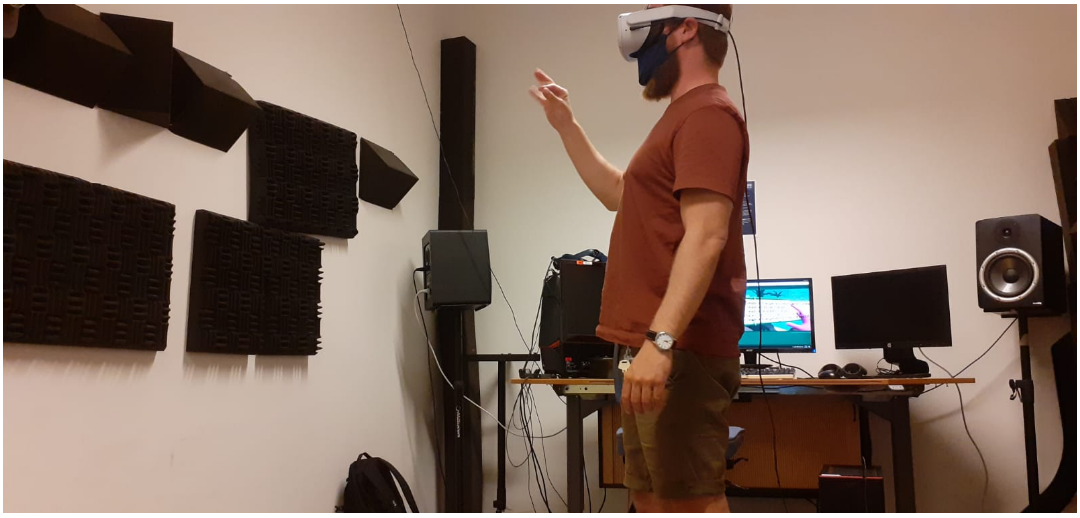


FIGURE 5.6: An expert in a walkthrough during a heuristic evaluation.

# Chapter 6

# Results

This chapter presents and reviews the results from the UX test and heuristic evaluation. The UX test collected qualitative data from 13 participants regarding system usability, presence and cognitive load. The heuristic evaluation gave us the opportunity to get feedback from 4 experts in the field of interaction design, embodied interaction and mathematical competency in digital technologies.
From the questionnaire data, the following table, figure 6.1, was produced:

| Participant # | SUS | IPQ - GP | IPQ - SP | IPQ - INV | IPQ - REAL | VEQ - ACC | VEQ - CTRL | VEQ - CHNG | CLQ - IL | CLQ - EL | CLQ - GL | CLQ - OL | Mental Effort |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 87.5 | 4 | 3.67 | 3.67 | 3.33 | 5.5 | 5 | 3 | 4 | 3.5 | 4 | 4 | 2 |
| 2A | 67.5 | 5 | 5 | 4 | 4 | 5 | 5.5 | 3.5 | 4.5 | 3 | 5 | 4 | 2 |
| 3B | 75 | 5 | 5 | 4 | 3.33 | 5.75 | 6.75 | 2 | 4 | 4.5 | 4 | 4 | 3 |
| 4B | 57.5 | 4 | 3.67 | 3.33 | 3 | 3.5 | 3.5 | 5 | 3 | 3.5 | 4 | 4 | 3 |
| 5B | 90 | 5 | 4.67 | 3.67 | 2.67 | 4.25 | 6.25 | 3.25 | 4.5 | 5 | 4 | 5 | 2 |
| 6A | 37.5 | 4 | 4.33 | 4 | 3.33 | 5.5 | 3.5 | 4 | 2.5 | 3 | 2 | 3 | 5 |
| 7B | 67.5 | 5 | 4.33 | 2 | 2 | 5.25 | 3.5 | 2 | 3.5 | 4 | 4 | 4 | 2 |
| 8B | 42.5 | 4 | 4 | 4 | 2 | 4 | 5.75 | 2 | 3 | 1.5 | 2 | 3 | 4 |
| 9A | 85 | 5 | 5 | 2.33 | 1.66 | 5.75 | 7 | 3 | 3 | 4.5 | 5 | 5 | 2 |
| 10B | 77.5 | 5 | 4.66 | 4.33 | 2.67 | 4.5 | 3.25 | 1.25 | 4.5 | 3 | 2 | 5 | 1 |
| 11B | 95 | 4 | 4.33 | 3.66 | 2.66 | 7 | 7 | 1 | 5 | 4.5 | 4 | 5 | 1 |
| 12A | 70 | 4 | 4 | 2.66 | 2.66 | 5.5 | 6.5 | 3 | 4 | 2.5 | 4 | 4 | 2 |
| 13B | 65 | 4 | 4 | 3 | 3 | 5 | 5.5 | 2.5 | 3 | 3.5 | 3 | 3 | 2 |
| Mean = | 70.57692308 | 4.461538462 | 4.358461538 | 3.434615385 | 2.793076923 | 5.115384615 | 5.307692308 | 2.730769231 | 3.730769231 | 3.538461538 | 3.615384615 | 4.076923077 | 2.384615385 |

FIGURE 6.1: Results from the UX questionnaire.

The following sections will discuss the meaning and relevance of the data.

## 6.1 SUS

The participant's SUS scores can be seen in figure 6.1 and figure 6.2. The mean of all participants' SUS scores was calculated, giving us a final SUS score for the UX test: *m = 70.6*.

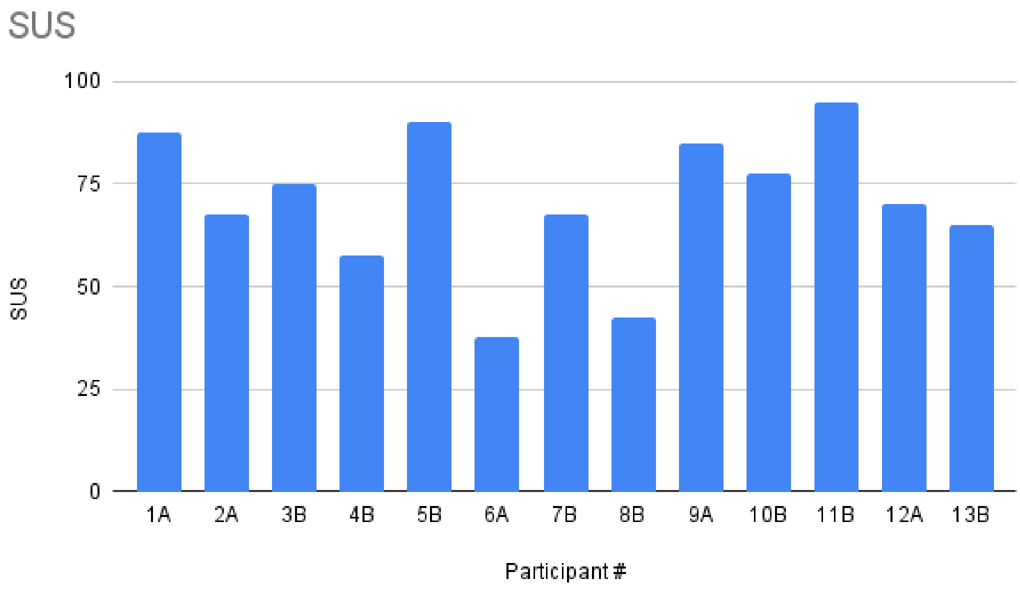



FIGURE 6.2: Chart created from SUS questionnaire responses.

This means that with a SUS score of *m = 70.6*, the usability of our system can be considered "good".

## 6.2 IPQ

From the questionnaire data, the following figure 6.3 was created for the 4 categories:

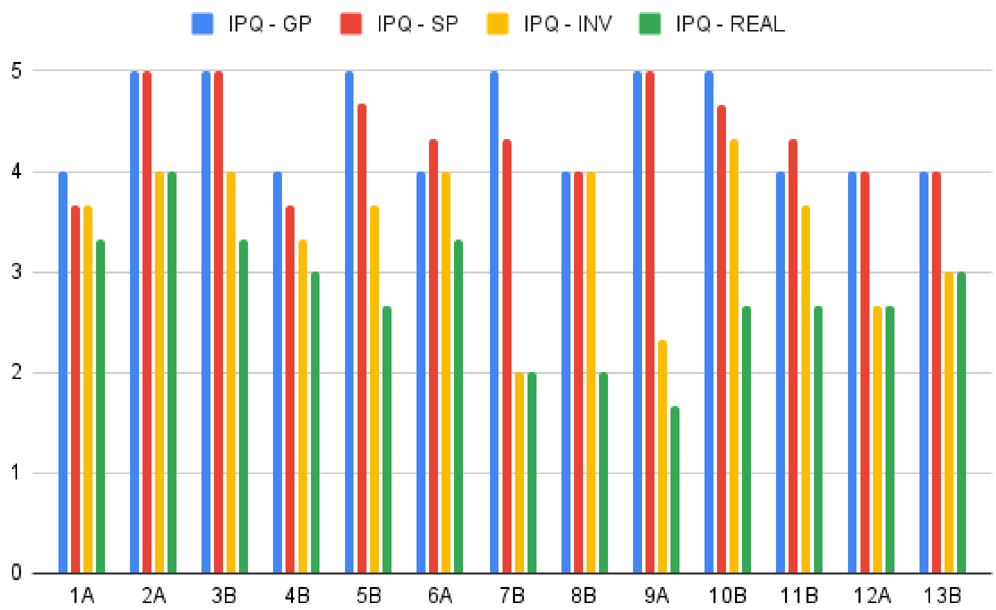



FIGURE 6.3: IPQ responses for the 4 categories.

A mean was then calculated between all the participants (as seen in figure 6.1).

- General Presence was very positively received (*m=4.46*).
- Spatial Presence was very positively received (*m=4.36*).
- Involvement was slightly positively received (*m=3.43*).
- Experienced Realism was slightly negatively received (*m=2.79*).

## 6.3 VEQ

For the VEQ results figure 6.4 was created, based on the results from figure 6.1,

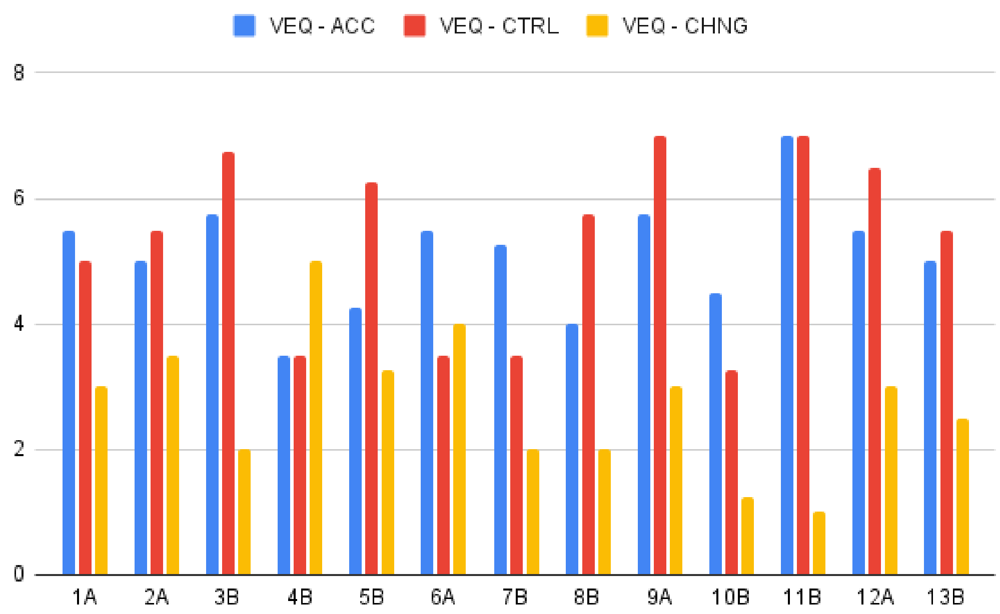



FIGURE 6.4: VEQ responses for the 4 categories.

- Acceptance of ownership received a score of *m=5.12*, meaning that overall the users accepted the virtual body as their own.
- Control & agency received a score of *m=5.31*, indicating that users felt in control of their virtual body.
- Perceived change received a score of *m=2.73*, showing that the user did not perceive a significant change in their body when using the application.

## 6.4 CLQ

Figure 6.5 shows the 4 categories' performance per participant.

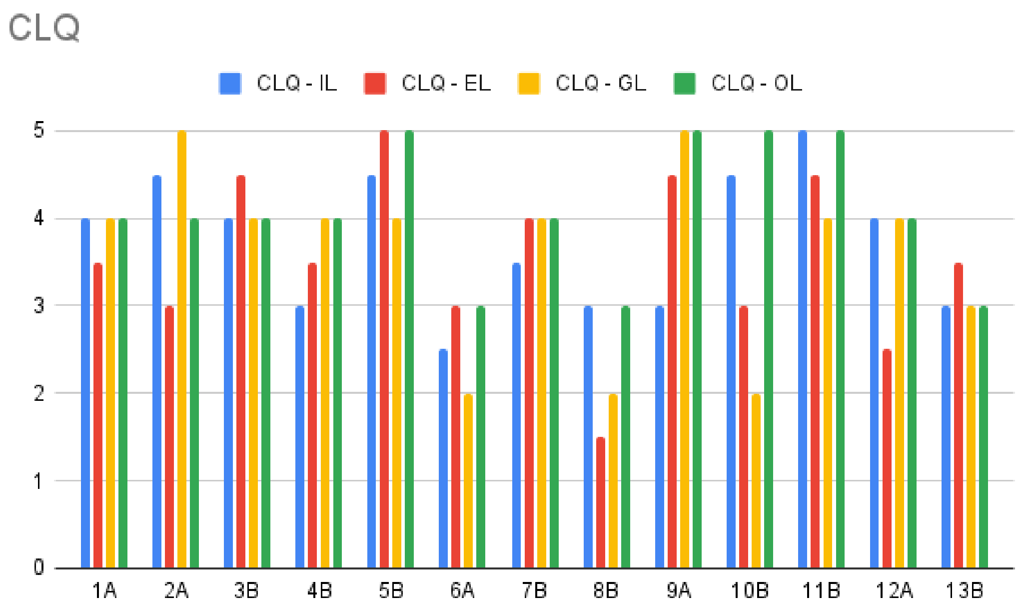



FIGURE 6.5: CLQ responses for the 4 categories.

The categories scored:

- Intrinsic Load, *m=3.73*.
- Extranous Load, *m=3.54*.
- Germane load, *m=3.62*.
- Overall load, *m=4.08*.

Overall, the cognitive load of this application is not significantly high. We asked each participant to rate their mental effort on a scale of 1 (very low) to 5 (very high) and scored an average of *m=2.38*, indicating that overall the mental effort of our participants was low.

There were 2 outliers, participant 6A and 8B. It is worth noting that for these 2 participants, their experiment was heavily influenced by bugs from our system. Namely, the creation of excess triangles interrupting their workflow. You can find this in the observation tables for participant 6A and 8b in appendix B and this will be further discussed in section 7.2.

## 6.5 Mean of means

Figure 6.6 shows the collected means in each questionnaire topic: SUS, IPQ, VEQ and CLQ.

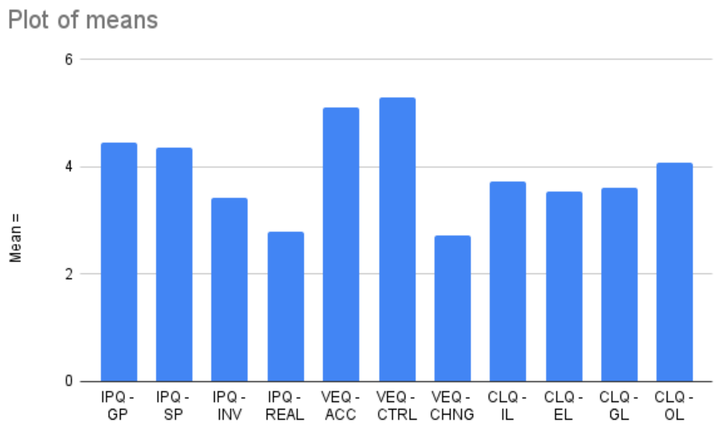



FIGURE 6.6: The means of questionnaire topics. IPQ and CLQ had a maximum possible score of 5, VEQ had a maximum possible score of 7.

The IPQ, VEQ and CLQ were divided into several categories, each with their own calculated mean. When combining these categories, we can calculate a *mean of means*, also referred to as *grand mean*[1] to have one indicating value for each questionnaire topic.
Figure 6.7 shows the table with the calculated mean of means for every topic.

| | IPQ | | | | VEQ | | | CLQ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | IPQ - GP | IPQ - SP | IPQ - INV | IPQ - REAL | VEQ - ACC | VEQ - CTRL | VEQ - CHNG | CLQ - IL | CLQ - EL | CLQ - GL | CLQ - OL |
| Mean | 4.46 | 4.36 | 3.43 | 2.79 | 5.12 | 5.31 | 2.73 | 3.73 | 3.54 | 3.62 | 4.08 |
| Mean of Means | 3.76 | | | | 4.386666667 | | | 3.7425 | | | |
| Alternative MoM | 4.083333333 | | | | 5.215 | | | | | | |

FIGURE 6.7: Table of topic means and calculated mean of means and alternative mean of means.

For the IPQ and VEQ topics, an alternative mean was suggested. The IPQ - REAL related to the feeling of realism in the virtual world. Although this was a suggested category in the IPQ, users were not expected to feel realism in our application thus potentially skewing the final result (as mentioned previously in section 4.4). Therefore, we calculated an alternative mean of means that excludes the IPQ - REAL mean. The VEQ - CHNG category was similarly excluded from the alternative mean of means. With the mean of means, the questionnaire topics can be represented by a single number.

- IPQ scored *m=3.76*, alternatively *m=4.083*, with a maximum possible score of 5.
- VEQ scored *m=4.39*, alternatively *m=5.215*, with a maximum possible score of 7.
- CLQ scored *m=3.74*, with a maximum possible score of 5.

[1]https://www.statisticshowto.com/grand-mean/

## 6.6 Time spent

In the observation tables, found in appendix B, the total time spent in the application and the task completion time were also tracked. From the observation tables, the table in figure 6.8 and chart in figure 6.9 was created.

| Participant # | Total Time (s) | Task completion time (s) |
|---|---|---|
| 1A | 640 | 460 |
| 2A | 1876 | - |
| 3B | 2280 | - |
| 4B | 1800 | - |
| 5B | 1200 | 824 |
| 6A | 2160 | - |
| 7B | 1710 | 1620 |
| 8B | 1560 | 713 |
| 9A | 900 | 372 |
| 10B | 780 | 610 |
| 11B | 840 | 750 |
| 12A | 1800 | 893 |
| 13B | 930 | 600 |
| Mean = | 1421.230769 | 760.2222222 |

FIGURE 6.8: Total time spent and task completion time per participant.

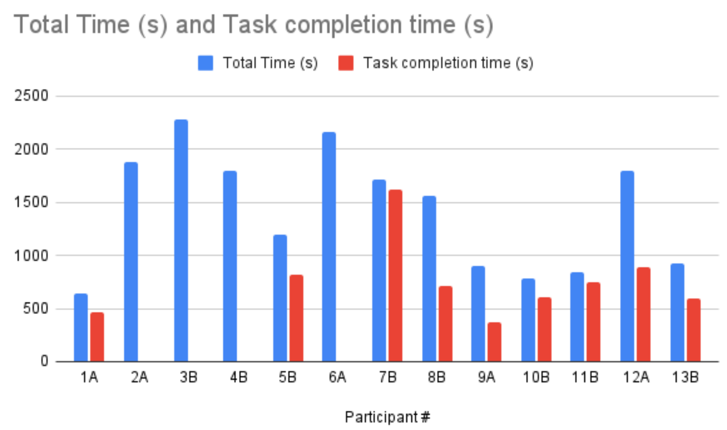



FIGURE 6.9: Chart from time spent in application.

4 participants never submitted and completed all tasks. It is worth noting that participant 2A did complete all tasks, but never used the submit button. Participants 3B, 4B and 6A all spent a significant amount of time in the application without completing all tasks, due to a high level of frustration. These frustrations came from the many accidental triangles that were created in their respective sessions. Both participant 3B and 4B were in the age category of 65+, 6A in 50-65. The age categories could potentially be related to these issues. The average total time spent (in seconds) in the experiment was *m=1421.23*, which is 23 minutes 41 seconds. The average task completion time was *m=760.22*, which is 12 minutes 40 seconds.

## 6.7 Individual system elements

This section covers the UX and heuristic results of each individual gesture implemented in the system. Figure 6.10 shows an overview of the questionnaire items regarding whether the user had experienced this element, whether that element worked well for them and whether the user thought it was an intuitive element for them.

| | User responses | | |
|---|---|---|---|
| Element | NOT experienced | Worked well | NOT intuitive |
| Create | 0 | 11 | 1 |
| Grab Point/Triangle | 0 | 10 | 2 |
| Scale triangle | 1 | 5 | 2 |
| Tape measure | 0 | 11 | 1 |
| Protractor | 1 | 7 | 4 |
| Area measure | 1 | 7 | 3 |
| Submit | 1 | 6 | 2 |
| Delete | 1 | 6 | 8 |
| Mode switch | 0 | 11 | 2 |

FIGURE 6.10: Overview of 3 questionnaire items: "Which of the elements did you NOT experience?", "Which of the elements did you think worked well?" and "Which of the elements were NOT intuitive to you?".

### 6.7.1 Create

The "create" gesture, seen in figure 6.11, received an overall positive response from our users.

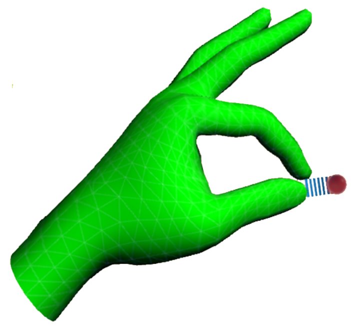


FIGURE 6.11: The "Create" gesture.

#### UX results

Every participant used this gesture with intent. However, only 1 participant managed to avoid using this gesture on accident. Based on our observations and the questionnaire feedback, the gesture was deemed too sensitive, as accidental creations took place in all but 1 participant. This led to frustrations on 4 participants (2A, 3B, 4B and 6A) and intervened with their performance in the experiment.

11 participants voted that this gesture worked well for them, 1 participant voted that this gesture was not intuitive.

#### Heuristic results

3 out of 4 evaluators gave specific feedback for the "create" gesture. All 3 agreed on expecting some form of confirmation when creating a triangle point. The creation happened suddenly and unexpectedly. Alternatively, an "undo" or "revert" function was suggested by all 3 evaluators.

### 6.7.2 Protractor

The "protractor" gesture, seen in figure 6.12, received an overall mixed response.

FIGURE 6.12: The "Protractor" gesture.

#### UX results

Looking at figure 6.10, 1 participant did not experience this gesture. 7 participants thought this gesture worked well and 4 deemed it not intuitive. 4 participants used this gesture without intending.
Observations showed us that all the participants used the intended interaction, however, the system did not always recognize the gesture. Improvements to the gesture detection algorithm should be made for this gesture.

#### Heuristic results

3 evaluators made direct comments on the protractor gesture. Each made their own suggestion on improvements for the user. Evaluator 1 commented that it would have been nice to show an angle indicator on the triangle itself, instead of showing the value over the hand. Evaluator 3 suggested that this interaction has a similar function as the "tape measure" gesture: you constantly get the angle between your index and thumb fingers. Evaluator 4 commented that the gesture worked well, but was expecting the value to show up between the index and thumb fingers.

### 6.7.3 Tape measure

The "tape measure" gesture, seen in figure 6.13, received an overall positive response.

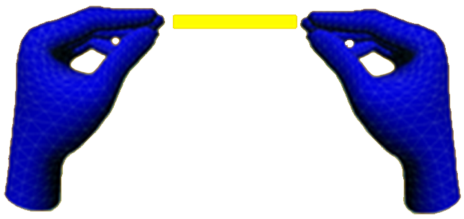


FIGURE 6.13: The "Tape measure" gesture.

#### UX results

Figure 6.10 tells us that every participant experienced this gesture. 11 participants voted that this gesture works well and 1 participant found this gesture not intuitive. 5 participants used the gesture without intent at least once. 1 participant directly commented on this gesture: a feature request to be able to "snap" the tape measure to two specific triangle points.

#### Heuristic results

Only 1 evaluator made a direct comment on the tape measure gesture and it was the same comment as the UX participant:

> *"Snapping on the points would have been nice when you are near them."*

### 6.7.4 Area measure

The "area measure", seen in figure 6.14, received an overall mixed response.

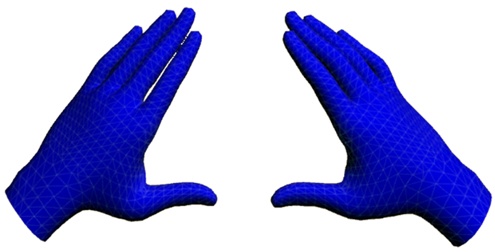


FIGURE 6.14: The "Area measure" gesture.

#### UX results

Figure 6.10 shows that 1 participant did not experience this gesture. 7 participants thought this gesture worked well and 3 participants voted that this gesture was not intuitive. No further feedback on this gesture was given by the participants. Observations indicated that 5 participants used this gesture without intending to. A slight adjustment to the gesture detection should be made for this gesture, to make it less sensitive. In the current state, the area gesture can get invoked without intent and can confuse the user.

#### Heuristic results

Evaluator 1 and 4 directly commented on this gesture. Evaluator 1 was expecting some visual feedback on the entire triangle's circumference. Evaluator 4 found the audio feedback from this gesture confusing and initially thought it was a celebratory audio cue for completing a task.

### 6.7.5 Grabbing

The "grab" gesture, as seen in figure 6.15, received an overall positive response.

FIGURE 6.15: The "Grab" gesture.

#### UX results

Figure 6.10 shows that every participant experienced this gesture. 10 participants found that the gesture worked well in its current state and 2 participants thought the gesture was not intuitive. 6 participants were observed to use this gesture without intent. Every participant was observed to initially try to use a pinch-like gesture to move triangle points and centroids, likely due to the size of the objects. One heuristic evaluator made a similar remark. Another observation was the limitation of the hand-tracking technology. Users often intuitively tried to grab with their palm facing away from the headset. This occurrence made it hard for the headset to detect a fully formed fist and was observed to be more precise when the user aimed their palm towards the headset.

#### Heuristic results

3 evaluators made direct remarks on the grabbing interaction. Evaluator 1 commented:

> *"The triangle point gizmo afford pinching rather than grabbing. Increasing the size might help the fist-grab affordance."*

Evaluator 2 commented:

> *"Perhaps make it more visible that you need to form a fist to grab."*

Evaluator 4 commented:

> *"It took time to understand this gesture exactly. The fine point on whether you grab or not was hard to notice."*

### 6.7.6 Scaling

The "scale triangle" gesture, seen in figure 6.16, received an overall negative response.

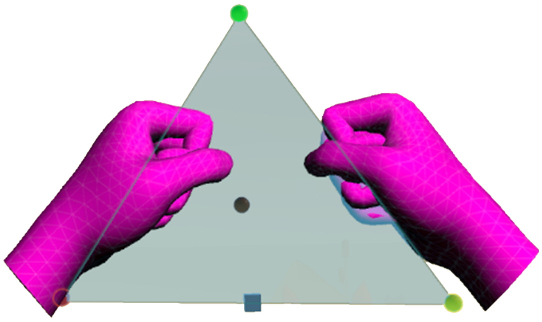


FIGURE 6.16: The "Scale triangle" gesture.

#### UX results

As seen in figure 6.10, the "scale triangle" gesture was not experienced by 1 user. 5 users reported that the gesture worked well and 2 participants specifically marked that this gesture is not intuitive. 2 participants were observed to have used this interaction without intention. Feedback from the UX testers indicated that the intended interaction is a good idea. However, the "grab" gesture not being properly detected every time and the confusing nature of having to grab the cubes alongside the triangle sides made this a poorly functional gesture. Making the entire triangle side an interactive object and increasing the accuracy of grabbing could improve the performance of this gesture.

#### Heuristic results

Only Evaluator 4 made a direct remark regarding the scale interaction: "I did not notice that the cubes were meant for scaling".

### 6.7.7 Menu

The "menu" gesture, seen in figure 6.17, received an overall positive response.

#### UX results

All participants explored this interaction. As this gesture was involved in making other interactions work (mode switch, submit and trash can) it was not added as an individual item on the questionnaire. 2 participants were observed to have used this gesture unintended at least once. Observations also revealed the limitation of the hand-tracking technology: hands getting too close to each other will stop the hand-tracking and your virtual hands disappear when this occurs. A solution could be to move the menu icons further away from the gesturing hand, to make interactions with the buttons inside the menu more usable.

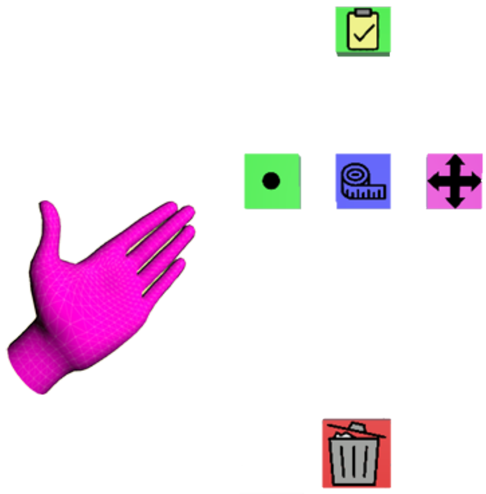


FIGURE 6.17: The "Menu" gesture.

#### Heuristic results

All 4 evaluators made direct comments on the menu gesture.
Evaluator 1 confirmed the solution previously mentioned:

> *"The menu might be more useful if it's further away from the hand itself."*

Evaluator 2 found that the menu is over complicating the application and suggested that the tools found inside the menu could be replaced with virtual objects that the user could pick up and use as you would in a real-world setting (a tangible virtual tape measure tool and protractor).
Evaluator 3 commented that the menu was hard to recognize initially, but was then easy to recall once learned.
Evaluator 4 liked the menu, but it took time to discover. The evaluator suggested making the menu "stand out" more, as in its current state it has a transparent background, possibly making it hard to distinguish from the rest of the virtual environment. Adding a non-transparent background might make it faster to distinguish the functions that the menu has to offer.

### 6.7.8 Submit button

The "submit" button received mixed responses, as seen in figure 6.10.

FIGURE 6.18: The "Submit" button, found inside the "Menu".

### UX results

1 participant did not explore this button. 6 participants voted that this interaction worked well and 2 participants noted that this interaction was not intuitive. 5 participants were observed to have used this without intention.
From both user feedback and observations, it became apparent that the submit function was not inherently intuitive. Users were observed to expect the task to be completed, once they performed it correctly, automatically. After users discovered the submit button, its function became clear.
The rationale behind a submit button was that the user would have to self-reflect on each task whether it was correct or not. Then once the user decided that it is correct, the user was intended to confirm this by submitting their assignment. Whether an automatic task-completion function is beneficial to the learning outcome is questionable and worth investigating in a future iteration. After these UX observations, we opened up a conversation with Evaluator 3 on this topic.

### Heuristic results

Evaluator 1 commented that the task should be automatically completed.
Evaluator 2 would have also liked to see an automatic task completion. Evaluator 3 would have liked to see our task design different: only showing 1 task at a time. The evaluator did agree that forcing a user to self-reflect instead of automatic task completion was a good task design.
Evaluator 4 never made the connection between the submit button in the menu and the task board but commented after being explained how this procedure was supposed to work, that it made sense.

## 6.7.9 Trash can

The "trash can" interaction received an overall very negative response.

FIGURE 6.19: The "Trash can" interaction, found inside the "Menu".

### UX results

1 participant did not experience this interaction at all. 6 participants found that it worked well after they discovered it. 8 participants noted that this interaction was not intuitive. No participant was observed to perform this interaction without intention. All participants were observed trying to "click" this icon like a button.
Feedback from the users revealed that the similarity of a button was not useful for this interaction. Users would have liked to see a virtual trash can to put triangles in or make the trash can another "mode", in which you can select triangles to delete. Another suggestion was made to implement deletion as a "swiping" gesture.

#### Heuristic results

3 evaluators made remarks on this interaction.
Evaluator 1 commented:

> *"It has a similar appearance as a button. A 3D representation of a trash can might be better, as long as it looks different from the "mode switch" buttons."*

Evaluator 2 commented:

> *"It looks like a button, for consistency that is not good it isn't actually a button. Perhaps a physical trash can is a solution."*

Evaluator 4 commented:

> *"I could not figure out this interaction on my own, but it does make sense to me. It did not come naturally to me to use both my hands: 1 for holding up the menu and 1 for moving the triangle in the trash can."*

### 6.7.10 Mode buttons

The "mode switch" buttons received an overall positive response.

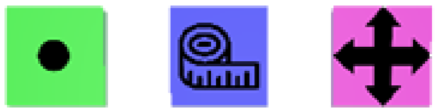


FIGURE 6.20: The "Mode switch" buttons, found inside the "Menu".

#### UX results

Every participant experienced this interaction. 11 participants voted that this interaction worked well. 2 participants noted that this interaction was not intuitive. 5 participants were observed to have used this interaction without intent. 1 participant commented that it took a while to realise this interaction worked like a button, due to the fact that only the index finger can press it. 2 participants commented that it would be nice to be able to click the buttons with any finger.

#### Heuristic results

Evaluator 2 commented that it would have been nice to not need modes. Being able to do all the gestures from 1 "mode" was suggested. We introduced modes in this iteration, to circumvent the problem of gesture inaccuracy and accidental gestures being picked up by the hand-tracking. Perhaps another solution could be found to circumvent the gesture-detection problem.

### 6.7.11 Grid

The "Interactive grid" was not a direct item on the UX questionnaire. However, it was taken into consideration during our observations.

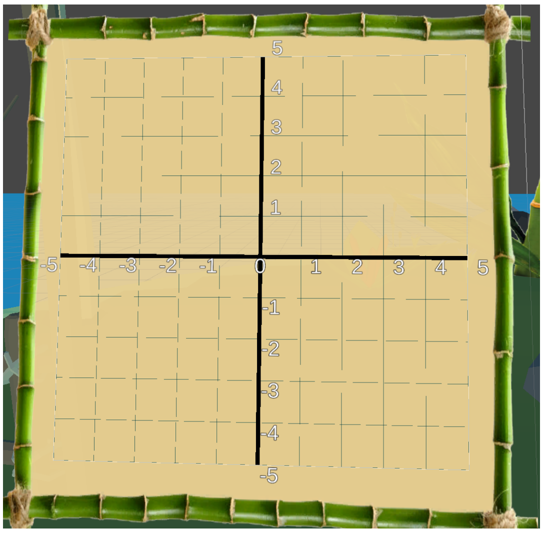



FIGURE 6.21: The "Interactive Grid".

#### UX results

6 participants were observed to accidentally snap an object to the grid. Every participant was observed to interact with the grid as intended. There was a single uncommon bug where one of the grid points would deactivate during snapping/unsnapping. 6 participants made direct remarks regarding the grid during the experiment. The comments were regarding the visual and auditory cues for snapping an object to the grid, which all participants remarked that they liked that these cues were present. Participant 10B mentioned that the coordinate visual feedback was especially helpful to confirm what coordinate your object is snapped to.

#### Heuristic results

Evaluator 1 commented that the visual and auditory cues given from the grid were nice and useful. No other remarks were made by the heuristic evaluators.

### 6.7.12 Hint GUI

The "Hint GUI", like the grid, was not a direct questionnaire item. It was, however, an item on our observation table.

#### UX results

11 participants clearly noticed this element, used it to conduct their tasks and consulted this visual element for guidance regarding the gestures they could perform. 2 participants never noticed this element, as their attention was focused on the grid and task board. It is also worth noting that these 2 participants both were observed to be distracted during their experiment, as they created many accidental triangles that were floating around in their virtual space.

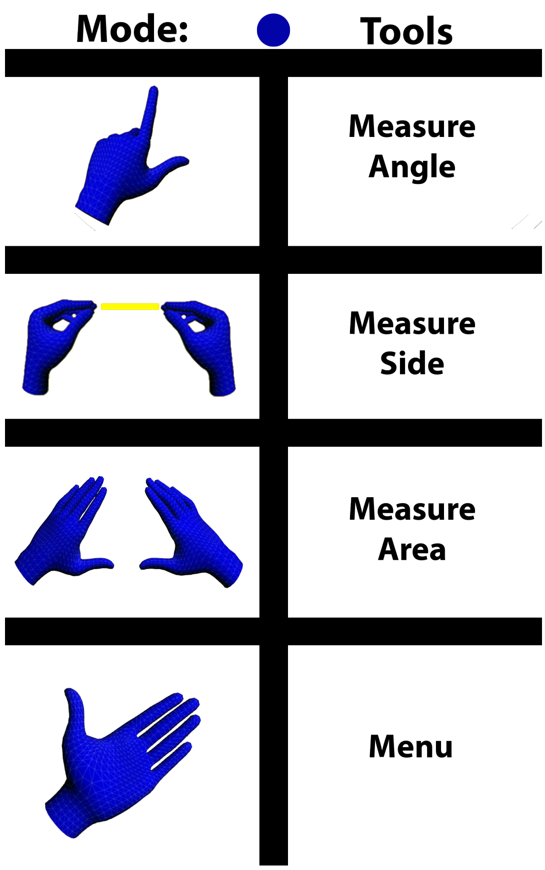



FIGURE 6.22: The "Hint GUI", found on the left-hand side of the "Grid". This image is when the user is in "Tools" mode.

#### Heuristic results

No direct feedback was given by our evaluators regarding the hint GUI. However, all evaluators were observed to have noticed this element, used it to conduct their tasks and consulted this element for guidance.

### 6.7.13 Task board

The "Task Board" was also not a direct UX questionnaire item. Like the previous 2 elements, it was an item on our observation table.

#### UX results

All participants were observed to notice this element and used it to conduct their tasks. Participants were observed to seem confused when they believed to have finished a task, but no visual or auditory feedback was given by the system until the user would "submit" their task. Participant 11B remarked directly that it was expecting to see a strike through the text. When user 11B then found the submit button later in the session, user 11B was happily surprised to see the expectation become a reality.

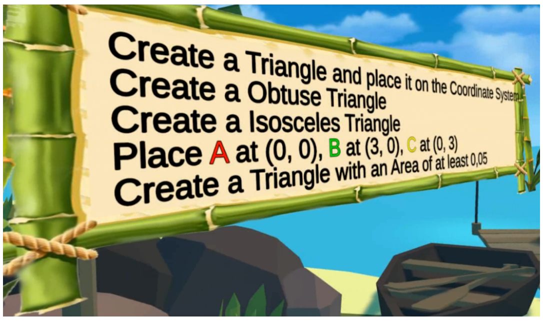



FIGURE 6.23: The "Task Board", found on the right-hand side of the "Grid".

#### Heuristic results

The feedback from our evaluators related to this element was already discussed under section 6.7.8 regarding the submit button. Evaluator 3 advised to only show a single task at a time to the user, but then perhaps show some form of progression status for the whole session instead. This way the user is more focused on the task at hand and submitting might come more naturally.

## 6.8 Heuristics

8 heuristics were evaluated by each evaluator, rated on a severity scale: red, orange, yellow and green. Red being most critical and green being least critical. The responses from our evaluators produced the following table:

| | Heuristics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Evaluator | Visibility | Match system/real | Error prevention | User control and freedom | Recognition vs Recall | Aesthethic | Synchronous movement | Mental Comfort |
| 1 | 3 | 4 | 4 | 3 | 3 | 4 | 4 | 4 |
| 2 | 3.5 | 2 | 1 | 1 | 2 | 3 | 4 | 3 |
| 3 | 1.5 | 3.5 | 3 | 1 | 3.5 | 3 | 1 | 4 |
| 4 | 4 | 3.5 | 3 | 2 | 4 | 3.5 | 4 | 4 |
| Mean | 3 | 3.25 | 2.75 | 1.75 | 3.125 | 3.375 | 3.25 | 3.75 |

FIGURE 6.24: Evaluator responses. A numerical value was tied to each color: red (1), orange (2), yellow (3), green (4).

The following sections show more detailed feedback on every heuristic.

### 6.8.1 Visibility of system status

The evaluators were read the following definition for this heuristic: "Is the user kept informed about what is going on, through appropriate feedback?".
This heuristic received a score of $m$=3.
Evaluator 1 commented:

> *"I would have liked to see more visibility of what mode you're in, some more icons on the hands perhaps."*

Evaluator 2 advised to use *skeuomorphism*[2] on the 2D icons. Evaluator 4 commented:

> *"The interactions and modes came to me little by little and I was able to keep track of it."*

[2] https://www.interaction-design.org/literature/topics/skeuomorphism

### 6.8.2 Match between the system and the real world

The evaluators were read the following definition for this heuristic:

> *"Are things like phrases and concepts something that would be familiar to the user?"*

This heuristic received a score of *m=3.25*
Evaluator 2 (who gave a score of 2 on this heuristic) commented: "You made me recall more than recognize. It was harder to recognize concepts than to recall them from real-world scenarios."
The other 3 evaluators detected no critical issues in this heuristic.

### 6.8.3 Error prevention

The evaluators were read the following definition for this heuristic:

> *"Is the application good enough to prevent errors / are there proper confirmation options?"*

This heuristic received a score of *m=2.75*.
Evaluator 4 remarked that there was a lack of warnings.

### 6.8.4 User control and freedom

The evaluators were read the following definition for this heuristic:

> *"Are actions/system options chosen by mistake easy to undo/redo?"*

This heuristic received a score of *m=1.75*.
All evaluators commented that they would have liked to see a "revert" or "undo" option when creating triangles and the "delete" function needs improvements (as discussed in section 6.7.9 Trash Can).

### 6.8.5 Recognition rather than recall

The evaluators were read the following definition for this heuristic:

> *"Are instructions for use of the system visible or easily retrievable?"*

This heuristic received a score of *m=3.125*.
Evaluator 3 (scored 3.5) commented:

> *"It was hard for me to recognize the interactions at first, but it was then easy to recall."*

Evaluator 4 (scored 4) commented:

> *"I did not need to break down any tasks, I knew where to look."*

Evaluator 1 and 2 used their comments from the Visibility heuristic to describe their problems with this heuristic, emphasizing the visibility of your current "mode".

### 6.8.6 Aesthetic and minimalist design

The evaluators were read the following definition for this heuristic:

> *"Is there any information that is irrelevant and diminishes the relevant information's visibility?"*

This heuristic received a score of *m=3.375*.
Evaluator 3 commented:

> *"I rate this orange, because of the way the tasks are displayed. The rest I would rate green."*

Evaluator 4 commented:

> *"I rate this yellow/green. I was confused about the placement of the numbers on the coordinate system."*

Evaluator 4 refers to the fact that the numbers on the grid are slightly on the side of the snapping grid point. We made this decision based on the fact that if the number was exactly in the middle, the grid lines would overlap the number, to which evaluator 4 replied:

> *"I guess that does make sense."*

### 6.8.7 Synchronous body movement

The evaluators were read the following definition for this heuristic:

> *"Are the application and interface in synchrony with the body's movement?"*

This heuristic received a score of *m=3.25*.
Evaluator 3 rated this red, because of the fact that the hand-tracking would often stop working or not show the position of the virtual fingers correctly.
Evaluator 4 commented: "The menu is synchronous, the triangles gave me some confusion as they were moving uncontrollably."

### 6.8.8 Mental Comfort

The evaluators were read the following definition for this heuristic:

> *"Anything that causes motion sickness, headaches, dizziness, and nausea."*

This heuristic received a score of *m=3.75*.
Evaluator 2 remarked that the floating triangles gave a slight feeling of dizziness. Other than that remark, all evaluators agreed that there was no mental discomfort in the application.

## 6.9 Summary

The system was rated "good" for usability (SUS score *m=70.6*). IPQ had an overall positive response (*m=3.76*), users felt immersion and presence in the application. VEQ scored positively as well (*m=4.39*). Users did not feel cognitively overloaded when using our system (CLQ *m=3.74*, Mental effort *m=2.38*).

The best-rated interactions were the "create", "tape measure" and "mode switch". Even though the "create" mode was a source of bugs and unintended interactions, due to the fact that on many occasions triangle points would be created by the system even though the user did not have their hands in front of the sensors, it was a very positively perceived interaction.
The worst-rated interaction was the "trash can". From both the UX and heuristic analysis it became clear that the icon looks too much like the other buttons in the menu and the intended interaction (drag and drop a triangle) was unclear. Suggestions by both UX testers and heuristic evaluators was made to change this to its own mode, or be replaced with a virtual trash can in the application.

Overall, the UX test and heuristic evaluation were successful, as we gained valuable insight into every element in the application. From all the feedback, a bug list and requested features list was produced for future development:

| Future Development Tasks | |
|---|---|
| **Bugs** | **Feature Requests** |
| Frame drops occur when in Manipulation Mode and "scene" window is open. | Always go to Manipulation mode when finishing a triangle in "create". |
| Unity crash on exiting Play mode in Editor. | Allow a pinch-like gesture for "grabbing" and increase the size of grabba |
| When displaying angle values in "protractor", rounding errors occur. | More visual feedback on grabbable objects. |
| Increase sensitivity on "protractor". | Add confirmation and "revert" functions to the "create" mode. |
| Decrease sensitivity on "create" and "area". | Protractor: display current angle on triangle instead of hand. |
| | Triangle sides should be grabbable. |
| | Rework the task board design: only show 1 task at a time with a total ses |
| | Deletion needs to be reworked: its own mode, a new gesture or a trash c |
| | Make the "mode switch" buttons pressable with all fingers. |
| | Adjust color scheme to work for users with Color Vision Deficiency |

FIGURE 6.25: Future development Tasklist: bugs and requested features.

# Chapter 7

# Discussion

This chapter aims to discuss the results of our experiments and explain their meaning. How do they relate to similar studies we have previously analyzed and are there other explanations of our findings? The results then lead to suggested guidelines for developing an IGE. Limitations of the project are presented and we end the discussion with a suggested course of future actions.

## 7.1 Problem statement & major findings

Our research was aimed at solving the following problem statement:

> *"How can an immersive geometry environment with a gesture-based interface facilitate lower-secondary geometry education?"*

From the results of our UX test, presented in sections 6.1 - 6.4, we state our major findings as follows:

- Usability received a good score, *SUS=70.6*.
- Immersion and presence received a score of *m=3.76*.
- Embodiment received a score of *m=4.39*.
- Cognitive load received a score of *m=3.74*.

The best-rated interactions were "create", "tape measure" and "mode switch".
The worst-rated interaction was the "trash can" interaction.
From the heuristic evaluation, 6 heuristics received a positive response, 2 heuristics came back with negative results: "error prevention" and "user control and freedom".

The following section aims to interpret the meaning of these results.

## 7.2 Interpreting the data

A usability score of 70.6 indicates that our suggested IGE is effective, efficient and satisfactory for the user. Taking a closer look at the calculated mean, we can see 3 main participant outliers: 4B, 6A and 8B. When trying to find a common reason as to why these participants rated the usability so low, a few data points piqued our interest: time spent in the application, whether they finished the tasks, how much they encountered bugs in our system and their perceived mental effort. Participants 4B and 6A spent a significantly longer time in the application (*t=1800 and t=2160* respectively), however participant 8B (*t=1560*) came close to the average (*t=1421*).

Participants 4B and 6A never finished the tasks during their experience, whereas 8B did. This led us to another observation: did the user encounter bugs in the system? All 3 participants did experience an excessive amount of accidental triangles being created and triangles floating around the virtual space (see figure 7.1).

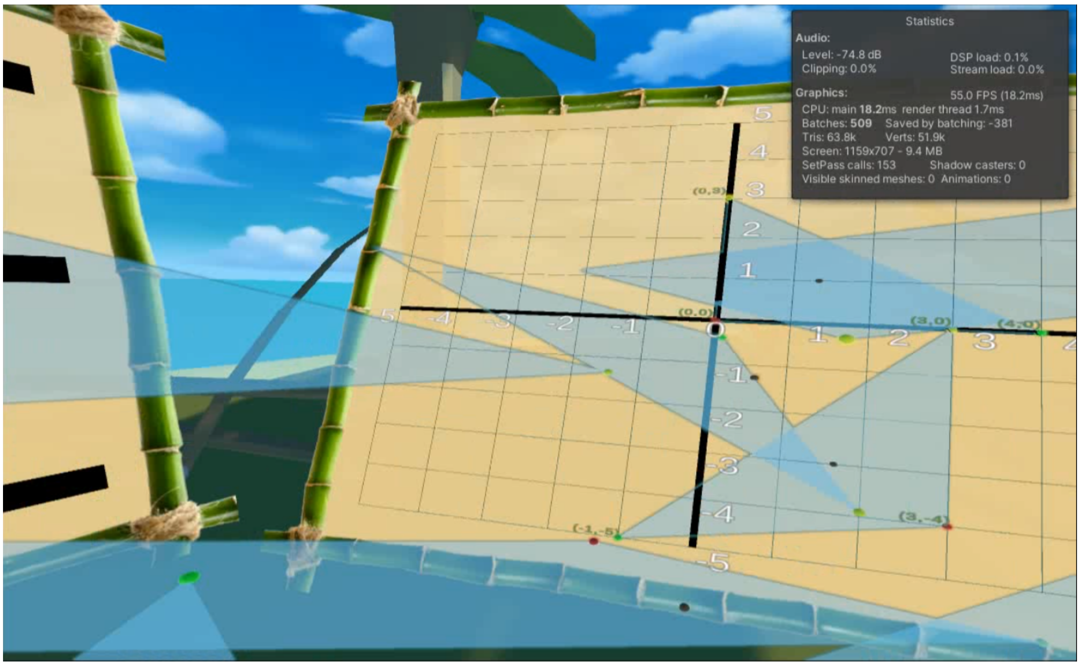



FIGURE 7.1: Participant 6B gets entangled in a web of triangles near the end of the experience.

These 3 participants did rate their perceived mental effort to be high during the experience (4B had a mental effort of 3, 6A rated 5 and 8B rated 4). Perhaps the answer lies in how their perceived mental effort affected their experience and rating of usability.
When we plot the perceived mental effort over the SUS score of each participant, the chart seen in figure 7.2 is produced.

This tells us that the 2 users that rated their mental effort highest, also gave the 2 lowest SUS scores. However, the data was collected using self-reporting, therefore we cannot dismiss the presence of this measurement bias. When we look at the opposite side of the spectrum, the two participants (10B and 11B) with the lowest perceived mental effort did both rate the usability high. These 2 participants also indicated to have experience in VR and are both students within a relevant field of study.

This leads to the following established guideline:

> *"Limit the construction to allow focus on a single geometric object."*

When looking at the source of the experienced frustration of participants 4B, 6A and 8B, the encounter of system bugs and inconsistencies seems the most likely explanation for their poorly perceived usability and highly perceived mental effort. Participant 6B described the reason for their dissatisfaction as:

> *"I found it difficult, and got confused and disoriented because of all the triangles I kept making, without knowing how!!"*

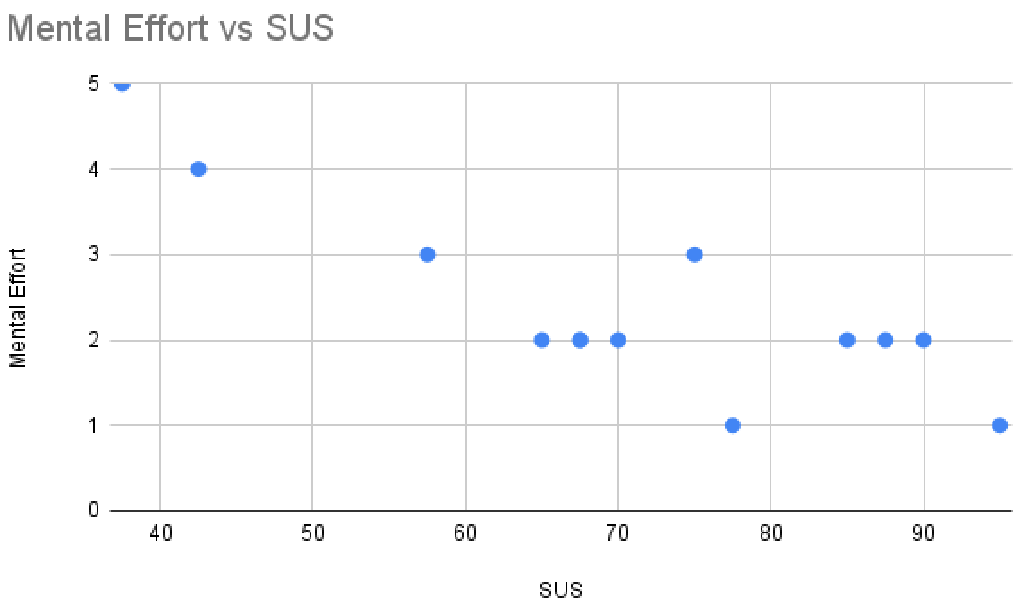



FIGURE 7.2: Mental effort (y-axis) vs SUS score (x-axis).

Therefore, it is crucial to take into account that the usability of triangle creation and deletion needs to be improved. This leads us to the discussion on the 2 worst rated heuristics and their underlying causes: "error prevention" and "user control and freedom".

From the results of the heuristic evaluation (see figure 6.24), "error prevention" (*m=2.75*) and "user control and freedom" (*m=1.75*) received the worst ratings from our evaluators. The feedback from our evaluators confirms that the process of creating and removing triangles needs to be improved. All evaluators remarked that a "revert" or "undo" option is lacking and when creating points of the triangle, some form of confirmation before placement was also lacking.

The "undo" function is also found in the popular DGE GeoGebra[1], see figure 7.3.

This leads to the following established guideline:

> *"Implement functions that can revert a user's action, or perform a previous user's action."*

During the discussion with Evaluator 2, a suggestion was made aiming to prevent errors upon creating shapes. Evaluator 2 suggested that to confirm a shape (a triangle in our application), the user should have to confirm the creation by connecting the last placed point back with the original point. GeoGebra uses this exact method for creating shapes as well, seen in figure 7.4

[1] https://www.geogebra.org/classic

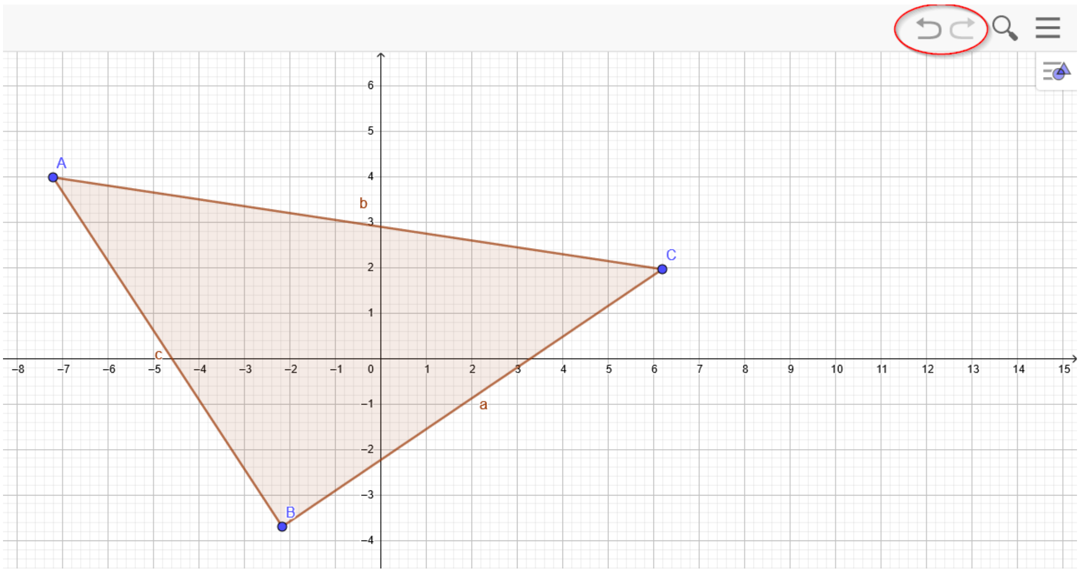



FIGURE 7.3: An example of the "revert"/"undo" function in GeoGebra, marked with a red circle in the top right-hand corner.

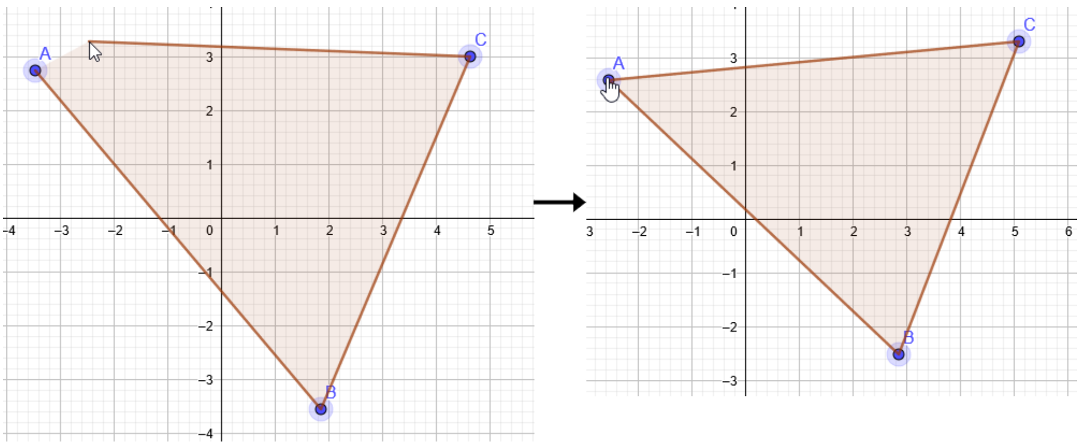



FIGURE 7.4: In GeoGebra, the user has to click the original point to confirm the shape.

This also opens up the possibility to create more complex shapes than triangles, which was also suggested by Evaluator 2, and leads us to the following design guideline:

*"Creation of geometrical shapes should contain a confirmation function."*

These interactions were the most detrimental to explain the outliers of the data. The overall SUS, CLQ and mental effort scores were positive. The IPQ and VEQ scores were also positive, confirming the advantages VR offers in education in terms of immersion and embodiment, as mentioned in section 2.1.2 (Georgiou, Ioannou, and Kosmas, 2021 and Akćayır and Akćayır, 2017). Combining this with hand-tracking and providing the user with a virtual model of their hands, it was expected to see positive embodiment scores.

Furthermore, we introduced several new features in this iteration. The "scale", "area", "menu" and the ability to create more than 1 triangle. The latter was tied together with the "create" gesture and will thus not be further discussed.
The "scale" interaction was negatively received, as only 5 participants noted that this interaction worked well. Participants had to be guided by a team member to discover the ability to scale a triangle. Observations revealed that the intended interaction itself was well-received, but the execution inside our application was insufficient. Evaluator 4's comment encapsulates this issue:

> *"I did not notice that the cubes were meant for scaling."*

A suggestion was made by participant 11B to make the entire triangle sides interactable, as to improve the affordance of grabbing and scaling the triangle.

From this feedback, we can establish the following guideline:

> *"Interactable capabilities should have visual indicators (e.g. operation symbols) to inform the user."*

The new "area" gesture's response was neither negative nor positive. 7 UX participants indicated that the gesture worked well for them. We observed this gesture getting triggered by our system when the hands were outside the tracking space which should be investigated. The auditory cue that comes with triggering this gesture was therefore observed to cause mild confusion with our UX testers, potentially contributing to an increase in cognitive load.
From the heuristic evaluators, 2 suggestions were given. Firstly, evaluator 1 remarked that a different visual feedback was expected. Currently, a yellow line gets rendered from the hands towards the centroid of the triangle that is being measured. Evaluator 1 suggested changing this visual feedback to an animated outline on the targeted triangle instead. Evaluator 4 confirmed our observations and found the audio feedback from this gesture confusing, initially thinking that the audio was related to completing a task.

This synthesizes the following design guidelines:

- *"Measurement tools should keep a uniform behavior (i.e. freeform vs. restricted), where specific types of gestures are used to invoke a visualization of geometric attributes."*
- *"The spatial placement of geometric attributes contributes to readability (e.g. use of symbolism from established practices in geometry education to indicate the attribute being measured)."*

The "menu" feature was introduced in this iteration. It received a positive response from our UX participants. We introduced this feature in an attempt to increase user control and error prevention. Segmenting the different gestures into modes decreased the possibility to perform a gesture unintended, because gesture detection is now checking a smaller list of possible gestures. Observations did reveal that this interaction needs to be improved. The menu forms too close to the hand of the user. As this is intended as a two-handed gesture (one hand to hold up the menu, the other hand to interact with the buttons), it was observed to often cause the hands to occlude each other. The Oculus Quest 2's hand-tracking stops working when hands occlude, causing confusion to the user. A solution could be to move the menu further away from the hand that triggers it, forcing the users to keep their hands away from each other and thus circumventing the problem of occlusion. Evaluator 1 confirmed this solution:

> *"The menu might be more useful if it's further away from the hand itself."*

From this, the following design guideline is made:

> *"Incorporating modes help guide the user and avoid irrelevant gesturing to the current mode and learning process."*

The "grabbing" interaction received a positive response from our testers. An important remark was made by a heuristic evaluator, regarding the grabbing affordance of the virtual manipulatives inside the IGE. The size and shape of a virtual manipulative should be met with an equally affording interaction. In our experiment, the triangle points and centroid were small objects and both users and evaluators were observed to use a "pinch-like" gesture intuitively for attempting to move the object. Therefore, we suggest the following design guideline:

> *"Sizes and shapes of virtual manipulatives should be in connection with an interaction or gesture that affords grabbing and other manipulating interactions."*

Finally, the task design and "submit" feature received a mixed response from both our UX testers and heuristic evaluators. Observations revealed that participants noticed the task board as one of the first elements in our application. Users would then either start questioning their own geometry knowledge, or attempt to get started on completing tasks. The "submit" button was moved into the menu in this iteration, to bring the controls closer to the user. As a result, very few users discovered the submit button and its functionality before they had already completed one or more tasks. In a previous iteration, the submit button was placed in front of the task board. Our test results indicate that the submit button in the menu was not intuitive, 5 users pressed it by accident while discovering the "mode switch" buttons, causing confusion.
In a discussion with evaluator 3 on task design, it became clear that our task presentation needs improvement. Evaluator 3 suggested to only present a single task at one time, so the user can focus better on each individual task. Instead, some form of progression bar could be placed to keep the user informed of the total session's progression, where a session could then have multiple tasks.

The submit button was intended to avoid users completing tasks by random exploration, instead making the solution a conscious effort. A way of emphasizing conscious effort would be by the use of *gamification* (Kiryakova, Angelova, and Yordanova, 2014). A scenario where accurate geometric shapes need to be created with limited resources available to the user could improve the conscious effort taken for each task, as there are consequences for wrongfully submitted tasks. In the current state, this could be simplified by using scoring for each task, with negative scoring for wrong submissions.

The following design guidelines are suggested, based on the feedback on submitting and task design:

- *"A conscious effort needs to be made by the user for submitting a task. There should be consequences in place for wrong submissions. Consider gamification or limited resources for completing tasks inside the IGE."*
- *"The spatial placement of geometric attributes contributes to readability (e.g. use of symbolism from established practices in geometry education to indicate the attribute being measured)."*
- *"Only 1 task should be presented towards the user at one given time. Session progression should be clearly indicated visually."*

The participants were labeled differently, A or B, whether they had taken part in our previous UX experiment (A) or not (B). No significant findings were made between the two populations and the sample size was too small to determine whether these findings are significant or not (Bjørner, 2016).

We have covered the most important findings. There were smaller detailed findings on each gesture, features that users liked to see but weren't necessarily detrimental to the experience. These features and the system bugs that were encountered were put together into a development list (see figure 6.25).

Finally, from the UX test and heuristic evaluation, 10 design guidelines for developing an IGE were synthesized and are presented in table 7.1.

| IGE design guidelines | |
|---|---|
| **Construction** | Creation of geometrical shapes should contain a confirmation function. |
| | Implement functions that can revert a user's action, or perform a previous user's action |
| **Manipulation** | Interactable capabilities should have visual indicators (e.g. operation symbols) to inform the user. |
| | Sizes and shapes of virtual manipulatives should be in connection with an interaction or gesture that affords grabbing and other manipulating interactions. |
| **Modes** | Incorporating modes help guide the user and avoid irrelevant gesturing to the current mode and learning process. |
| **Measuring** | Measurement tools should keep a uniform behavior (i.e. freeform vs. restricted), where specific types of gestures are used to invoke a visualization of geometric attributes. |
| | The spatial placement of geometric attributes should contribute to readability (e.g. use of symbolism from established practices in geometry education to indicate the attribute being measured). |
| | The spatial placement of geometric attributes contributes to readability (e.g. use of symbolism from established practices in geometry education to indicate the attribute being measured). |
| **Task design** | A conscious effort needs to be made by the user for submitting a task. There should be consequences in place for wrong submissions. Consider gamification or limited resources for completing tasks inside the IGE. |
| | Only 1 task should be presented towards the user at one given time. Session progression should be clearly indicated visually. |

TABLE 7.1: 10 guidelines for developing an IGE, synthesized from the experimental results.

## 7.3 Our findings and other studies

So, our SUS, IPQ, VEQ and CLQ came out positive, what does this mean for the student's potential knowledge acquisition? According to the work by Makransky and Petersen, 2021, as discussed in section 6.4, factors contributing to gaining knowledge were addressed by our experiments. Makransky and Petersen, 2021 specifies that IVR inherently affords presence and agency, which are two of the contributing factors. But it is not merely the medium that causes more or less learning, Makransky and Petersen, 2021 suggest that besides the factors that IVR inherently brings to the table, cognitive load and self-regulation are equally important for a good transfer of learning. This technology show to have the affordances of IVR, DGE of VR more generally and high usability and low cognitive load.

Therefore, we can say that the suggested technology of this thesis could facilitate an effective transfer of learning, if the aspects detrimental to the user experience mentioned in the previous section would be improved.

## 7.4 Outlook

However, we cannot conclude that our suggested IGE could replace the established practices in geometry based on the data from this thesis alone. A longitudinal study investigating student performance is what we suggest for future research to be done. We would recommend following a similar procedure as Georgiou, Ioannou, and Kosmas, 2021, where GeoGebra was investigated for similar reasons against traditional methods of teaching.
An ideal procedure for collecting UX data would involve testing the IGE in the intended environment: a classroom with student and teacher using the IGE together. In this scenario, the teacher would have an asymmetric environment, where the teacher can follow the student's immersive environment and change task content on another medium such as a smartphone, tablet or PC. More research is required to reveal whether an IGE contributes to an improvement in learning outcome and student performance, and whether mathematical competency development is improving or not.

## 7.5 Biases

As developers of this IGE, we have inherent biases. We know every detail of the system and how each interaction is supposed to work in our system. Because of our developer bias, we had to perform a UX test to find usability problems within our IGE. First and foremost, it is important to remember that this IGE was aimed at a younger audience (students the age of 12), but the UX test was performed on adults. 9 participants were between the ages of 20 and 30. The other 4 were 50 or older. Although feedback from adults is still valuable for detecting usability problems, no conclusive evidence can be taken from experiments with adults. The UX test was also designed for qualitative feedback from our users. To truly determine the cognitive load, a quantitative study with the correct demographic and target group should be performed.

Besides the wrong demographic, there were also some inconsistencies within our UX test in regards to how much help and advice we gave each participant. We established that we would give no help to our users to begin with, and the application has very limited capabilities for first-time user tutorials. This was done on purpose, to observe how our users could find their way through the interactions with almost no outside help.
However, during testing it became clear that if we want valuable feedback, we need to give our participants small hints if too much frustration is observed. The number of hints and what the hints were should have been agreed upon before starting the UX test. We did note down which participants were guided and how much, but a future iteration should take this into consideration beforehand. The participants of the UX study were sampled using convenience sampling as, due to COVID-19, schools were not cooperative in students participating in our study. Therefore, the

test population consisted of users that are familiar with the research team and introduced bias. It is also worth noting that Oculus themselves recommend[2] the user to be of age 13 or older to use their hardware.

The procedure of using self-reporting should also be avoided when measuring cognitive load. Each participant has their own scale for deciding how much they agreed with statements regarding cognitive load and mental effort. Collins et al., 2019 and Armougum et al., 2019 suggest methods for measuring cognitive load using physiological measurements, such as the use of an electrocardiogram or galvanic skin response, where the heart and sweat is measured from the user, thus providing a less biased response for measuring cognitive load.

Besides the biases mentioned, there were also technological biases and limitations that became clear after running the experiments. These will be discussed in the following section.

## 7.6 Technological limitations

The technological limitations are related to the experimental hand-tracking feature of the Oculus Quest 2.
Although this feature allowed us to introduce an IGE on a stand-alone platform using inside-out tracking, it introduced limitations and potential biases to our measured data. Firstly, the tracking space for the user's hands is very limited. It is a relatively small area in front of the user. On top of that, the user's hand cannot occlude each other. Designing intuitive interactions became a tougher task to take up because of this, which is seen in our results from the "menu" gesture. Interactions that would normally seem intuitive to the user that involves your hands being close to each other, have to all be discarded and the intended result from such interactions have to be designed in such a way that it does not require the user's hands to be in proximity of each other.
Another remark is found with the "grab" gesture. A gesture that was often bugged by the hand-tracking capabilities. When the user would attempt to grab in the intended manner, hand-tracking would often not pick up the gesture. Any gestures that the user performs that involves their palms facing away from the headset, cannot be detected. Similarly, users were observed to grab a triangle and then look in other directions while holding the triangle. Hand-tracking stops working when the user moves their focus away and triangles would start floating into space.
We did attempt to solve this, by using Oculus' own integrated "Tracking Confidence". Theoretically, when the hands are out of view from the cameras, Oculus' tracking confidence should return a value of "low". When implementing this function, it was simply not working, the value returned by Oculus remained "high" and thus it became impossible to use the tracking confidence. An image processing script could have been written, if there were a way to access the data from the cameras. However, the data from the cameras is not directly accessible for developers.

The monochrome cameras inside the Quest 2 are also very sensitive to light sources. For example, during participant 7B the sunlight entering the laboratory

[2] https://www.oculus.com/safety-center/

setup started interfering with the hand-tracking to a point where it became unusable. A future setup should make sure that the environment is completely covered from direct natural light.

There is positive news for future hand-tracking development with the Quest 2, however. Facebook has shown promising future development for hand-tracking, such as the elasticity-based implementation for hand-tracking[3].

The Quest 2 was not the only technological limitation that was introduced with this project. Unity3D's editor would also often crash or freeze during development and during testing. The experimental nature of hand-tracking also made it impossible in our time frame to make a proper "build" that can use hand-tracking, and we had to run our UX tests tethered instead of stand-alone. In a final iteration, it would be detrimental that the Quest 2 can run an IGE on its own.

[3] https://research.fb.com/publications/constraining-dense-hand-surface-tracking-with-elasticity/

# Chapter 8

# Conclusion

This thesis suggests a new type of DGE, the "Immersive Geometry Environment", for learning geometry at a lower-secondary education level, using theoretical underpinnings of embodied and immersive learning in an attempt to improve student performance from traditional teachings.
Research related to immersive learning was studied and theories brought forth by such research were used as a foundation for the design of the IGE.

Our problem statement for this thesis is:

> *"How can an immersive geometry environment with a gesture-based interface facilitate lower-secondary geometry education?"*

Implementation details on the first and second iteration are presented in this thesis, along with the methodology for evaluating the IGE. Results from UX testing and heuristic evaluation have shown that the IGE suggested by this thesis could facilitate a new and possibly enhanced method for teaching geometry at a lower-secondary education level, based on our positive responses regarding usability, presence, agency and cognitive load. The IGE was reportedly lacking in 2 heuristics: error prevention and user control and needs to be improved in future iterations.
As a result from implementing and testing the IGE, 10 guidelines were synthesized that are to be followed in future iterations of IGEs.

A future course of action was then suggested for a longitudinal study investigating the direct student performance and improving specific interactions and elements of our IGE that relate to error prevention and user control.

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## Appendix A

# System state flowchart

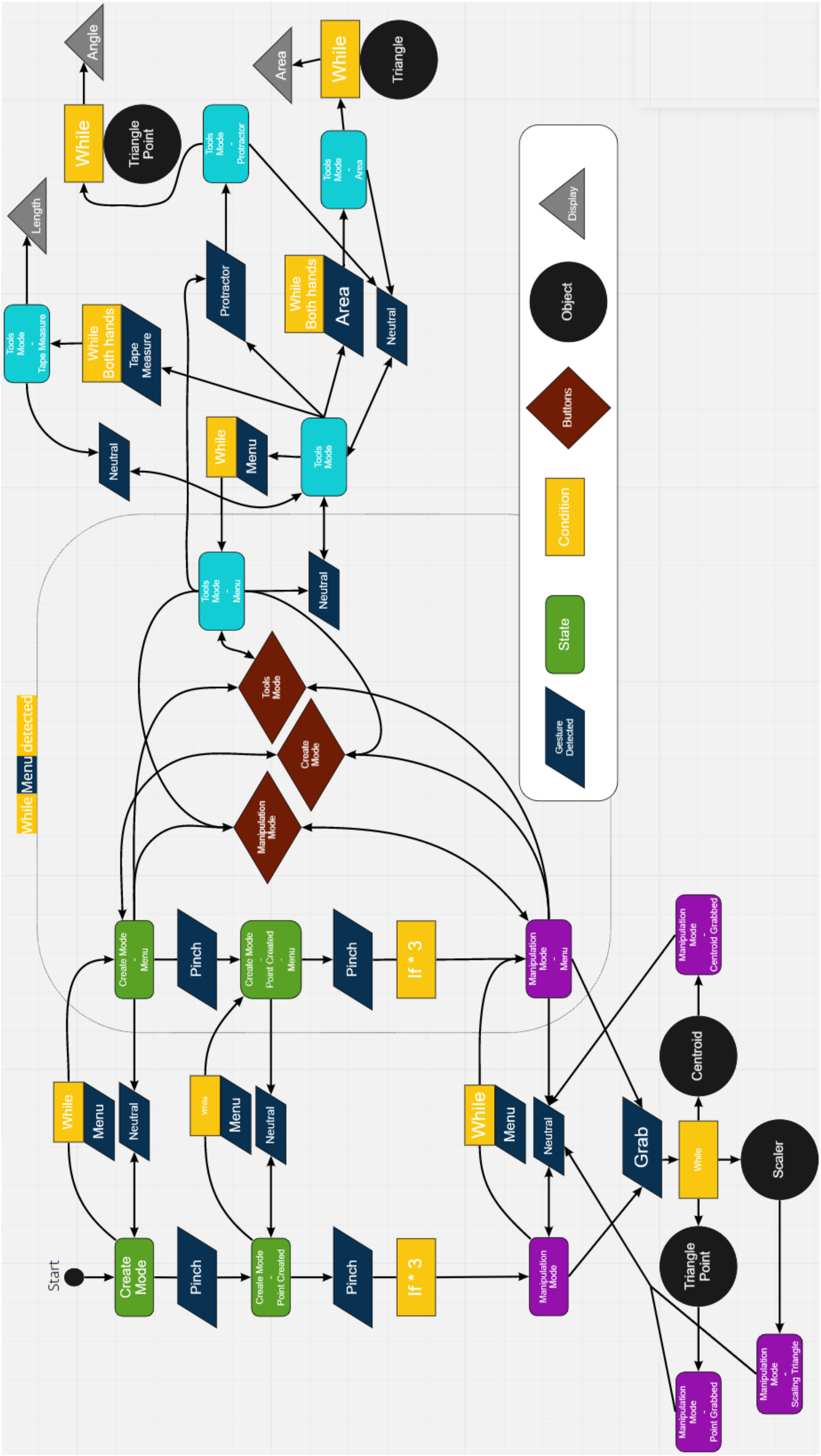
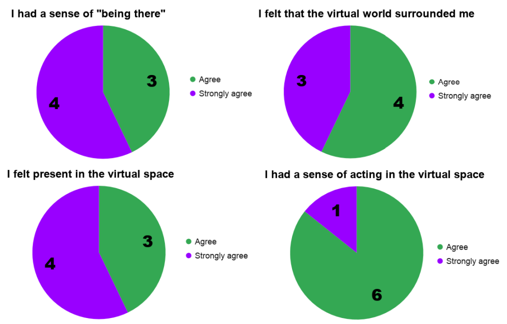



FIGURE A.1: State machine flowchart.

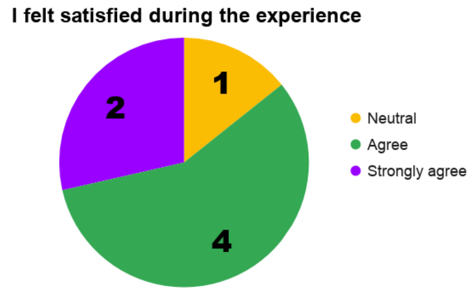
# Appendix B

# UX test

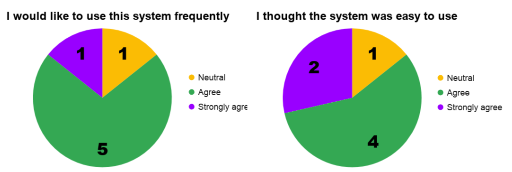
## Previous work UX test figures



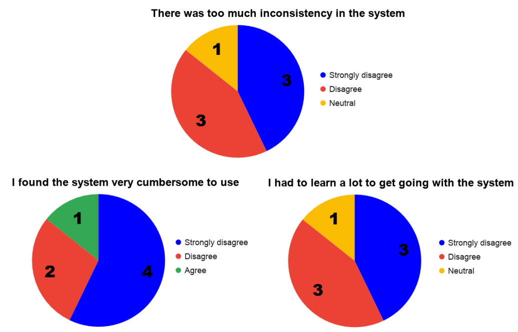

(A) Presence and immersion.




(B) Overall satisfaction.




(C) Perceived ease-of-use.




(D) Usability: inconsistency and cumbersomeness.

FIGURE B.1: Results from the UX experiment in previous works on immersion, satisfaction and usability from.

## UX test welcome script

Welcome to our user test! Thank you for participating today.

> Check for mask

We are conducting this user test under Aalborg University's COVID-19 regulations, therefore we ask you to put on a facemask, and keep distance as much as possible.

> Hand over a facemask

We ask you to wear this at all times during the test.

Our project aims to educate 6th grade students in Geometry. We have developed an application in Virtual Reality that could ultimately be used inside the classrooms as a teacher's tool. We are still in a work-in-progress and currently we need user feedback on basic interactions inside the application.

This is where we need you. For this user test, we will ask you to step into our virtual geometry world and get familiar with the application, it's graphical elements and the interactions.

The test will be conducted in the following manner:

First you will be asked to fill out the first section of the questionnaire on the laptop in the kitchen -

> Show kitchen

This will be regarding your basic information. When you are done, please come in to the living room -

> Show living room

The user test will take place there.

After the test, we will ask you to fill out the rest of the questionnaire in the kitchen. Please sanitize on your way between rooms.

The bathroom can be found over here.

> Show bathroom

Please sanitize your hands now, have your mask on over your nose and mouth and proceed into the kitchen. You will find water, tea, coffee and cookies at your disposal, feel free to take what you like. You may take off your mask in the kitchen to eat or drink. When you are ready, come join us in the living room :) . If you have any questions, don't hesitate to ask a team member. Your participant number is:

## UX test Experiment script

Welcome!

First, we'd like to ask if we can have your consent for being filmed while performing our user test?

Please take place in the marked box on the floor, in the direction of the arrow.

A team member will help you get comfortable with the headset.

> Puts on headset

You should see a menu in front of you, does it look centered?

> Center with controller if necessary

If at any moment you want to stop, just let us know and we will stop the experience.

Alright, i'm going to start our application in a moment. Take a moment to get familiar. If you get too close to real objects, a box will appear in the virtual world, indicating that you are getting close to an object.

Please think out loud during your experience.

## UX test questionnaire

# Virtual Geometry - Usability, Immersion, Embodiment and Cognitive Load

Thank you for joining the user test for our Virtual Geometry application!

We are a small research group investigating interactions in our virtual reality application. The application is intended for 6th graders learning about geometry. This is our second user testing of the application and we are focused on investigating our user interaction in the current state.

During the experience, we ask you to speak your thoughts: there are no wrong answers and we appreciate any feedback you have during or after the experience.

During the experience you will receive some tasks, it is up to you to complete them. We also recommend to spend some extra time to get familiar with the application and the interactions.

In the next section, we ask you to fill out basic information about yourself. After filling this out, please contact a researcher to get started with the experience. After the experience, there will be a last section to this questionnaire, where you will be asked to give feedback.

*Required

## Participant information and VR experience

Let's start with some basic information about yourself.
Take your time, if you have any questions about the content of this form, just ask one of the researchers, we are happy to help :).

-------------------------

Your data will be processed anonymously and under GDPR regulation.
By participating in this test, you are agreeing to these terms.

1. Participant number (ask a team member if you forgot): *

2. What is your age? *

*Mark only one oval.*

- 10-15 years
- 15-19 years
- 20-25 years
- 26-30 years
- 30-40 years
- 40-50 years
- 50-65 years
- 65+ years

3. What is your gender? *

*Mark only one oval.*

- Male
- Female
- Other: ____________

4. VR familiarity *

*Mark only one oval per row.*

| | Never | A few times | Regularly | Daily user | Professional |
|---|---|---|---|---|---|
| Have you ever tried Virtual Reality (VR)? | | | | | |

5. What is your occupation? *

____________

6. If you are a student, what is your field of study?

**This is the end of the questionnaire before the test. Please notify a team member that you are ready for the test.**

## Evaluation of the experience

The following questions will be regarding your experience with our application.

7. Overall satisfaction *

*Mark only one oval per row.*

| | Strongly disagree | Disagree | Neutral | Agree | Strongly Agree |
|---|---|---|---|---|---|
| I felt satisfied during the experience | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |

8. Please elaborate your answer: *

9. The following statements are regarding the "usability" of our application. *

*Mark only one oval per row.*

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| I think I would like to use this system frequently | | | | | |
| I found the system unnecessarily complex | | | | | |
| I thought the system was easy to use | | | | | |
| I think that I would need the support of a technical person to be able to use this system | | | | | |
| I found the various functions in this system were well integrated | | | | | |
| I thought there was too much inconsistency in this system | | | | | |
| I would imagine that most people would learn to use this system very quickly | | | | | |
| I found the | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| I found the system very cumbersome to use | | | | | |
| I felt very confident using the system | ◯ | ◯ | ◯ | ◯ | ◯ |
| I needed to learn a lot of things before I could get going with this system | ◯ | ◯ | ◯ | ◯ | ◯ |

10. The following statements are regarding feeling presence and immersion in the experience. *

*Mark only one oval per row.*

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| In the computer generated world I had a sense of "being there". | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| Somehow I felt that the virtual world surrounded me. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I felt present in the virtual space. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I had a sense of acting in the virtual space, rather than operating something from outside. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I was aware of the real world surrounding me while navigating the virtual world. (like sounds, room temperature, other people) | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I still paid attention to | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |

| | | | | | |
|---|---|---|---|---|---|
| I still paid attention to the real environment. | | | | | |
| I was completely captivated by the virtual world. | | | | | |
| The virtual world seemed real to me. | | | | | |
| My experience in the virtual environment was consistent with my real world experience. | | | | | |
| The virtual world seemed more realistic than the real | | | | | |

11. The following statements are regarding embodiment in the virtual environment *

*Mark only one oval per row.*

| | Strongly disagree | Disagree | Somewhat disagree | Neither agree nor disagree | Somewhat agree | Agree | Strongly agree |
|---|---|---|---|---|---|---|---|
| It felt like the virtual body was my body. | | | | | | | |
| It felt like the virtual body parts were my body parts. | | | | | | | |
| The virtual body felt like a human body. | | | | | | | |
| It felt like the virtual body belonged to me. | | | | | | | |
| The movements of the virtual bodyfelt like they were my movements. | | | | | | | |
| I felt like I was controlling the movements of the virtual body. | | | | | | | |
| I felt like I was causing the movements of the virtual body. | | | | | | | |
| The movements | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| The movements of the virtual bodywere in sync with my own movements. | | | | | | | |
| I felt like the form or appearance of my own body had changed. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I felt like the weight of my own body had changed. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I felt like the size(height)of my own body had changed. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |
| I felt like the width of my own body | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |

12. The following statements are regarding cognitive load during the experience: *

*Mark only one oval per row.*

| | Very easy | Easy | Neutral | Difficult | Very difficult |
|---|---|---|---|---|---|
| How easy or difficult do you consider Geometry at this moment? | ◯ | ◯ | ◯ | ◯ | ◯ |
| How easy or difficult do you find it to be inside VR? | ◯ | ◯ | ◯ | ◯ | ◯ |
| How easy or difficult was it for you to work with the learning environment? | ◯ | ◯ | ◯ | ◯ | ◯ |
| How easy or difficult was it to distinguish important and unimportant information in the learning environment? | ◯ | ◯ | ◯ | ◯ | ◯ |
| How easy or difficult was it for you to collect all the information that you needed in the learning environment? | ◯ | ◯ | ◯ | ◯ | ◯ |
| How easy or difficult was it to understand | ◯ | ◯ | ◯ | ◯ | ◯ |

the simulation?

13. Indicate on the scale the amount of mental effort you had to invest to follow the simulation *

*Mark only one oval per row.*

| | 1- low effort | 2 | 3 | 4 | 5 - a lot of effort |
|---|---|---|---|---|---|
| Mental effort | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ |

14. Which of the following interactions did you NOT experience at all?

*Tick all that apply.*

- [ ] Pinching to create triangle points
- [ ] Grabbing to move triangles/triangle points
- [ ] Grabbing to scale a triangle
- [ ] Gesture for tape measure, to measure triangle sides
- [ ] Gesture for protractor, to measure triangle angles
- [ ] Gesture for area, to measure triangle area
- [ ] Button - Submit button, to submit an assignment
- [ ] Button - Delete, to drag a triangle to delete
- [ ] Button - mode switches, to switch to different modes

15. Which of the following interactions did you think worked well?

*Tick all that apply.*

- [ ] Pinching to create triangle points
- [ ] Grabbing to move triangles/triangle points
- [ ] Grabbing to scale a triangle
- [ ] Gesture for tape measure, to measure triangle sides
- [ ] Gesture for protractor, to measure triangle angles
- [ ] Gesture for area, to measure triangle area
- [ ] Button - Submit button, to submit an assignment
- [ ] Button - Delete, to drag a triangle to delete
- [ ] Button - mode switches, to switch to different modes

16. Please elaborate your answer

17. Which of the following interactions did you feel were NOT intuitive to you?

*Tick all that apply.*

- [ ] Pinching to create triangle points
- [ ] Grabbing to move triangles/triangle points
- [ ] Grabbing to scale a triangle
- [ ] Gesture for tape measure, to measure triangle sides
- [ ] Gesture for protractor, to measure triangle angles
- [ ] Gesture for area, to measure triangle area
- [ ] Button - Submit button, to submit an assignment
- [ ] Button - Delete, to drag a triangle to delete
- [ ] Button - mode switches, to switch to different modes

18. Please elaborate your answer

## Almost there!

Thank you for making it this far, this final section is for your last reflections or additional feedback you were unable to give before

19. Overall, did it feel like the application was missing something you found crucial and should have been included?

20. Did you feel like there was an important interaction missing? If so, please describe what kind of interaction you would have liked to see.

21. Is there any additional feedback you would like to provide us with?

22. What was your total time spent inside the application? Ask a team member if it wasn't mentioned. *

**Thank you!**
Thank you for testing our application!

Google Forms

## Observation Tables

| Participant #: 1A | Total time spent: 10 m 40 s | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | | x |
| | Used to conduct tasks | | x |
| | Consulted this element for guidance | | x |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | x |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 7 m 40 s | |
| Observer notes | Switching to Manip Mode causes triangles to move erratically some of the times.<br>Frame drops occur when in Manip Mode and Scene view window is open | | |

| Participant #: 2A | Total time spent: 31 m 16 s | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | | x |
| | Used with intent | | x |
| | Used without intent | x | |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tries to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | x |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | | x |
| | Submitted all tasks with intent | | x |
| Time elapsed for task completion with intent: | | | |
| Observer notes | Menu buttons were unclear to 2A, tried grabbing and "karate chopping"<br>Submit was never discovered | | |

| Participant #: 3B | Total time spent: 38 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | | x |
| | Consulted this element for guidance | | x |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | | x |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | x | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | | x |
| Time elapsed for task completion with intent: | | | |
| Observer notes | Tried grabbing using Pinch<br>Unity crashes often when exiting Play mode | | |

| Participant #: 4B | Total time spent: 30 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | | x |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Scaling Triangle | Attempted exploration | | x |
| | Used with intent | | x |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | | x |
| | Used with intent | | x |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | x | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | | x |
| | Submitted any completed task with intent | | x |
| | Submitted all tasks with intent | | x |
| Time elapsed for task completion with intent: | | | |
| Observer notes | User 4B was guided through the interactions after 15 minutes | | |

| Participant #: 5B | Total time spent: 20 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | x | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 13 m 44 s | |
| Observer notes | User 5B has color vision deficiency.<br>Cubes aren't a clear indicator for Scaling.<br>User was told there was 1 interaction unexplored (trash can). User did explore this interaction independently | | |

| Participant #: 6A | Total time spent: 36 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Area | Attempted exploration | | x |
| | Used with intent | | x |
| | Used with intent more than once | | x |
| | Used without intent | | x |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | | x |
| | Used with intent | | x |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | x | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | | x |
| | Submitted any completed task with intent | | x |
| | Submitted all tasks with intent | | x |
| Time elapsed for task completion with intent: | | | |
| Observer notes | User 6A was heavily guided due to frustration. | | |

| Participant #: 7B | Total time spent: 28 m 30 s | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | | x |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | x |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 27 m | |
| Observer notes | User 7B unfortunately experienced bad hand-tracking due to direct sunlight entering the laboratory setup. The sunlight was covered by a researcher but hand-tracking remained poor during this experiment. | | |

| Participant #: 8B | Total time spent: 26 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | x |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 11 m 53 s | |
| Observer notes | User 8B was hinted where the delete function takes place, but not how it is done. User 8B had a lot of accidental triangles created during the experiment, but managed to complete all tasks regardless. | | |

| Participant #: 9A | Total time spent: 15 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | | x |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | x | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 6 m 12 s | |
| Observer notes | User 9A has Color Vision Deficiency. | | |

| Participant #: 10B | Total time spent: 13 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | | x |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | | x |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | x | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 10 m 10 s | |
| Observer notes | | | |

| Participant #: 11B | Total time spent: 14 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | | x |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | x |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 12 m 30 s | |
| Observer notes | User 11B was instructed on how to remove triangles. | | |

| Participant #: 12A | Total time spent: 30 m | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | x | |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | x |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | | x |
| Time elapsed for task completion with intent: | | 14 m 53 s | |
| Observer notes | User 12A submitted all tasks in the correct manner, but did not intend to submit.<br>User 12A was hinted to try the scaling interaction. | | |

| Participant #: 13B | Total time spent: 15m30s | | |
|---|---|---|---|
| - Gestures - | Observation | Yes | No |
| Create | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Menu | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Angle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Side | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |
| Measure Area | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | x | |
| Grabbing Point | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Grabbing Centroid | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | |
| Scaling Triangle | Attempted exploration | x | |
| | Used with intent | x | |
| | Used with intent more than once | x | |
| | Used without intent | | x |

| - Graphical Elements - | Observation | Yes | No |
|---|---|---|---|
| Task Board | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| Hint GUI | User clearly noticed this element | x | |
| | Used to conduct tasks | x | |
| | Consulted this element for guidance | x | |
| - Interactive Elements - | Observation | Yes | No |
| Submit | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| Create Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | |
| Tools Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | |
| Manipulation Mode Button | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | |
| Trash can | Attempted exploration | x | |
| | Used with intent | x | |
| | Used without intent | | x |
| | Tried to click | x | |
| Grid | Snapped triangle point with intent | x | |
| | Snapped triangle centroid with intent | x | |
| | Snapped object without intent | | |
| - Task Completion - | Observation | Yes | No |
| | Completed all tasks | x | |
| | Submitted any completed task with intent | x | |
| | Submitted all tasks with intent | x | |
| Time elapsed for task completion with intent: | | 10m | |
| Observer notes | User 13B suggested to make every finger able to press the Mode Buttons. | | |

# Appendix C

# Heuristic Evaluation

## Script read to evaluators

# Pre-testing

**Introduce the evaluators to the test**

We have made a VR application for teaching geometry at a 6th-grade level. Our application uses a gestures-based interface via hand tracking, meaning you will be using your hands to create, move and measure triangles in the application.

We would like you to evaluate the usability based on the point of view of the **Target Audience**, 6th-grade children in a math class. When you evaluate the application, we would like you to base it on a set of **Heuristics** and rank the problems you encounter on a severity scale:

Red

Orange

Yellow

Green

Based on how critical you believe the problem is, Red being most critical, Green being least critical. You are of course welcome to use other heuristics you find fitting. You can always ask us for help with the application or if you want us to repeat something during the evaluation.

**Visibility of system status**. Is the user kept informed about what is going on, through appropriate feedback?

**Match between the system and the real world.** Are things like phrases and concept something that would be familiar to the user?

**Error prevention.** Is the application good enough to prevent errors/ are there proper conformation options?

**User control and freedom.** Are options/ system function chosen by mistakes easy to undo/redo

**Recognition rather than recall.** Are instructions for use of the system, visible or easily retrievable.

**Aesthetic and minimalist design.** Is there any information that is irrelevant and diminishes the relevant information's visibility?

**Synchronous body movement.** Are the application and interface in synchrony with the body's movement?

**Mental Comfort.** Anything that causes motion sickness, headaches, dizziness, and nausea

There will be two walkthroughs. In the first walkthrough, you can freely use the application from start to finish and familiarize yourself with the application and the gesture interface.

For the second walkthrough, we would like you to go more in-depth with individual elements of the application.

Lastly, there will be a debriefing, where we would like to summarize and ask a few questions about your experience in the application.

## Notes from the Heuristic Evaluation

Evaluator: 1

Notes: The triangle point gizmo's afford pinching rather than grabbing. Increasing the size might help the grab affordance.
On create: There were accidental actions happening, maybe a revert
On menu: The menu might be more usable further away from the hand itself.
On Delete: It has a similar appearance as a button. A 3D representation of a trashcan might be better, just as long as it looks different from the buttons.
On submit: Automatically submit assignments instead of a button.
On Protractor: It would be nice to have an angle indicator on the triangle.
On Area: It would be nice to have visual feedback on the entire triangle.
On Tape measure: Snapping on the points would be nice if you are near them.
Visibility: Yellow
System/real world: Green
Error prevention: Green
User control and freedom: Yellow
Aesthetic and minimalist design: Green
Synchronous body movement: Green
Mental Comfort: Green

Evaluator: 2
On create: Maybe some kind of double confirmation for creating. An undo function would be nice. Maybe a physical trash can.
On menu: The menu is overcomplicating the application.
On Delete: It looks like a button, for consistency that is not good if it isn't actually a button.
On Tape measure: An actual object that can measure objects in the virtual world.
On Grab: Perhaps make it more visible that you need to form a fist to grab
On Scale:
On Assignment board: Maybe some feedback when I've completed a task.
Visibility: Yellow/green
System/real world: Orange
Error prevention: Red
User control and freedom: Red
Aesthetic and minimalist design: Yellow
Synchronous body movement: Green
Mental Comfort: Yellow
Recall vs Recognition: Orange

Evaluator: 3
Notes:
On menu: Hard to recognize, easy to recall
On Assignment board: Only show 1 task at a time, instead of all the tasks at once
Visibility: Red/orange
System/real world: Yellow/Green
Error prevention: Yellow
User control and freedom: Red
Recall vs Recognition: Yellow/Green

Aesthetic and minimalist design: Orange because of the tasks Green otherwise
Synchronous body movement: Red
Mental Comfort: Green

Evaluator: 4

Notes: I thought that my body would become part of a triangle, instead of using a grid/coordinate system.

On create: I'm used to a finalizing click, some form of confirmation would be nice. It was confusing when I changed mode and it still had a point.

On menu: I liked the menu, but it took some time to figure out. There are other menus that are more focused as the background In your implementation

On Delete: I did not figure out the deletion, but it makes sense to me I didn't figure out this interaction. It didn't come natural to me to use both hands , 1 for the menu and 1 for the trashcan.

On Protractor: This worked well, I was expecting the number to show up between my fingers, but the text was fine.

On Area: I thought the audio was a celebration for completing the tasks correctly.

On Tape measure:

On grabbing: It took time to understand the gestures exactly. The fine point of when you grab or not was hard to notice. The centroid didn't occur to me that it was grabbable.

On scaling: Didn't notice that the cubes are for scales.

On the grid: I liked the bubble that showed me I can click it back in the grid

On taskboard: I didn't relate anything of the taskboard with the menu

Visibility: Green, the interaction and modes came little by little and I was able to keep track of it.

System/real world: Yellow/green

Error prevention: Yellow, lack of warnings

User control and freedom: Orange

Recall vs Recognition: Green I didn't need to break down any tasks, I knew where to look

Aesthetic and minimalist design: Yellow/green I was confused about the placement of the numbers on the coordinate system.

Synchronous body movement: Green The menu is synchronous, the triangles gave me some confusion as they were moving uncontrollably.

Mental Comfort: Green