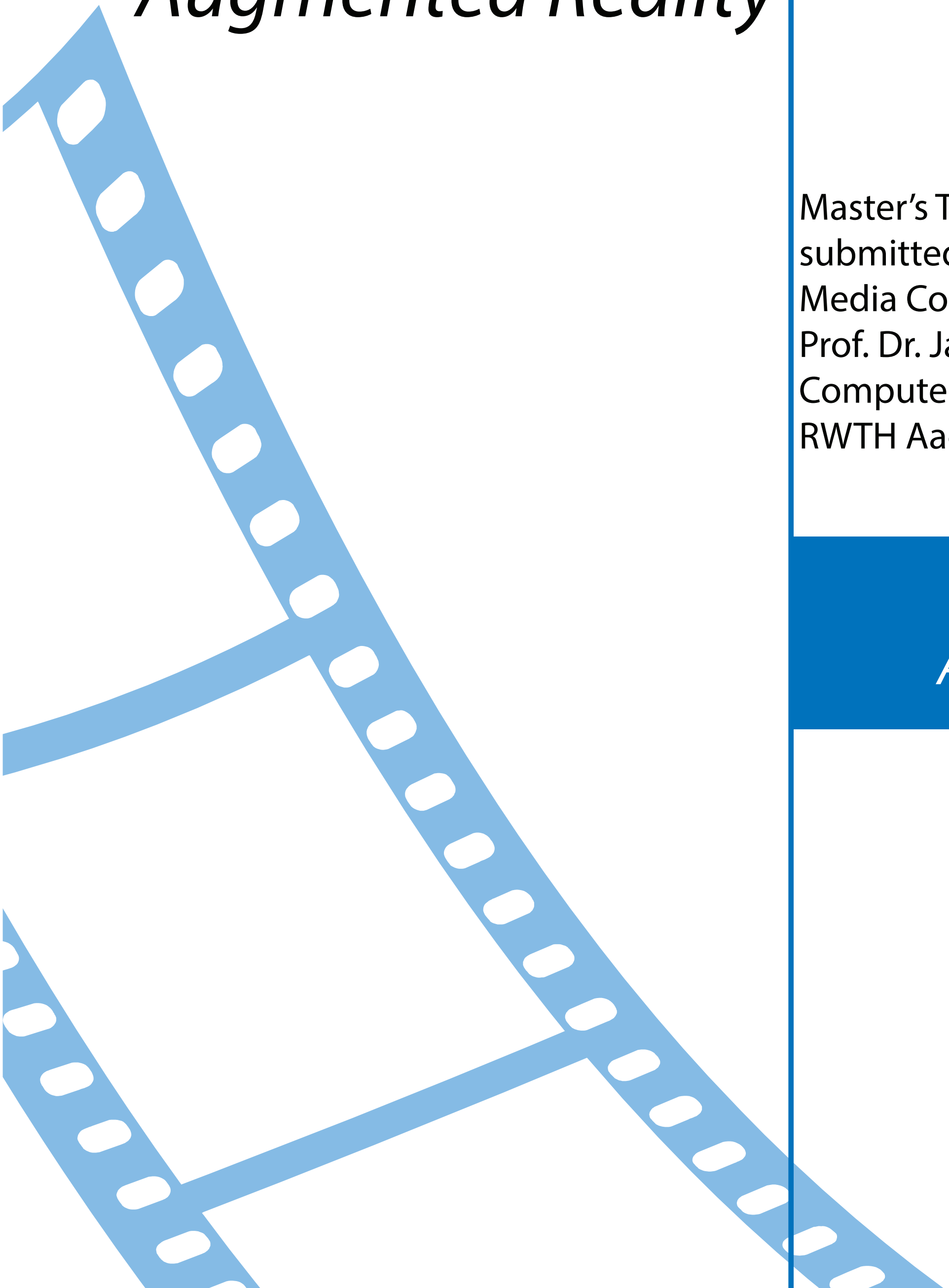
Analyzing 3D Sketching Performance on Physical Objects in Augmented Reality



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Abstract

Sketching in general is one of the first steps of prototyping new ideas. Because working with sketches is only 2 dimensional, basic limitations in interpretableness apply. Extracting 3-dimensional prototypes from 2 dimensional sketches is not easily accomplished and is a cognitive and motoric workload. Implementation of a 3-dimensional sketching tool on the basis of Augmented Reality is desirable.

Augmented Reality enables, just like Virtual Reality, to sketch in mid-air. Advantageous for Augmented Reality is the possibility of incorporating real objects into the process, in contrast to Virtual Reality. With this advantage novices get the chance to personally fabricate new objects and enhance existing objects using known paradigm from sketching in 2 dimensions. Real objects in contrast to virtual ones guide the drawing utensil, through multiple means, while sketching. We categorize these different ways of guidance in 4 categories. Flat objects without an additional guidance, concave objects with grooves, convex objects with edges and just pure visible markings on the surface.

Our study analyzes the different guidance types for the achieved accuracy while drawing along an object of this type. The possibility of adding virtual objects to the scene, in the context of Augmented Reality, enabled us to further analyse differences between virtual and physical objects. Our result show expected results, like the enhanced accuracy in the case of concave, physical guidance, but also shows interesting contrasts. Like the complete opposite case for concave, virtual guidance, especially behind the object.

In general, our findings provide initial values for the expected accuracy a human achieves while sketching along arbitrarily shaped objects.

Überblick

Zeichnen ist einer der ersten Vorgänge um neue Ideen umzusetzen. Zeichnungen unterliegen dabei grundlegenden Einschränkungen die der Arbeit mit zwei Dimensionen geschuldet ist. Einfache Extraktion 3-dimensionaler Prototypen ist nicht einfach umsetzbar und benötigt weitere kognitive oder motorische Arbeit. Die Umsetzung einer 3-dimensionalen Zeichenlösung auf Basis von Erweiterter Realität ist erstrebenswert.

Erweiterte Realität ermöglicht, genau wie Virtuelle Realität, das 3-dimensionale Zeichnen in der Luft. Vorteilhaft ist dabei die Möglichkeit die Realität im Gegensatz zur Virtuellen Realität mit in die Zeichnung einzubeziehen. Anfänger haben so eine Möglichkeit im Bereich der personalisierten Fabrikation eigene Objekte und Erweiterungen bestehender Objekte zu designen. Reale Objekte führen dabei Zeichenutensilien durch verschiedene Arten der Wegleitung an sich entlang. Wir unterscheiden hier im Rahmen der Benutzerstudie 4 Kategorien. Flache Objekte ohne weitere Wegleitung, konkave Formen wie Kerben, konvexe Formen wie Ecken und einfache sichtbare Markierungen ohne weitere Haptik.

Unsere Studie analysierte dabei die unterschiedlichen Wegleitungskategorien auf mögliche Genauigkeit beim Entlangfahren mit einem Stift. Um die Möglichkeiten der Erweiterten Realität effektiv auszunutzen verglichen wir die physikalischen Objekte mit virtuell eingeblendeten. Unsere Ergebnisse zeigen erwartete Ergebnisse wie die erhöhte Genauigkeit bei konkaver, physikalischer Wegleitung, aber auch interessante Gegensätze. So erzielt der konkave Fall auf virtuellen Objekten vor allem hinter dem Objekt die schlechtesten Ergebnisse.

Allgemein lassen sich aus unseren Ergebnissen erste Werte für die erwartete Genauigkeit eines Menschen bei der freien Zeichnung auf beliebig geformten Objekten ableiten.

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Thirdly, I would like to thank everyone who assisted the creation of the items needed to conduct the study, especially Oliver Nowak.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

Definition:
Excursus

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in American English.

Download links are set off in coloured boxes.

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Chapter 1

Introduction

Interest in Virtual Reality (VR) and Augmented Reality (AR) always peaks in correlation with advances in the respective fields. In recent years projects like Google Cardboard, HTC Vive and Oculus Rift surfaced in the VR space. Similarly, Google's ARCore developed from Project Tango, Apple's ARKit and Microsoft HoloLens increased interest in AR. As of late, with the mentioned VR projects and ARCore and ARKit, these new technologies found their way into the hand of the general population by being an addition to the omnipresent smartphones (Google Cardboard, ARCore, ARKit) or catering to the pc gaming community (HTC Vive, Oculus Rift). Because this is a recent development, the possibilities of new interactions with our devices, aided by these technologies, have to explored.

With projects like the basic drawing application Gravity Sketch (VR), the more advanced Google Tiltbrush (VR) and the virtual storyboard Sketchbox (VR and AR) it is possible for the general population to design and create. Especially the gaming aspect of VR introduced these design technologies on a business level via integration into game engines (Unreal Engine 4) and therefore game development workflow.

The creation of 3D models in VR on a purely virtual level may suffice for game development, but for designs fit for the real world, multiple additional steps have to be taken.

For example, if we want to design a cupboard, it is crucial to first take measurements of the area, where it will be installed. We then transfer the measurements into the Computer Aided Design (CAD) software of choice and begin to create the 3D model of the cupboard. If the cupboard is part of a greater installation we also may need to recreate the already existing parts in the virtual environment of our CAD software. Recreating the surroundings of the cupboard is also the only possibility to see the created model in the destination environment and judge the design in context. After the creation process has finished, we transfer the generated building instructions and measurements to a fabrication facility (this could also be a consumer grade 3D printer). We install the produced parts in the real location.

Too many steps separate design from creation.

Considering the basic principles of interaction design, this course of actions exhibits several issues, which may introduce errors in the process. We may take faulty measurements or miss measurements, like the space in front of the cupboard entirely, which would end up in building a cupboard with doors to wide to be opened properly. Additionally, we may introduce offsets by transferring measurements wrong into the CAD software, resulting in a wrong virtual representation of already existing parts and surrounding objects. Because the only possibility to see the created model in the destination environment is to recreate the environment, there may be faults introduced by simplifying the virtual environment too much. We most likely have not measured a rug laying on the ground, which might prop up some of the cupboard legs, resulting in a tilted position only seen in the installation step.

Possibility for human error in design has to be reduced.

In contrast to VR the real environment can be directly integrated in the design process, without the need of additional transfer steps, in AR. Designing an object, like a cupboard, or even enhancing objects, like adding a shelf to an existing cupboard, can be achieved by directly sketching in the destination space and along the existing parts. With the mentioned consumer grade applications, this can be achieved without the knowledge required for CAD software and opens up the design process for novices in a similar way how 3D printing enabled novices to create physical parts without the need to have access to laser cutting or similar expensive and complex technologies. The physical feedback given by the real objects is called haptic guidance.

In the VR example getting the measurements was error prone. In the AR example, the sketching process directly encompasses the measuring. The resulting question is, how accurately humans are able to sketch on real objects, virtual objects or a mixture of both. The question has already been answered for VR and planar shapes, where accuracy improves by providing a physical surface as guideArora et al. [2017]. For AR every real object can be used as guide, this includes all possible shapes and surfaces, like a round glass or a box shaped book. Additionally, AR does not fully occlude the real world. The physical guidance surface has to be aligned with a virtual representation in VR, but not in AR. This opens up the opportunity to use real objects also as visual guide, for example the contents of a printed page.

Sketching on haptic objects helps accuracy.

In this thesis, we will begin with a review of related work. This includes sketching in VR, personal fabrication projects including mixed reality 3D modelling and differences in AR and VR. We then give an overview of the planned system and the motivation behind its design. The overview also contains a classification of guidance types, that real objects offer, visually as well as haptic. We introduce examples for these guidance classifications and extract edge cases for study. In the fourth chapter, we present the devices and implemented code for the system and user study. The description of the user study follows in chapter five. We compile the results of the study in chapter six and draw a conclusion in chapter seven.

Chapter 2

Related work

Augmented Reality as a subdomain of mixed reality, as mentioned in the introduction, shows potential to ease the use of CAD. In this chapter we will first present research conducted in the field of personal fabrication using varying degrees of mixed reality content. We will give an overview on the exact subdomain of mixed reality our study was conducted. Giving reference values from VR studies on input accuracy and sketching conclude this chapter.

2.1 Personal Fabrication

Personal fabrication is hindered by usability.

Personal Fabrication in its current state is heavily dependent on mostly the same workflow of starting design in a virtual environment. This design is then realized physically with 3D printing or laser cutting Mota [2011]. This workflow decision is reinforced by the recent price drop of consumer grade 3D printers and rise of open source software like Blender. The ease of fabricating is directly connected to the usability of these software products and their interoperability with the production devices Willis et al. [2011]. Especially novices might be deterred by these limitations, which are not uncommon. One of the most used free software products, Blender (Figure 2.1), is constantly redesigned to tidy up the user interface Felinto [2017].

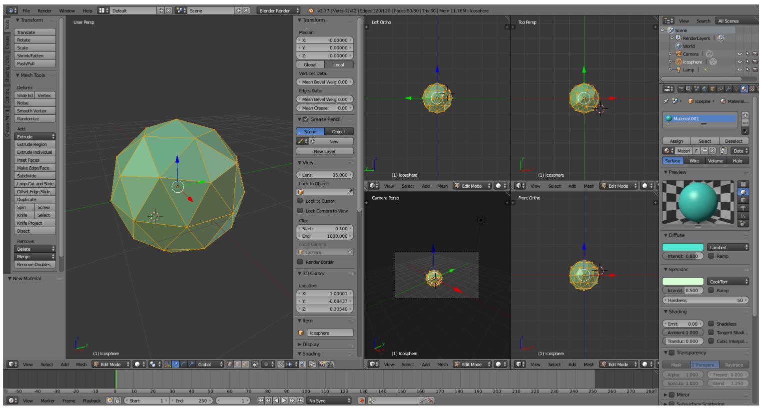


Figure 2.1: An example user interface of the software Blender.

2.1.1 Bidirectional Workflow

Several studies and projects exist to combat the disconnect between virtual and physical design. With 'ReForm' Weichel et al. Weichel et al. [2015] introduced an approach to break the unidirectional workflow and enabling the user to seamlessly work on the physical and virtual representation of the design. Every change in the virtual design is reflected in the physical representation and vice versa (Figure 2.2). This is achieved, by enabling additive and subtractive fabrication through clay as physical medium. The virtual representation is partially projected onto the physical medium as a texture and a semitransparent glass pane in front of it to display a user interface. Manual changes are scanned back into the system by strategically placed sensors around the working surface. These manual changes may include deforming the object or sketching a line on the clay to guide an integrated mill Weichel et al. [2015].

A second approach in breaking the unidirectional workflow is 'ProtoMold' by Yamaoka et al. Yamaoka and Kakehi [2017]. This approach uses a plastic sheet, which is heated up to become moldable and then pushed against a surface by suction to attain the same structure. The surface, the plastic sheet is pushed against, consists of small cube shaped elements, which can be raised and lowered, to

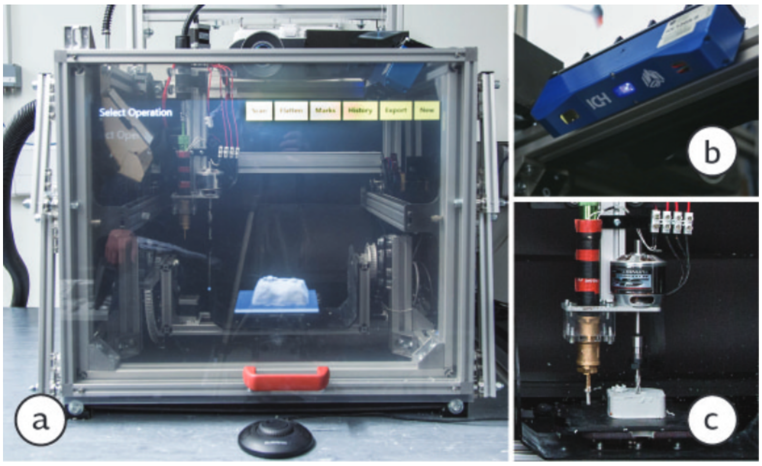


Figure 2.2: (a) The ReForm system in its whole. (b) The sensor array to detect manual changes to the modelled object. (c) Tools to automatically realize the virtual model in physical clay. (Image taken from Weichel et al. [2015])

change the overall structure of the surface. The height of the surface elements can be set by the traditional way of designing on the computer and sending the data to the apparatus (in this case a heightmap). Additionally, two other input methods exist. The first one is gesture based and uses a finger gesture to raise or lower individual elements. The second one maps the color of the moldable plastic sheet itself to a specified height (Figure 2.3). This enables sketching on the plastic sheet to raise or lower individual parts Yamaoka and Kakehi [2017].

Bidirectional design reduces the disconnect between planning and executing.

2.1.2 Sketching

Sketching in particular has been widely accepted as a first prototyping step to 3D geometry Branco et al.. Planning refinement of a surface by sketching changes onto it, is also common practice and can be observed in ReForm Weichel et al. [2015] as well as ProtoMold Yamaoka and Kakehi [2017].

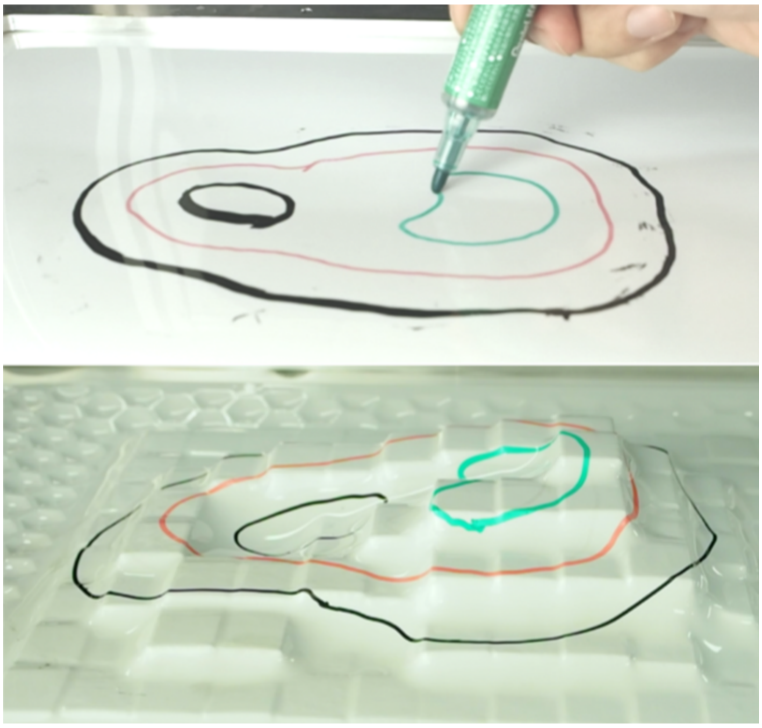


Figure 2.3: Sketch based 3D modelling with ProtoMold. By raising parts of a surface according to drawn strokes and color. (Image taken from Yamaoka and Kakehi [2017])

Sketching 3D Objects

Automatically inferring the 3D model from a 2D sketch, to simplify the process of 3D modelling, is an important topic of research. A 2D sketch of a 3D object is inherently missing information on at least one dimension. To derive the missing information, several different approaches have been examined. To directly get information about missing dimensions, sketching the object from another viewport proves successful Bae et al. [2008, 2009], Igarashi et al. [1999], but vastly increases the amount of sketching needed.

To decrease the amount of sketching needed, research has been conducted on resketching only missing information. One approach uses cross sections on different planes Grimm and Joshi [2012] to reconstruct the 3D object.

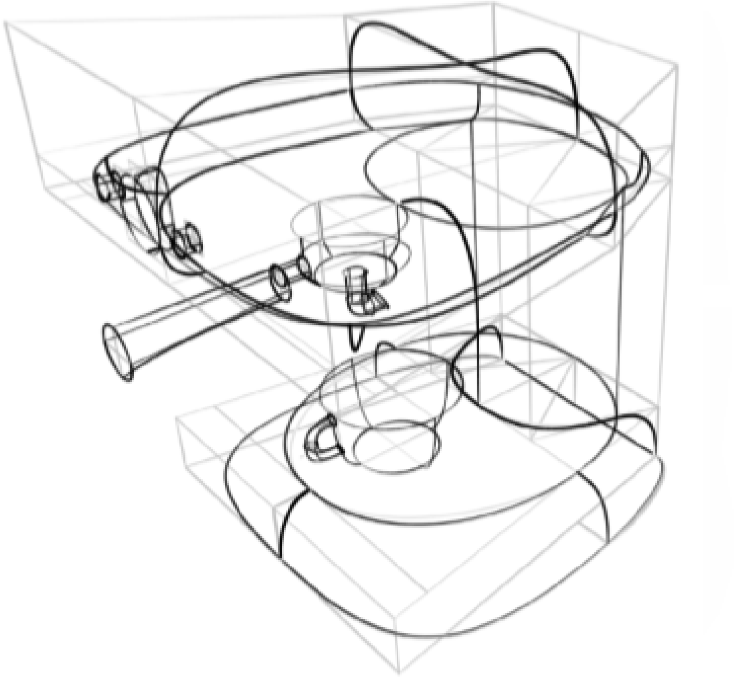


Figure 2.4: Drawing complex shapes into a basic scaffold of straight lines. (Image taken from Schmidt et al. [2009])

Adding more information to the surroundings of a sketch, in form of casted shadows, adds missing information without usage of several sketches in the approach of Cohen et al. Cohen et al. [1999]. Sketching shadows is a specific type of interpreting lines in context of other lines, which is also used by Schmidt et al. to interpret curved strokes in the context of a scaffolding of straight lines Schmidt et al. [2009] (Figure 2.4). Another approach is sketching an object in full context of its surroundings. Straight lines from easily identifiable surroundings, like wall or table surfaces, can act as a type of scaffolding Lau et al. [2010].

Sketches with context aid interpretation.

Iterative approaches like sketching missing information from different angles or cross sections are combined by Xin et al. in 'Napkin Sketch' Xin et al. [2008]. In this approach the user specifies drawing planes with a handheld tablet onto a tracked area and strokes performed on the tablet are

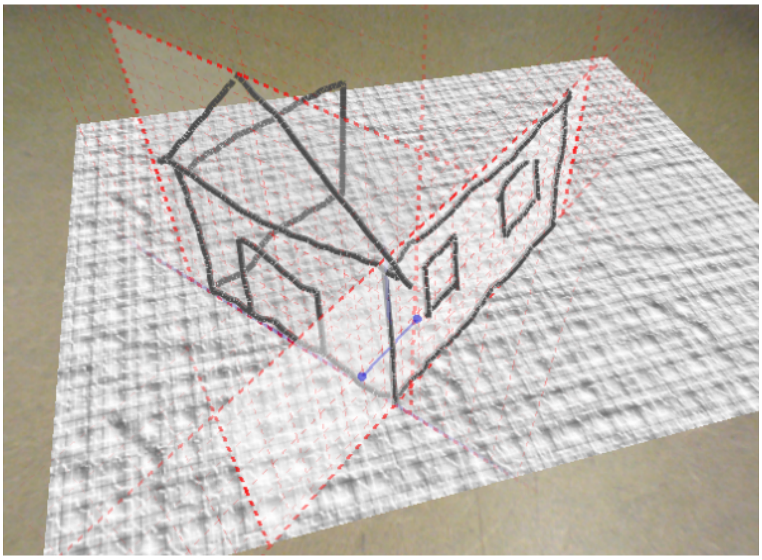


Figure 2.5: Napkin Sketch enables the user to choose a plane to project drawn strokes onto. (Image taken from Xin et al. [2008])

projected onto the active drawing plane (Figure 2.5).

Sketches can be enhanced with cues.

Extracting the whole 3D information from one sketch only without adding additional sketched information like scaffolding or surroundings is the key to simplify the process of sketching 3D objects enough to make it a viable step from paper prototype to first 3D object, which later can be refined. Xu et al. use a fitting algorithm to create basic 3D objects from a 2D sketch and give cues about line relation to find the best solution Xu et al. [2014] (Figure 2.6). This approach is independent from additional information in the sketch apart from the cues and does not depend on additional sketches, but is highly dependent on an appropriately chosen viewing angle onto the sketched object.

Sketching Aids

The quality of sketches directly influences the capability of creating 3D objects from 2D sketches. Drawing shadows for objects like in the approach of Cohen et al. Cohen

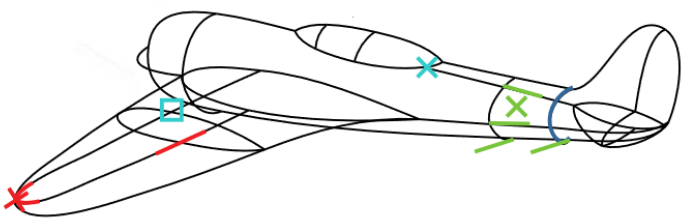


Figure 2.6: Adding cues to sketched lines helps True2Form find the right 3D shape. (Image taken from Xu et al. [2014])

et al. [1999] needs cognitive work and talent from the user sketching the object. This is also the case for the needed abstract model in the user's head while drawing cross sections Grimm and Joshi [2012].

Drawing strokes accurately is not solely dependent on the mental capacity of the user, but also on the motorial skills. Studies show, that corners impact drawing speed, but the angle of the corner is far less important, than the length of the stroke needed to sketch fully along the corner Pastel [2006], Cao and Zhai [2007]. Practicing strokes may therefore actually decrease accuracy, as the speed in which a corner is drawn directly affects accuracy and practiced users trade speed for carefulness Vatavu et al. [2013].

Corners in strokes slow down drawing.

Aiding the process of creating sketches, not only for novices, is therefore a set goal of research.

Basing sketches on photos or other reference material is common practice. By extracting visual guides from these reference materials, the proportions of sketches, resulting from following the guides, can be enhanced Iarussi et al. [2013]. This assumes already existing 2D representations of reference material. If the reference material is a 3D object, projecting onto the surface where sketching is applied, helps users visualize different viewing angles or cross sections of the model they intend to design Laviole and Hachet [2012] (Figure 2.7).

Reference material aids sketching.

Directly sketching in mid-air is a more immersive approach to help sketching, especially for the goal of creating 3D

Figure 2.7: Drawing over a projection of a 3D model in PapARt. (Image taken from Laviole and Hachet [2012])

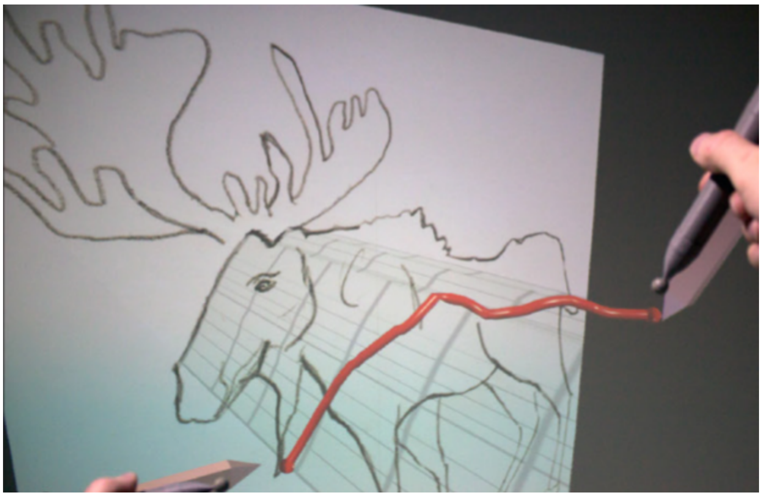


Figure 2.8: The Lift-Off workflow works by arranging 2D sketches in space and extracting strokes for usage in 3D modelling. (Image taken from Jackson and Keefe [2016])

objects. Using an immersive visualization technique and tracking a drawing utensil in mid-air enables direct drawing of complex bended shapes, without the possibility of misinterpretation from 2D sketches Wesche and Seidel [2001]. 2D sketches can still be used as basis in this approach, by arranging scans in space, drawing along them or using automatically extracted lines as basis Jackson and Keefe [2016] (Figure 2.8).

3D sketching can be achieved in AR.

Apart from one handed gestures using a drawing utensil it is also possible to use both hands in immersive modelling if appropriate tracking information is available. That two-handed approach can be used to create 3D objects like editing vector graphics on a computer, by using digital strips of deformable strokes, directly influenced by a two-handed device mimicking a tape measure Grossman et al. [2002], Balakrishnan et al. [1999]. These approaches use varying degrees of Mixed Reality.

2.2 Mixed Reality

Mixed Reality (MR) is an umbrella term for every concept, which mixes virtual and real elements. Augmenting reality with virtual elements under AR or augmenting virtual worlds with real elements under Augmented Virtuality (AV) are both fields of MR Tamura et al. [2001]. To create MR multiple technologies are employed today.

The most common for the end user is a handheld mobile device as a window into AR Van Krevelen and Poelman [2010]. By enabling the rear camera of a smartphone and showing its image on the display enhanced with virtual objects, AR can be used widely in different applications. Frameworks for this technology are already build into the operating systems of today's smartphones under the name ARCore Google in Android and ARKit Apple [b] in Apple devices. These use additional information from the smartphones sensors, like GPS, accelerometer, gyroscope and magnetometer to display virtual enhancements roughly in relative position to the real world. A widely known example for an application in this space is the mobile game Pokémon GO Pokémon.

Mobile devices enable consumer AR.

Spatial AR displays in cave or bench like setups are mostly used in research sites and restrict the user's movement more than handheld mobile devices, because they are confined to a specific space. In contrast to handheld devices however, they can be setup with more computational power and be used by multiple users at once Van Krevelen and Poelman [2010].

The last category and the one which promises the best results in the future are head mounted devices. They are not restricted to a small image on a smartphone display as a

Figure 2.9: The Microsoft HoloLens is a head mounted AR device. (Image taken from Microsoft)

Head mounted displays do not restrict movement.

view port and can move with the user. Tethered setups may employ computational power of stationary computers Caudell and Mizell [1992] and untethered devices employ the same technology as a smartphone.

2.2.1 HoloLens

The Microsoft HoloLens is a device from the head mounted AR category and the used AR display device in the study of this thesis (Figure 2.9). At the moment this headset is in the stage of developers preview, but the goal is to ultimately have an end user's device for augmented reality ubiquitous like a smartphone.

HoloLens viewport is a problem.

The HoloLens overlays virtual objects over the real world, by forcing the wearer to look through one translucent display for each eye, resulting in seemingly 3D holograms floating in the users view. While head mounted solutions do not restrict the viewport to a camera image on a small display, like handheld devices, the viewport in which virtual objects can be seen is restricted with the size of the translucent display panels. This results in only partially visible holograms, cut off at the edge of the display panel, with the real world being seen beyond that edge as HoloLens does not obstruct the view of reality Microsoft.

Like smartphones, HoloLens uses multiple sensors to fix holograms to a position relative to real world. HoloLens also contains an accelerometer, gyroscope and magnetometer to get relative positional data, but does not contain a GPS chip. Microsoft tries to achieve full inside out tracking with the HoloLens. This means, that the HoloLens should always know where it is positioned in reality even though there are no base stations or other external tracking aids, like satellites for GPS. To track its relative position to reality, the HoloLens therefore contains 4 cameras and one depth camera to understand the environment around it, find anchor points that seem significant and immovable and position itself relative to these anchor points. Moving around a bit after startup of HoloLens is therefore necessary for the device to relocate the previously seen anchor points and get initial tracking information before any hologram can be displayed in a fixed position Microsoft.

HoloLens uses inside out tracking.

2.3 Virtual Reality

Head mounted displays, like HoloLens for AR, are available for VR as well, but already in a consumer grade state. Three examples for these devices are Oculus Rift, HTC Vive and PlayStation VR. These devices are tethered to a computer and are therefore comparatively cheap and have access to high computational power. The named devices do not use inside out tracking, but have base stations to anchor them to the real world, which, especially in wide surroundings with no significant points, is superior to inside out tracking. The Rift and Vive locate the headset and base stations by infrared, while PlayStation VR uses an optical solution. Vive, Rift and PlayStation VR also enable tracking of handheld controllers and pointing devices with the same base station (Figure 2.10). Because of these possible advantages and the wide availability of these devices, many accuracy studies have been conducted using them. We will give an overview on these studies in relation to mid-air sketching to set the base for our AR approach.

VR devices are in the consumer market.

Figure 2.10: The Oculus Rift is a head mounted VR device. The image shows the headset, the base stations and the handheld controllers. (Image taken from Oculus)

2.3.1 Input Accuracy and Guidance

Haptic guides enhance accuracy.

The performance of mid-air sketches without additional help is affected by the missing feedback known from traditional drawing methods. Haptic feedback and movement constraints, existing in non-mid-air methods, enhance accuracy Wiese et al. [2010]. While practice is a factor in this setup, the accuracy achieved is still lower than with haptic aid in place Wiese et al. [2010]. Additionally, as stated, habituation might also reduce accuracy in the long run Vatavu et al. [2013]. Thus, missing haptic feedback is one of the major limitations of immersion in VR Brooks [1999], Challis and Edwards [2001].

Physical objects may also be used in VR.

Physical objects, aligned with virtual representations add haptic feedback at the cost of synchronizing the virtual and real world, but enhance the immersion Insko [2001]. Using the physical objects as a guide for sketching has been researched by Song et al. Song et al. [2006] in an offline approach. Drawings on a paper prototype of the 3D object modelled in CAD, can be scanned and used to change the CAD model. In an immersive setting Jackson et al. Jackson and Keefe [2011] sketched over a handheld prop, which was a physical proxy for a virtual object. The actual strokes could be seen on the virtual object but were not aligned with the physical prop.

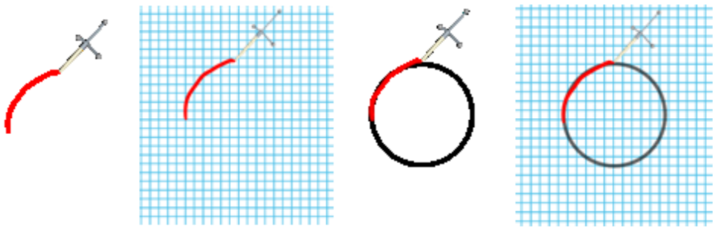


Figure 2.11: Types of guidance tested by Arora et al. in VR. From left to right the images show the case of no guidance, guidance by displaying a virtual surface, guidance by displaying the intended line and a combination of both (Image taken from Arora et al. [2017])

The VR study, most closely related to our AR study was performed by Arora et al. Arora et al. [2017]. They aligned physical surfaces with virtual representations in VR to give accurate haptic feedback while sketching. This improved accuracy while drawing in mid-air drastically. Further tests showed improvements in accuracy when only visual aids were shown in form of the same virtual surfaces without the haptic surface present (Figure 2.11). This also proved true for just displaying the intended line to be drawn without any surface representation Arora et al. [2017].

Haptic feedback in VR achieves positive results.

Chapter 3

Classification of Guidance

In this section we introduce the possible guidance types a surface of an object might present to a user, while sketching on it. Drawing a stroke onto a surface is affected by multiple factors:

- Does the surface deform under pressure? (soft or hard)
- Is the tip of the drawing utensil easily slid across the surface texture? (rough or smooth, maybe even slippery)
- What is the inner surface shape, the drawing utensil needs to be slid over? (planar or nonplanar)
- Is the surface even in reach? (location, size and orientation)
- What does the surface look like? (opaque, translucent, transparent, reflective)
- Are there any markings on the surface? (lines may guide drawing)

Surfaces have a multitude of properties.

Some of these questions include how the user or the used drawing device interact with the surface. For the study we

Properties dependent on interaction between drawing utensil and surface are omitted.

focused on factors, which are not dependent on these interactions. This excludes softness or hardness, which is dependent on applied pressure by the user. We used rigid objects which were not deformable, to exclude this factor. As the questions already states, roughness is also dependent on the drawing utensil. To omit this factor, the used objects and drawing utensil approximately grind against each other like a pencil would on paper. We also assume, that the surface is in reach and is opaque. The remaining factors like inner surface shape and markings on the surface are explored further.

Guidance in general always includes a limitation in degrees of freedom, we call constraints. These constraints may be logical, soft or hard.

Soft constraints are logical.

We classify logical, soft constraints as constraints, which are not enforced by the surface itself. These are enforced by the users thought process and may be introduced by rules. An example for a logical constraint would be a rule given to the user beforehand, like 'Draw a circle on this planar surface.'. Nothing hinders the user of drawing a square, except the 'self' imposed restriction of shape.

SHard constraints are physical.

Our classification for hard constraints is enforced by the surface. An example would be the impossibility of puncturing the surface. This constraints the possible translation of the drawing utensil in space, which cannot be circumvented.

3.1 Haptic Guidance

Haptic guides remove degrees of freedom.

We classify any physical force directly or indirectly exerted on the drawing utensil as haptic guidance. Haptic guides constraint movement of the drawing utensil in varying degrees of freedom and are not always strictly hard constraints. We divide this class up into two subclasses for planar surfaces and surfaces, which include grooves or edges.

3.1.1 Planar Surfaces

We assume the planar surface to be axis aligned to an arbitrary cartesian coordinate system. The planar surface removes one half degree of freedom by the soft constraint of holding the drawing utensil against the surface. Another half degree is removed by the hard constraint of not being able to penetrate the surface with the drawing utensil. An example for a planar surface would be the top of a wooden table.

3.1.2 Grooves and Edges

Surfaces, which are non-planar, show two types of structures. These types are distinct by their directional change of the surface.

Grooves are concave dents, which induce a directional change in the drawing utensil, by locking it into a position. This change is dependent on the depth and angle of the groove itself as well as the strength the user exerts on the drawing utensil in a different direction. Angle and depth of the groove are described by the concaveness. With increasing concaveness, the constraint increases. An example for a groove would be the inner ring of a glass, where the side hits the bottom.

Edges are convex dents, which induce a directional change in the drawing utensil, by logically pushing it away. As with grooves, the same properties influence the drawing utensil's directional change. An example for an edge, by the definition of just being convex, would be the traced line from one end of a pipe to the other end (not around the pipe).

3.2 Visual Guidance

We classify visual surface markings as visual guidance. Visual guidance is a soft constraint, as it does not guide a drawing utensil without the user's intent. For example, 'Follow the line.' would be a rule given to the user in order to enforce the constraint.

Visual markings always remove at least one degree of freedom (when tracing a line), but may also remove two (when holding the drawing utensil at one exact marked position).

Visual guides may be unintentional.

Visual guidance in the form of markings printed on the surface is intentional and purely visual. Additionally, visual guidance may be an unintentional side effect, for example the water line inside a bottle. These unintentional visual guides may also be the side effect of other surface properties. If the surface contains grooves, the shadows or ambient occlusion in the grooves may provide visual guidance as a side effect. Therefore, any other guidance class is accompanied by visual guidance.

Chapter 4

System Design

After an overview of the system requirements is given, this chapter introduces the actual device setup used in the study. We give details about implementation of the developed software and integration of provided software packages specific to the used devices.

4.1 Overview

Directly creating models for objects, in the place they are used after assembly, is called in-place fabrication. The idea of making this type of fabrication accessible for a wide range of users, especially novices, drove the first design of the system. We call this personal in-place fabrication.

To achieve this goal, an input device is needed, which can be tracked in 3D and enables the user to dispatch commands related to sketching. These include virtually 'lowering' and 'lifting' the pen tip, resulting in lines being drawn or omitted while moving the device. In our case, this device will be shaped like a pen, includes buttons and means to be tracked further detailed in the design chapter.

Drawing device mimics pen.

Furthermore, the user has to be able to see the result of drawing. As presented in the related work, the device we chose, is the experimental headset HoloLens.

Both input device and output device are connected via a central server, which enables the geometry processing, included in the model creation. This would be the CAD software part.

Later the design shifted to a user study framework, resulting in a system developed with expandability in mind.

4.2 Architecture

We split the system up into three parts called *source*, *processing* and *destination*. *Source* and *destination* are exchangeable like plugins, while *processing* is mostly static.

Splitting the system up, we got more freedom of testing multiple data sources (*source*) and data destinations (*destination*). The *processing* part executes a few simple cleanups of malformed data and administers the connection between, possibly multiple, *sources* and *destinations*. A device may be both classified as *source* and *destination* and any device can register as many connections from and to the *processing* server as it needs.

4.3 Network Setup

In this section the possible ways of communication between the different software and hardware systems with the *processing* server are layed out.

4.3.1 Layout

Star layout for network.

We designed the layout of the system networking to resembles a star. The midpoint of the network layout is the *processing* server. Data from the *sources* gets routed over the central network *processing* server to the *destinations*. We allowed to directly connect a *source* and *destination*, which may be the better choice for speed or highly specific data only useful to two nodes of the network. Integrating the provided software packages is also greatly simplified with this non-restrictive layout choice.

4.3.2 Protocols

The bidirectional communication with the processing server is achieved via multiple different connection types and protocols. The processing server allows for the following types of connection in our setup:

1. UDP packets both over wired and wireless connection.
2. A custom service build upon Bluetooth LE.
3. File system buffered exchange of information based on files with comma separated values (CSV).

4.4 Source Setup

The following devices are mostly used as *source* in the study setup. We classified them into this category as the main data flow is directed to the central *processing* server. That does not exclude a possible data flow to these devices, especially in the case of first synchronization.

4.4.1 Devices and Software

Vicon Motion Capture System

The Vicon Motion Capture System consists of different exchangeable devices of the Vicon family. We used 6 Vicon Bonita cameras connected via two switches, providing power over ethernet.

Vicon tracking cameras use infrared.

Vicon Bonita is an infrared camera with VGA resolution available at 240 frames per second Vicon. It records light in the infrared spectrum and generates images in grayscale, which can be transmitted to several software suites. In order to track an object, the object has to be fit with reflective markers. The markers are passive, therefore the camera sports two rings of infrared light emitting diodes around its lens, to be able to capture the reflected light from the reflective markers.

Vicon Nexus is the software package delivered with the Vicon Motion Tracking Systems. We used this software package to configure our Vicon Bonita cameras and send the resulting motion data with $100Hz$ over wired network to the *processing* server. Communication is handled via UDP packets and network broadcasts via a protocol provided by Vicon. The Vicon Nexus software handles all these use cases out of the box, so no additional code on the Vicon side was needed Vicon.

Bluetooth Pen

We used a Bluetooth enabled pen in our study setup in order for the participants to send easy commands to the processing server. The pen consisted of a 3D-printed shell, which contained an Arduino derived board, two buttons, a Bluetooth low energy (LE) module and an USB rechargeable battery pack. The pen tip was fit with a passive reflective to enable tracking with the Vicon Motion Capture System. The tracking system performs best with at least three markers placed in a pattern, which looks different from different points of view. At the back of the pen we mounted 4 appendages of irregular length, angle and position fit with more passive reflective markers, to fulfill the requirement for good tracking.

The software running on the board inside the pen is based on Arduino BLE. Arduino BLE is the reference implementation of Bluetooth Low Energy (BLE) for the Arduino platform. Out of the box this framework is able to connect to a multitude of Bluetooth enabled devices, but the standard settings pose a problem connecting to computer platforms running on macOS. Any connection established with settings not allowed by macOS is send into a fallback state with very high delay and low speed while data transfer. We solved this problem by consulting the official Bluetooth Accessory Design Guidelines for Apple Products. Additionally, setting the Bluetooth pen to be a Human Interface Device (HID) enabled connection intervals to be frequent and as low as $11.25ms$ Apple [a].

Apple Bluetooth devices expect specific settings.

Python Study GUI

We implemented the graphical user interface running on the device used by the study conductor in python. This enabled us to conduct the study from devices with different operating systems (in our case macOS Sierra and Windows 10) provided Python was available. The devices used with the Study GUI were a mid-2012 MacBook Pro and a stationary PC from 2016.

The Study GUI was implemented in Tkinter and connected to the *processing* server via UDP implemented with the standard Python socket module. A second connection via UDP directly to the *destination* device HoloLens enabled specific and manual debugging.

4.5 Processing Setup

The *processing* setup consist of a central server handling data from the *sources*, processing the data and retransmitting it to the *destinations*.

4.5.1 Devices and Software

The central *processing* part of the system is not exchangeable and may only be present once in contrast to *sources* and *destinations*.

Central Server

The central server connects via different network protocols.

The server software was installed on a mid-2012 MacBook Pro running macOS Sierra. We implemented it natively in Swift with Cocoa as GUI framework. The central server had to handle all the supported networking types, we used multiple frameworks for this task. Connections over Bluetooth were handled by the native CoreBluetooth. To handle connections over UDP we used the CocoaAsyncSocket framework written in Objective-C and included into our Swift project using a bridging header. The same procedure was applied to the ViconDataStream framework, needed to decode the tracking data from Vicon Nexus.

The data from the ViconDataStream framework provided us with some challenges. Position data had to be corrected, as only the z axis was provided correctly. The x axis turned out to be the negative of the provided y axis value and the y axis was the provided x axis value. We tried changing the coordinate system, used by the ViconDataStream framework to determine value to axis assignment, but this resulted in other values being wrong. Finally, we implemented a small function mapping the reported values to the right axis.

4.6 Destination Setup

The devices classified under *destination* are data destinations. Any device registered as *destination* mostly receives data from *processing* and provides no further capabilities visible to the rest of the system.

4.6.1 Devices and Software

Unity on HoloLens

To run our software on the HoloLens AR headset we used the integration with Microsoft Mixed Reality provided by the Unit game engine. Implementing code for a Unity based HoloLens application was done in C#. C# applications run on top of the .NET framework and have access to a vast library for implementing networking. This will work in Unity itself on a stationary PC running Windows, which is the default state of the Unity engine, but fails on HoloLens. To accommodate for the special Windows version running on HoloLens and restrictions Microsoft introduced to save battery life and CPU time on the headset, only a special subset of the C# libraries are available. We used the UDP socket implementation found in the 'Windows.Networking.Sockets' library on HoloLens to receive data.

We also included Vuforia, an AR framework for mobile devices, that enables tracking of visual markers, especially normal images. HoloLens applications should target a framerate of $60Hz$, but integrating Vuforia enables the camera of the HoloLens, which cuts the maximal framerate in half Microsoft. This is a hardware limitation and cannot be circumvented. With the ability of tracking physical image-based markers in the real world, we were able to implement a synchronization process for the coordinate systems of our *sources* and the HoloLens *destination*. This process is described further in the user study course of action.

The display technology of HoloLens works with independent panels for the different subpixels. One display for red and blue and two displays for green. Each of these displays gets refreshed once per frame, at slightly different times. A fast head or eye movement may result in separation of colors known from digital light processing (DLP) projectors Microsoft. All of the holograms our application displays for the user are therefore either red, green or blue, because just one display panel is involved in displaying them and color separation cannot occur or are a one to one mix of two

HoloLens projection works like DLP.

of these primary colors to only use two panels and reduce the possibility of color separation.

Python Data Analysis

CSV files were used as interchangeable format.

We implemented a script in Python for the data analysis, to be able to pipe the data into Blender, an open source solution for 3D-modelling. The script used the file system-based exchange of information in form of CSV files. The *processing* server saves these recordings of information flow, while the whole system is running. Afterwards, our script takes these files and analyses the contents for our evaluation.

Piping the data into Blender enabled us to render the tracked path of our Bluetooth pen for further inspection and the images presented in this thesis.

Chapter 5

User Study

In the following sections we describe the motivation, design and procedure of the user study. We refined the study design multiple times after conducting pilot studies.

5.1 Motivation

The basic motivation for the user study was the question:

- How accurate are humans able to sketch on real and virtual objects?

With this question in mind we try to quantify the influence of real and virtual objects in the context of the already classified guidance types.

5.2 Hypothesis

HYPOTHESIS:
Using haptic guides increases the accuracy of strokes drawn in mid-air.

Definition:
Hypothesis

5.3 Study Design

This section presents the study design split up into the created environment, conditions within the environment, the procedure of the study and the demography of the participants.

5.3.1 Environment

Setting

We conducted the study in a space of the size $25m^2$ in the middle of a media space. The space was separated from the rest of the room by curtains, pillars and walls. Most of the sunlight entering the room was blocked by blinds in order to prevent interference with the tracking system. Sufficient artificial light was supplied by fluorescent tubes on the room ceiling. At the time of the study no one except the participant was present in the study space.

The environment is isolated from outer factors.

Inside the study space we set up a table for one person with a generic office chair in front. The table was fixed to the ground and fit with a rigid mounting for the study objects. We attached the visual marker for the synchronization between the HoloLens AR Headset and the Vicon Motion Capturing System on top of the table surface behind the mounting (as seen from the participants viewpoint)(Figure 5.1).

Camera layout has been optimized through testing.

Surrounding the table, we installed the 6 Vicon Bonita cameras on tripods. Two cameras were installed to capture over the shoulder of the participant and two to capture a similar viewing angle from the opposite side of the table (Figure 5.1). One camera capture a bird's eye view from the ceiling straight down onto the mounting on the table. The last camera captured a view from the side opposite to the participant straight onto the participant. We used the direct camera feed in Vicon Nexus to configure the aperture, focus, focal length and strength of the infrared LEDs of the Vicon Bonita cameras to exactly capture the space above the

Figure 5.1: The table used in the user study surrounded by Vicon cameras. The visual marker and mounting on the table can be seen.

table surface, with most accuracy in the area the participant would interact with the study objects.

Outside the study space we setup the supporting infrastructure, including switches, cables, our MacBook Pro running the central processing server and study software. The participants were unable to see the contents of the screen, which displayed the study software and condition choices, but could communicate with the study conductor normally to pose questions or give feedback in case a problem arose.

Study Objects

From the guidance types, classified by us, we derived 4 edge cases to be tested in this study. We call these cases *no guide*, *visual*, *convex* and *concave*.

The *no guide* case does not show any visual or haptic guides except the surface itself. *Visual* is essentially the same case as *no guide* with the difference of showing a clear and only visual surface marking to the participant. Both *convex* and *concave* are haptic guides. With *convex* we chose a convex edge with an angle of 45° as the case for haptic guides which protrude from the surface. For *concave* we chose a concave groove with an angle of 45° as the case for haptic guides which cave in the surface.

These 4 cases of guidance were tested in 2 different *shape* conditions. We used *circle* as a shape condition for a continuous curved stroke and *square* for partial straight strokes divided by sharp angles.

The size of study objects was appropriate for one hand usage.

With every combination of guidance and shape conditions, we designed 3D-printed objects to be mounted onto the table in front of the participant. In order to save setup time, two guidance conditions were combined on one object, resulting in 4 objects for the 8 combined conditions. The physical objects had a height of $16cm$ and were $8cm$ wide and deep. They could be attached to the mounting on the table upright or upside down depending on the guidance condition tested in the run. Either mounting possibility resulted in the guidance condition being placed in $12cm$ height from the table surface in front of the participant (Figure 5.2).

The physical objects presented us with real world measurements. With the possibility of displaying arbitrary shapes in front of the user with the AR headset, we also had to include virtual representations of the physical objects. Even though the virtual objects did not suffer from setup time and did not have to be mounted, they were designed in exact the same way as the physical objects to ensure visual consistency. This resulted in 8 more virtual objects, showing the combined conditions on either end.

5.3.2 Procedure

Variables

The independent variables of the study are directly derived from the chosen conditions for the study objects. The de-

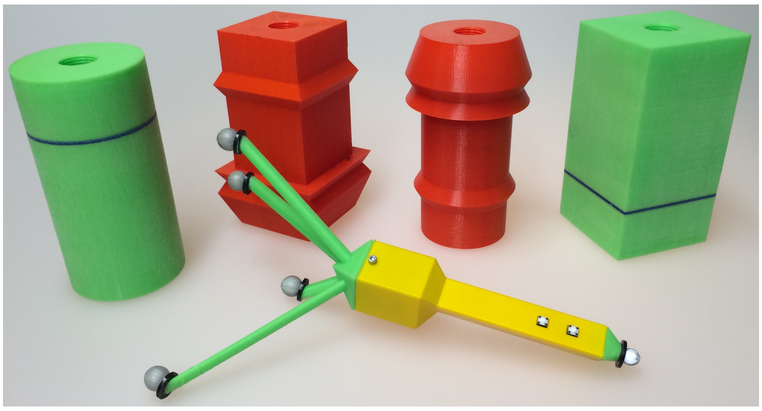


Figure 5.2: Displayed are the study objects with different conditions. From left to right the first one is the *circle shape* with *no guide* and *visual* conditions, the second one is the *square shape* with *convex* and *concave* conditions, the third one is the *circle shape* with *convex* and *concave* conditions and the last one is the *square shape* with *no guide* and *visual* conditions. The drawing utensil used in the user study is displayed in front.

sign can be described with a grid of 2 × 2 × 4.

- 2 conditions are given by the *shape* to be drawn (either *circle* or *square*).
- 2 conditions are given by the object type (either *physical* or *virtual*), we call this *surface guidance*.
- 4 conditions are given by the guidance types *no guide*, *visual*, *convex* and *concave*, we call this *line guidance*.

The resulting grid is *shape* (*circle* / *square*) ×*surface guidance* (*physical* / *virtual*) ×*line guidance* (*no guide* / *visual* / *convex* / *concave*).

To counteract learning effects and variable sequence in general, we used a Latin square.

Latin square was used in the study design.

Questionnaire

We handed out a questionnaire with fields regarding basic information about the participant:

- Age
- Sex

These helped in analyzing the demography of our participants.

Furthermore, the questionnaire contained basic true/false questions to be answered before the study was conducted:

- Do you wear glasses / contacts?
- Do you have any movement impairments?
- Do you have experience with any kind of augmented reality headset?
- Do you have experience with any kind of virtual reality drawing tool?

With the result of these questions we could determine the amount of aid needed to handle the AR headset and the tracked Bluetooth pen. Especially the questions about movement and visual impairments helped us to exclude runs of the study and replace the participant with a new one, if needed.

We also provided basic true/false questions to be answered after the study was conducted:

- Did you feel guided by the visual aids?
- Did you feel guided by the physical aids?
- Would these tasks have been easier without the headset?

- Did you get fatigued by drawing in mid-air?

The questions aimed for general feelings of the participant regarding the conducted study.

Course of Action

The conduction of the study began right after the informed consent form and the questionnaire (except questions for after the study) were filled out. We introduced the participant to the setup around the table and instructed them to sit down and remain seated throughout the whole study procedure. The only exception were possible pauses to counteract fatigue.

After sitting down in the office chair, we rolled the chair in a marked position in front of the table and asked the participant to assume a straight posture. We then helped the participant with the HoloLens by showing them the right way to put it on. Afterwards we gave the user the tracked Bluetooth pen to be held in the dominant hand.

Synchronization was a multi-step process.

After the headset was tightened around the head to remain in a fixed position relative to the head of the participant, we started the synchronization step. This step included holding the straight posture assumed before until a virtual, visual cue was presented to the participant. As soon as the virtual, visual cue showed up, the participant was asked to look down onto the physical, visual marker on the table surface to start the synchronization process between HoloLens and Vicon Motion Capturing System. When the automatical synchronization finished, a virtual sphere was placed in the middle of the physical, visual marker and we instructed the participant to move the tracked Bluetooth pen tip inside this sphere. If the participant was content with the placement of the pen tip, he could press the synchronization button on the pen to continue with the first manual, cooperative readjustment of the automatically synchronized system (Figure 5.3).

The manual, cooperative readjustment included placing a

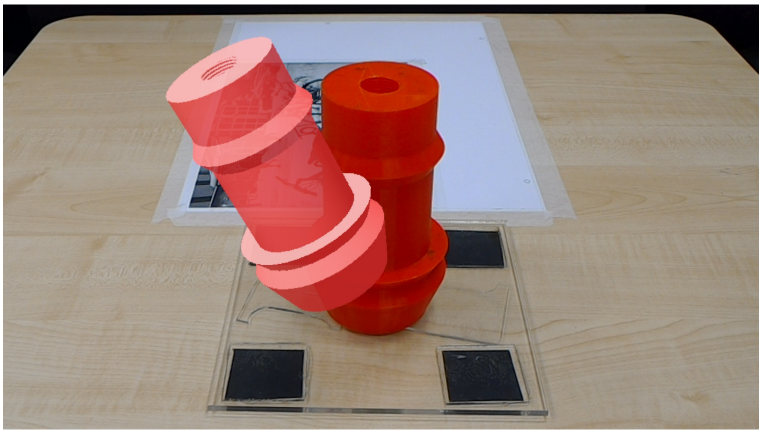


Figure 5.3: Exagerated misalignment after the automatic alignment step of Vicon and HoloLens.

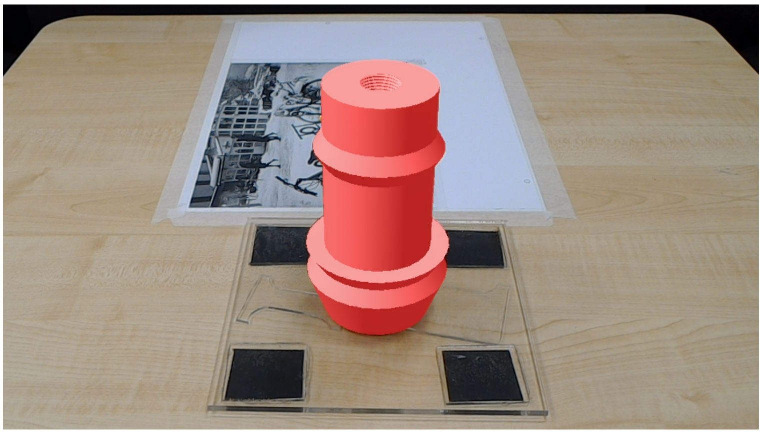


Figure 5.4: Physical and virtual object aligned perfectly. The study may now begin.

physical study object of choice onto the mounting on the table and showing the same virtual object on the same position. If these positions aligned perfectly, no further steps were needed (Figure 5.4). In the other case, the participant was asked for information about the misalignment and we used the study user interface to manually correct these errors via the processing server. This readjustment could be done multiple times throughout the study, when needed, because of tracking loss or adjustment by the HoloLens.

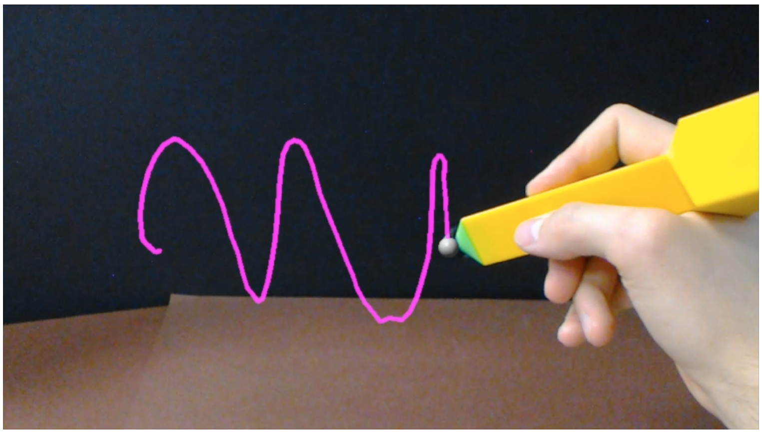


Figure 5.5: To acquaint himself with the drawing process, the user was allowed to draw freely in the tracking area.

After the readjustment step, the participant was able to draw anywhere in the tracked area, over the table surface, to acquaint himself with the pen and the drawing process (Figure 5.5). The participant could resume to the next step by telling us, that he was ready.

The movement of the dominant hand was not restricted during the study.

As soon as the participant was ready, the trial phase started. Each trial began with the introduction to the object to be drawn around and including description of the position, where to draw (Figure 5.6). For the *virtual surface guidance* the participant was instructed to rest the non-dominant hand on the mounting. In the *physical* case, the non-dominant hand grabbed the study object for further stabilization. We did not restrict the dominant hand in any form, this includes allowing the participant to move through the *virtual* objects, if wanted. Furthermore, we instructed the participant to draw in a regular drawing speed with precision in mind.

For each of the 16 trials, the participant was allowed to practice a bit before 5 repetitions were recorded. Overall the participant drew 80 strokes within a time frame of 45 to 60 minutes, depending on the speed of the participant.

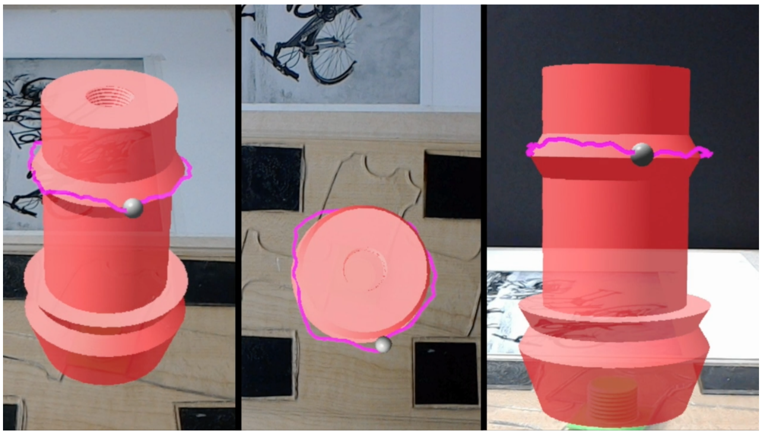


Figure 5.6: One finished stroke of a trial is shown from multiple different angles.

5.3.3 Demography

We searched for participants in the age range of a fully developed younger adult (18 to 35). Our questionnaire asked for possible knowledge and experience in AR and VR, but neither was required. Most requests for participants were distributed in the university and online.

Chapter 6

Evaluation

In the following sections we describe the process of evaluating the user study and present the results.

6.1 Participants Information

The proximity of the study space to several computer science chairs mostly brought computer scientists and students to our study. An online request for participants also interested some individuals from the computer gaming scene.

To fill the Latin square for our 16 conditions, we initially recruited 16 participants. Over the course of the study 2 of the initial 16 had to be removed from the study. One of the participants wore big glasses, which significantly hindered the execution of the study, as the HoloLens headset did not stay in its position. This resulted in shifting of viewpoint relative to the HoloLens display and the displacement of the holograms. The other participant was not able to perceive distance in the HoloLens at all. This participant tried to draw about $15cm$ out of place in the first practice step of the user study. We recruited 2 replacements for these participants to fill the Latin square again.

2 participants had problems with the study setup.

The final assembly of participants consisted of 4 females and 12 males. Ages ranged from $19 - 29$ years with a mean of 24.9 years and a standard deviation of 2.4 years. 9 participants were near-sighted and wore glasses, which were compatible to the HoloLens and our study setup. Apart from that, all participants were able-bodied and in health.

Only 4 participants had prior experience with AR in general. 1 participant was experienced in VR drawing tools. These two groups did not overlap, no one had experience in AR as well as drawing tools in VR. The remaining 11 participants had no prior experience in both fields.

6.2 Qualitative

In this section we present the qualitative results of the user study. This includes results from the questionnaire and differences in the drawn strokes, which were recognized.

6.2.1 Results of Questionnaire

We present the results of the questions to be answered after the user study.

The questions regarding visual aid were all answered positive. This also holds true for the physical aids. This corresponds with the perception, of having the most problems on the *no guide* objects, expressed by most participants.

Fatigue was also not felt by any of the participants while drawing in mid-air. This corresponds to the fact, that no participant requested a pause.

Head mounted displays are not the best solution.

If the tasks would have been easier without the headset, turned out to be more than a true/false question. The participants were given the chance to write a few sentences of explanation here. Most participants, wearing glasses, described the experience as uncomfortable but necessary. One participant thought about future possibilities and would like to see the headset become smaller or be replaced by something different but still able to show holograms wherever the user might be.

6.2.2 Visible Stroke Differences

The sketched strokes showed several recurring patterns.

Skewed Shapes

Rendering the strokes over the optimal line, it appeared, that in the case of the *virtual square* shape a general slight rotation was present (Figure 6.1). This rotation was counterclockwise, the same direction as 75% of the strokes were drawn.

Distribution of Inaccuracies

The drawn strokes on *virtual* objects differed more in the front and back of the shape than the sides (Figure 6.1). This was most pronounced in the *square* shape, but appears also in the *circle* shape.

Front and Back Differences

Looking at the strokes from the side reveals, that the participants consistently drew higher in the back of the shape than the front (Figure 6.2). Furthermore, strokes sketched on the *virtual* objects showed a tendency to be drawn further outside on the front and inside on the back. These observations prompted us to also conduct a quantitative front and back comparison not initially planned.

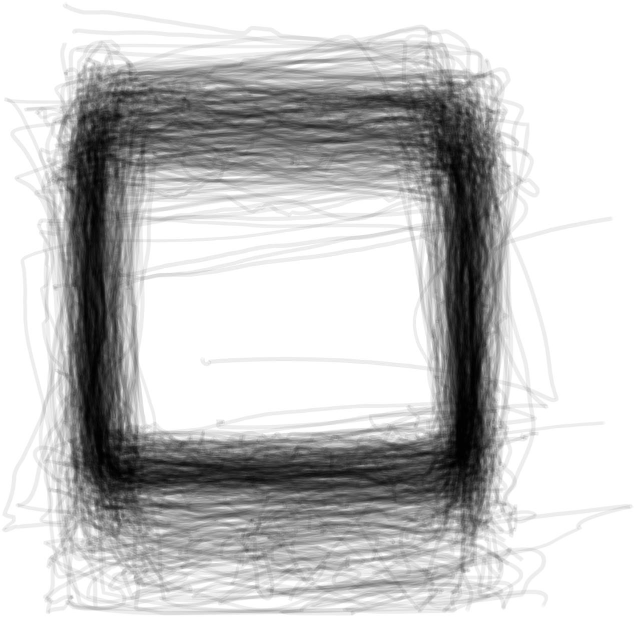


Figure 6.1: All virtual strokes for *square shape* overlayed show inaccuracies in the front and back are far more pronounced then on the sides.

6.3 Quantitative

In this section we present the quantitative results of the user study. Basis is the raw point data from the strokes drawn by the participants.

6.3.1 Data Preprocessing

The data for each stroke, saved in a CSV file, consisted of a timestamp and the position of the pen tip at this point in time. We filtered jitter and small outlier with a low pass filter averaging over a 10 frame window. The resulting point data was resampled to 100 roughly equidistant

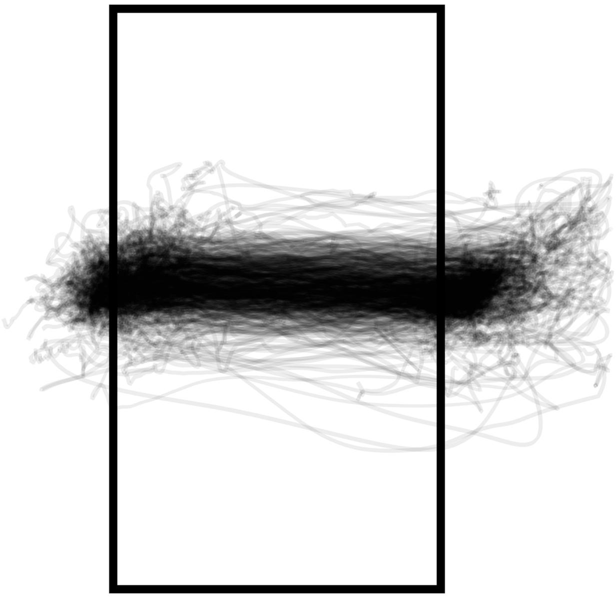


Figure 6.2: All virtual strokes overlayed show a pattern of upwards drift in the back (in this image the right side) of the object.

points (using only points that were actually observed in the data) to accommodate for the different movement speeds of the pen tip. We performed repeated measures ANOVA on the log transformed resampled data and post-hoc pairwise comparisons using Tukey's Honestly Significant Difference tests.

6.3.2 Full Shape Analysis

The following sections contain the result of analyzing the whole drawn stroke. The x&y plane is the view from top onto the drawn stroke and the z axis is the side view.

Stroke Duration

The duration it took the participants to draw a stroke shows significant differences for the *shape* ($F_{1,225} = 41.2876, p < .0001$) of the object, which was drawn around. The other conditions or interactions did not show a significant difference. Post-hoc test results can be taken from Table 6.1.

Condition	Significance		Mean	Std. Deviation
Circle	A		7.85	3.68
Square		B	9.95	5.04

Table 6.1: Significant differences of *duration* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in seconds and rounded to two decimal places.

3-dimensional Mean Deviation

The means of the 3-dimensional distance, the drawn stroke had to the optimal line, show significant differences for *surface guidance* ($F_{1,225} = 263.3287, p < .0001$) and *line guidance* ($F_{3,225} = 6.1692, p < .0005$) and the interaction *surface guidance* ×*line guidance* ($F_{3,225} = 6.0024, p < .0006$). Post-hoc test results can be taken from Table 6.2.

Mean Deviation on X&Y Plane

Comparing the means of the 2-dimensional distance, the drawn stroke had to the optimal line on the x&y plane, show significant differences for *surface guidance* ($F_{1,225} = 333.0535, p < .0001$) and the interaction *surface guidance* ×*line guidance* ($F_{3,225} = 5.0689, p < .002$). The post-hoc test results show no significance differences for the interaction *surface guidance* ×*line guidance* and can be taken from Table 6.3.

Condition	Significance	Mean	Std. Deviation
Physical	A	4.94	1.47
Virtual	B	9.45	3.73
Convex	A	6.69	3.32
Visual	A	6.89	3.34
Concave	A	7.11	4.12
No guide	B	8.09	3.58
Physical, Concave	A	4.12	1.24
Physical, Visual	A B	4.77	1.08
Physical, Convex	A B	4.96	1.15
Physical, No guide	B	5.92	1.77
Virtual, Convex	C	8.43	3.84
Virtual, Visual	C	9.01	3.50
Virtual, Concave	C	10.11	3.79
Virtual, No guide	C	10.26	3.64

Table 6.2: Significant differences of *3-dimensional mean deviation* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Condition	Significance	Mean	Std. Deviation
Physical	A	2.81	1.17
Virtual	B	6.92	2.98
Physical, Concave	A	2.50	0.88
Physical, Visual	A	2.74	1.10
Physical, No guide	A	2.88	1.46
Physical, Convex	A	3.14	1.12
Virtual, Convex	B	5.92	2.71
Virtual, Visual	B	6.51	2.89
Virtual, Concave	B	7.42	2.65
Virtual, No guide	B	7.83	3.38

Table 6.3: Significant differences of *2-dimensional mean deviation on the x&y plane* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Mean Deviation on Z Axis

The 1-dimensional distance, the drawn stroke had to the optimal line on the z axis, show significant mean differences for *surface guidance* ($F_{1,225} = 82.6369, p < .0001$) and *line guidance* ($F_{3,225} = 6.2082, p < .0005$) and the interaction *surface guidance* ×*line guidance* ($F_{3,225} = 7.8977, p < .0001$). Post-hoc test results can be taken from Table 6.4.

Condition	Significance		Mean	Std. Deviation
Physical	A		3.44	1.21
Virtual		B	5.22	2.44
Convex	A		4.11	2.06
Concave	A		4.22	2.80
Visual	A		4.24	1.89
No guide		B	4.75	1.49
Physical, Concave	A		2.78	1.07
Physical, Convex	A		3.20	0.84
Physical, Visual	A		3.28	0.96
Physical, No guide		B	4.49	1.23
Virtual, Convex		B	5.01	2.50
Virtual, No guide		B	5.01	1.70
Virtual, Visual		B	5.20	2.11
Virtual, Concave		B	5.65	3.24

Table 6.4: Significant differences of *1-dimensional mean deviation on the z axis* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Analyzing the directed means on the z axis, the drawn stroke had to the optimal line, show significant differences for *surface guidance* ($F_{1,123.7} = 77.5955, p < .0001$) and *line guidance* ($F_{3,124.8} = 6.3846, p < .0005$) and the interactions *surface guidance* ×*line guidance* ($F_{3,122.6} = 10.8837, p < .0001$) and *shape* ×*line guidance* ($F_{3,121.9} = 2.7673, p < .0447$). Post-hoc test results can be taken from Table 6.5.

Looking at the standard deviation of the directed z deviation significant differences for *surface guidance* ($F_{1,225} =$

$47.6716, p < .0001$) and *line guidance* ($F_{3,225} = 12.0420, p < .0001$) and the interaction *surface guidance* ×*line guidance* ($F_{3,225} = 6.9560, p < .0002$) can be found. Post-hoc test results can be taken from Table 6.6.

6.3.3 Front and Back Comparison

The qualitative analysis showed differences for front and back of a drawn stroke. The following analysis was then conducted.

3-dimensional Mean Deviation

The means of the 3-dimensional distance, the drawn stroke had to the optimal line, show significant differences for *side* ($F_{1,465} = 3.9335, p < .0479$). Post-hoc test results can be taken from Table 6.7.

Mean Deviation on X&Y Plane

We found significant differences for the interaction *shape* ×*surface guidance* ×*side* ($F_{1,465} = 5.8655, p < .0158$) analyzing means on the x&y plane. Post-hoc test results can be taken from Table 6.8.

Mean Deviation on Z Axis

The means of the 1-dimensional distance, the drawn stroke had to the optimal line on the z axis, show significant differences for *surface guidance* ($F_{1,225} = 82.6369, p < .0001$) and *line guidance* ($F_{3,225} = 6.2082, p < .0005$) and the interaction *surface guidance* ×*line guidance* ($F_{3,225} = 7.8977, p < .0001$). The post-hoc test results can be taken from Table 6.9.

The directed means of the distance, the drawn stroke had to the optimal line on the z axis, show significant differences for *side* ($F_{1,267.9} = 17.3293, p < .0001$). The post-hoc test results can be taken from Table 6.10.

6.4 Discussion

At first it has to be stated that the results of the study reveal that H0 can be declined. Participants show several significant differences in accuracy while drawing around objects of different guidance types.

6.4.1 Duration

We told participants to draw around every condition in the same speed and with the same accuracy in mind in order to eliminate potential differences in effort of the participants. The results of the stroke duration show no significant differences for any condition or interaction except *shape*. Condition objects had the same diameter, but different circumference dependent on the *shape*, which explains the difference and shows that the expected conditions of participant effort have been met. Furthermore, close inspections of the data show slowdown on the edges of the square shape. The abrupt change in direction seems to affect the speed of sketching.

6.4.2 Full Shape

In this context we could evaluate the significant differences in accuracy, which shows a strong dependency on both *surface guidance* and *line guidance*. Especially in the case of *surface guidance*, it shows, for any accuracy measurement taken, that *physical* objects improve accuracy significant over the virtual objects. The overall deviation, as well as, deviation on x&y plane and in z direction show less drift from the optimal line. Additionally, the standard deviation shows significantly lower variation within the different repetitions on physical objects. As expected, the hard constraint of the impenetrable, physical surface increases sketching accuracy more than the soft, logical constraint of the virtual surface.

The conditions for *line guidance* differ significantly only for *no guide*, especially in the case of deviation in z direction. It shows that the impact of *no guide* for sketching accuracy in z direction is so significant, that it affects the result of overall accuracy, as there is no significant difference on the x&y plane.

The interaction of *surface guidance* and *line guidance* also shows significant results for any accuracy measurement taken 6.3. Best overall accuracy in sketching was achieved for *physical* objects with *concave* surface condition. This further supports the conclusion, that hard constraints increase accuracy in contrast to soft constraints. Consequently all *virtual* objects no matter the surface condition are significantly worse than the *physical* objects in overall accuracy. An interesting outlier is the *physical* objects with *no guide* for the deviation in z direction. This condition does not significantly differ in accuracy from the *virtual* objects and performs among the worst. Again, the effect of *no guide* in z direction is apparent. It can be concluded, that any guide is better than *no guide* for z direction accuracy.

Looking at the directed z deviation shows a tendency to draw below the optimal stroke on the *physical* objects and higher than the optimal stroke on the *virtual* objects. The interaction of *surface guidance* and *line guidance* shows the same result except for the *no guide* surface condition on *physical* objects, which does not significantly differ from any surface condition on *virtual* objects. The optimal line for the *no guide* surface condition was not set in advance, like the optimal lines for the other conditions, but was expected to be the same height as the starting point of the participants sketch for this condition, which leads to the conclusion, that participants misjudge height even when they determine the comparison value.

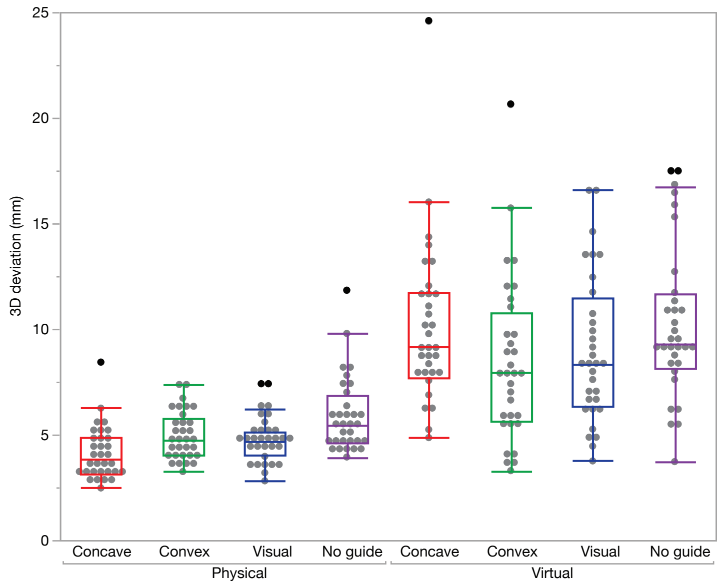


Figure 6.3: Effect of interaction between *surface guidance* and *line guidance* on mean 3D deviation. *Physical* result in better accuracy.

6.4.3 Front and Back

Further inspection of the stroke shape showed the need of evaluating differences for *front* and *back* of the sketched line. In the visualizations of the strokes it seemed like the *back* showed more deviation, which was confirmed for overall accuracy and accuracy in z direction. There was no significant effect on the x&y plane. Furthermore, there were no significant interactions of *side* with *surface guidance* and *line guidance* in overall and x&y plane accuracy, which was not expected after visualizing the strokes. The visualizations for *virtual* objects showed a tendency to draw inside the object at the *back* and outside at the *front*. As the *side* analysis was not planned initially, further study of these effects should be considered.

In the z direction the interaction of *side* with *surface guidance* and *line guidance* was significant and show interesting results. The best accuracy could be achieved on the *back* of

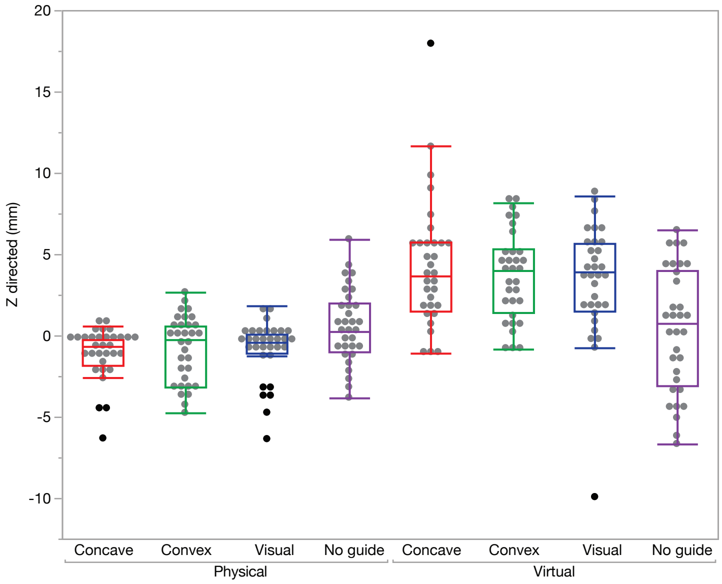


Figure 6.4: Effect of interaction between *surface guidance* and *line guidance* on the directed mean of z deviation. It shows, that the *no guide* condition has a significant negative effect on accuracy. Furthermore *physical* objects result in lower strokes than *virtual*.

physical objects with *concave* surface condition, which may be connected to the study setup. Participants were not allowed to stand up from their seat, which may have impaired their movement slightly near their bodies. On the back of the object the participants then had full movement capabilities. In conjunction with the strongest constraint (*concave*) on the back, high accuracy could be achieved. Interesting is the contrast to the *back* of *virtual* objects with *concave* surface condition, which showed the worst accuracy. This can also be explained by the full movement capabilities on the back of the object, but with missing hard constraints and additional visual obstruction by having to sketch inside a groove.

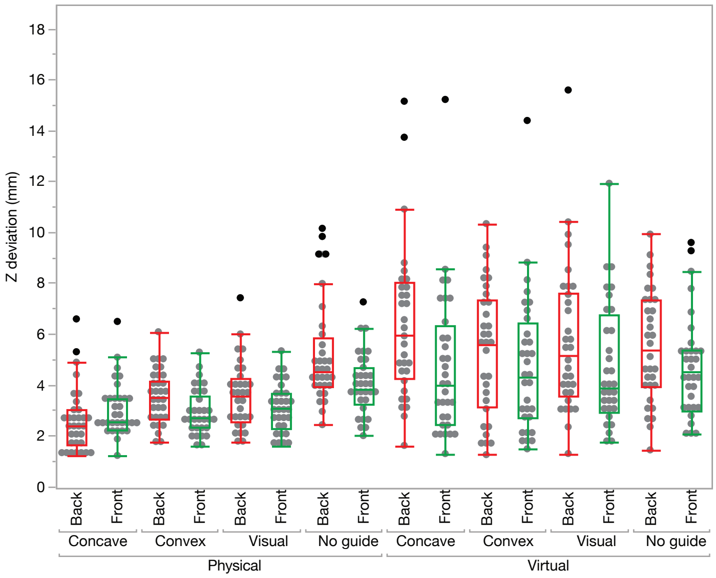


Figure 6.5: Effect of interaction between *side* with *surface guidance* and *line guidance* on mean z deviation. Interesting are the differences for *concave* between *virtual* and *physical*.

6.4.4 Qualitative Observations

The results of the questionnaire coincide with the quantitative results. Participants did not like the *no guide* surface condition and felt guided by both visual and haptic aids.

The skewed shapes in the case of *virtual square* object conditions are in the same direction, that 75% of strokes were drawn. An explanation for this observation could be the tendency of penetrating the virtual shape in order to recognize, when the pen should be on the surface. If the motion of penetrating the surface to test position is continued over the edge on the back side of the object, without correction possible by visible cues, the stroke is skewed in drawing direction. The first correction of this mistake can be made, when the pen tip is visible again on the other side of the object. Considering the speed of movement and the feedback loop of first seeing the pen tip reappear, then choosing the appropriate action of changing direction and then executing the motion, we are left with an overshoot in drawing direction. This may further explain the observation. We excluded handedness from this study and did not give any instructions on intended drawing direction. Further study is required to evaluate the effect of these variables.

Higher accuracy on the side compared to the front and back may be connected to the altered depth perception in virtual environments Wann et al. [1995], Jones et al. [2008]. Furthermore, the sides of the objects, when looked at from the front, present the participant with a good visible edge to align the pen tip to.

6.4.5 Additional Remarks

We presented the participants with a virtual pen tip overlaying the real pen tip, to create a connection between the virtual objects and physical pen tip. From talking to participants we found out, that we also had a slight disconnect between physical pen tip and physical objects. As we prompted our participants to exactly draw on the surface of virtual objects, submerging the pen tip about half into the object, which was not possible in the physical cases. We corrected the data for physical objects by accommodating for the $1cm$ diameter of the physical pen tip, but further study on the effect of the perceived disconnect is suggested.

Condition	Significance			Mean	Std. Deviation
Physical	A			-0.62	2.03
Virtual		B		2.88	3.81
No guide		B		0.39	3.11
Visual	A			1.22	3.49
Convex	A	B		1.38	3.28
Concave	A	B		1.53	4.07
Physical, Concave	A			-1.22	1.52
Physical, Visual	A			-0.90	1.78
Physical, Convex	A			-0.87	2.09
Virtual, No guide		B		0.28	3.81
Physical, No guide		B		0.51	2.26
Virtual, Visual		B		3.33	3.52
Virtual, Convex		B		3.63	2.66
Virtual, Concave		B		4.29	3.97
Square, No guide		B	C	-0.18	2.82
Circle, No guide			C	0.96	3.32
Square, Visual	A	B	C	1.01	3.82
Circle, Concave	A	B		1.28	3.28
Square, Convex	A	B	C	1.33	3.52
Circle, Visual	A			1.43	3.18
Circle, Convex		B	C	1.43	3.08
Square, Concave	A	B	C	1.78	2.50

Table 6.5: Significant differences of *1-dimensional directed mean deviation on the z axis* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Condition	Significance			Mean	Std. Deviation
Physical	A			2.49	0.83
Virtual		B		3.31	1.38
Convex	A			2.65	1.08
Concave	A			2.66	1.29
Visual	A			2.89	1.18
No guide		B		3.39	1.15
Physical, Concave	A			1.96	0.54
Physical, Convex	A	B		2.27	0.53
Physical, Visual	A	B		2.42	0.65
Virtual, Convex		B	C	3.02	1.34
Physical, No guide			C	3.29	0.91
Virtual, Concave			C	3.36	1.44
Virtual, Visual			C	3.36	1.39
Virtual, No guide			C	3.50	1.35

Table 6.6: Significant differences of *standard deviation of the directed z deviation* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Condition	Significance		Mean	Std. Deviation
Front	A		7.05	4.04
Back		B	7.29	3.60

Table 6.7: Significant differences of *3-dimensional mean deviation* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Condition	Significance		Mean	Std. Deviation
Circle, Physical, Back	A		2.67	1.28
Square, Physical, Front	A		2.68	1.04
Square, Physical, Back	A		2.78	1.12
Circle, Physical, Front	A		3.06	1.70
Square, Virtual, Back		B	5.85	2.07
Circle, Virtual, Front		B	6.88	3.64
Circle, Virtual, Back		B	6.91	3.29
Square, Virtual, Front		B	7.48	3.94

Table 6.8: Significant differences of *2-dimensional mean deviation on the x&y plane* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Condition	Significance							Mean	Std. Deviation
Front	A							3.98	2.07
Back		B						4.75	2.62
Physical, Concave, Back	A							2.61	1.26
Physical, Concave, Front	A	B						2.98	1.09
Physical, Convex, Front	A	B						2.93	0.88
Physical, Visual, Front	A	B	C					3.08	0.95
Physical, Visual, Back		B	C	D				3.55	1.32
Physical, Convex, Back		B	C	D	E			3.49	1.05
Physical, No guide, Front		B	C	D	E	F		3.99	1.21
Virtual, Concave, Front			C	D	E	F		4.71	2.86
Virtual, Convex, Front			C	D	E	F		4.72	2.75
Virtual, Visual, Front				D	E	F		4.75	2.45
Virtual, No guide, Front				D	E	F	G	4.71	1.99
Virtual, Convex, Back					E	F	G	5.34	2.56
Physical, No guide, Back						F	G	5.14	2.01
Virtual, No guide, Back						F	G	5.44	2.19
Virtual, Visual, Back						F	G	5.72	2.94
Virtual, Concave, Back							G	6.70	3.79

Table 6.9: Significant differences of *1-dimensional mean deviation on the z axis* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Condition	Significance		Mean	Std. Deviation
Front	A		0.76	3.35
Back		B	1.54	4.34

Table 6.10: Significant differences of *1-dimensional directed mean deviation on the z axis* per condition. Only main effects and interactions, which are significant, are shown in the table. Rows, which are not connected by the same letter, are significantly different. The means and standard deviations are measured in millimeter and rounded to two decimal places.

Chapter 7

Summary and future work

In the last chapter, we present a summary of the thesis and the contributions made. This is followed up by an outlook on possible future work in the field.

7.1 Summary and contributions

Using AR to create 3D objects with widely known drawing utensils, like a pen, can be an easy way of introducing novices to the field of Personal Fabrication. AR in contrast to VR enables the user to use its surroundings as base for virtual sketches. Attaching virtual sketches to physical objects to design new product parts may simplify Personal Fabrication workflow in the future. The altered workflow promises the possibility for novices to design their own 3D models in-place.

First, we gave an overview of several studies and projects in the field of breaking the Personal Fabrication workflow Weichel et al. [2015], Yamaoka and Kakehi [2017], using 2D sketching to design 3D objects Bae et al. [2009], Cohen et al. [1999], Lau et al. [2010] and one study on accuracy of drawing mid-air in VR Arora et al. [2017].

We then classified the guidance types physical objects present to a human, while drawing on them. The guidance types consist of constraints. These constraints may be hard, like an impenetrable surface of a table or soft, like a water surface. We called the constraints the surface represents depending on the material 'hardness' as *surface guidance*. The structural makeup of a surface, like grooves or just visual markings, was summarized under the term *line guidance*.

After classification of the guidance types, we designed a system based on the AR headset HoloLens and the visual tracking system of Vicon. To connect these two systems, a central server handled the data flow, synchronization and provided means to add control user interfaces and export study data.

With this system in place, we conducted a user study on the expected accuracy of drawing in mid-air using different combinations of *surface guidance* and *line guidance*. The participants had to draw a stroke around a *physical* or *virtual* object of different *shape* in a normal speed, trying to be as accurate as possible.

Analyzing the data of the user study, we found significant indication for *physical* conditions enhancing accuracy greatly. The best case was a *physical* object with *concave line guidance*, as it enforced the strongest constraints. Consequently every *virtual* object performed significantly worse, not enforcing any hard constraints. Interesting was the effect of *no guide* on the deviation in z direction particular. Any *line guidance* was helpful in this case, but as soon as it was missing, the accuracy decreased significantly.

7.2 Future work

As mentioned in the evaluation, future work can be directly derived from the results of the study.

The skewed shapes, rotated in the drawing direction, need further investigation. Especially the handedness of the participants might play a role in the observed qualitative results.

If the assumption, that the distribution of inaccuracies on the front and back in contrast to the sides is the result of depth perception in virtual environments is right, further studies to enhance depth perception should be conducted. Apart from depth perception, this effect in general should be researched further.

Our front and back analysis was the result of seeing the effect of side in visualizations of strokes drawn in the user study. We did not plan for this beforehand, so further investigation is required.

Further research should also be conducted regarding the other effects a surface might have on the user and the drawing utensil. For example, the texture of the surface and resulting friction between drawing utensil and surface and its effect on accuracy were not evaluated, yet. This is also true for orientation of the surface, its position relative to the user and the size of the surface.

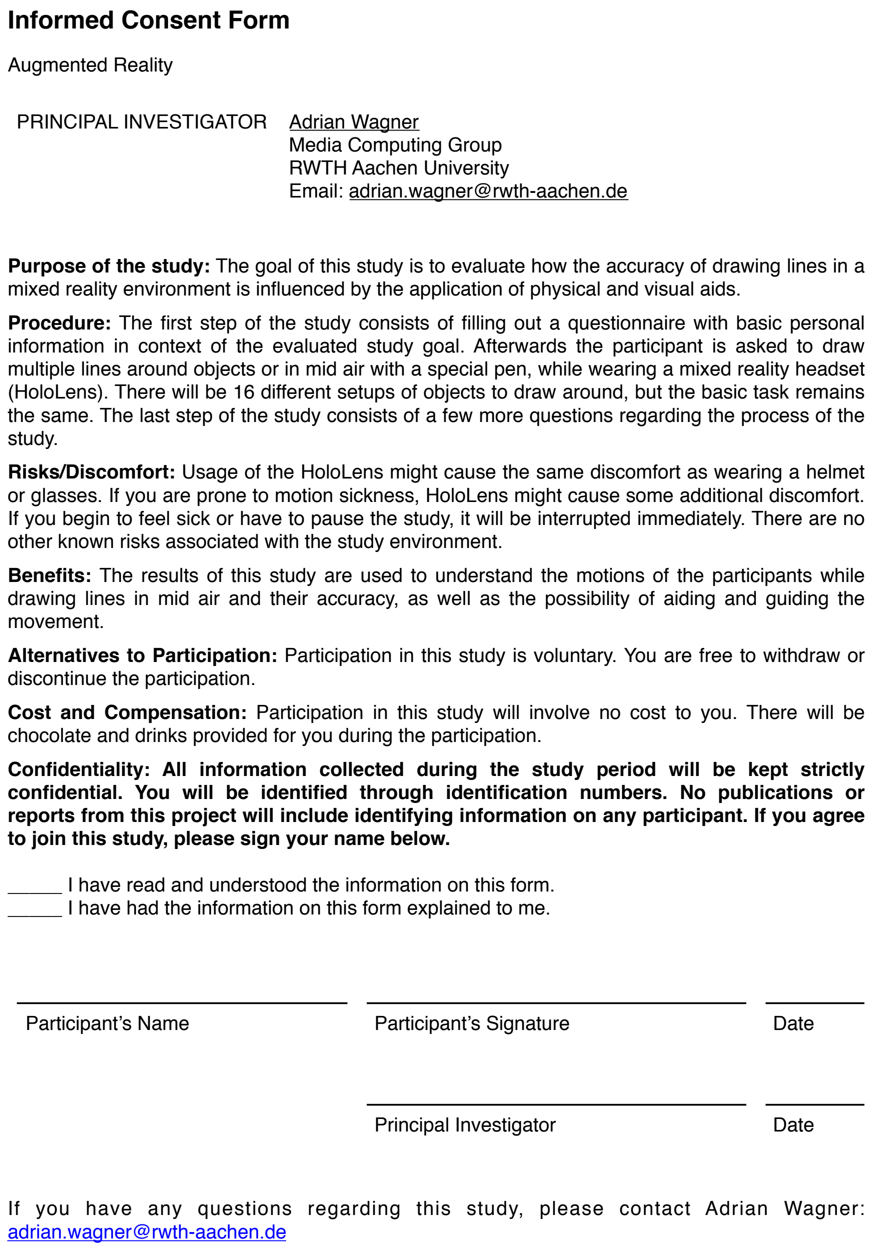
Furthermore, we restricted the guidance types we tested to specific 'common cases'. An example for this would be the one opening angle of *concave* grooves we tested. Different angles and other guidance types in the design space might show different results and should be investigated.

The feedback for our pen was mixed. The result of technical limitations was a pen tip with a diameter of $1cm$ and a center of mass not balanced like a normal pen. Different pen tip sizes and shifts in the center of mass may have an effect on accuracy and should be studied.

Our study also only tested interactions with one hand. Bimanual interactions with objects in AR have to be investigated to close the gap, our setup has to natural interaction, further.

Appendix A

User Study Consent Form



Informed Consent Form

Augmented Reality

PRINCIPAL INVESTIGATOR
Adrian Wagner
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Purpose of the study: The goal of this study is to evaluate how the accuracy of drawing lines in a mixed reality environment is influenced by the application of physical and visual aids.

Procedure: The first step of the study consists of filling out a questionnaire with basic personal information in context of the evaluated study goal. Afterwards the participant is asked to draw multiple lines around objects or in mid air with a special pen, while wearing a mixed reality headset (HoloLens). There will be 16 different setups of objects to draw around, but the basic task remains the same. The last step of the study consists of a few more questions regarding the process of the study.

Risks/Discomfort: Usage of the HoloLens might cause the same discomfort as wearing a helmet or glasses. If you are prone to motion sickness, HoloLens might cause some additional discomfort. If you begin to feel sick or have to pause the study, it will be interrupted immediately. There are no other known risks associated with the study environment.

Benefits: The results of this study are used to understand the motions of the participants while drawing lines in mid air and their accuracy, as well as the possibility of aiding and guiding the movement.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue the participation.

Cost and Compensation: Participation in this study will involve no cost to you. There will be chocolate and drinks provided for you during the participation.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.
_____ I have had the information on this form explained to me.

Participant's Name
Participant's Signature
Date

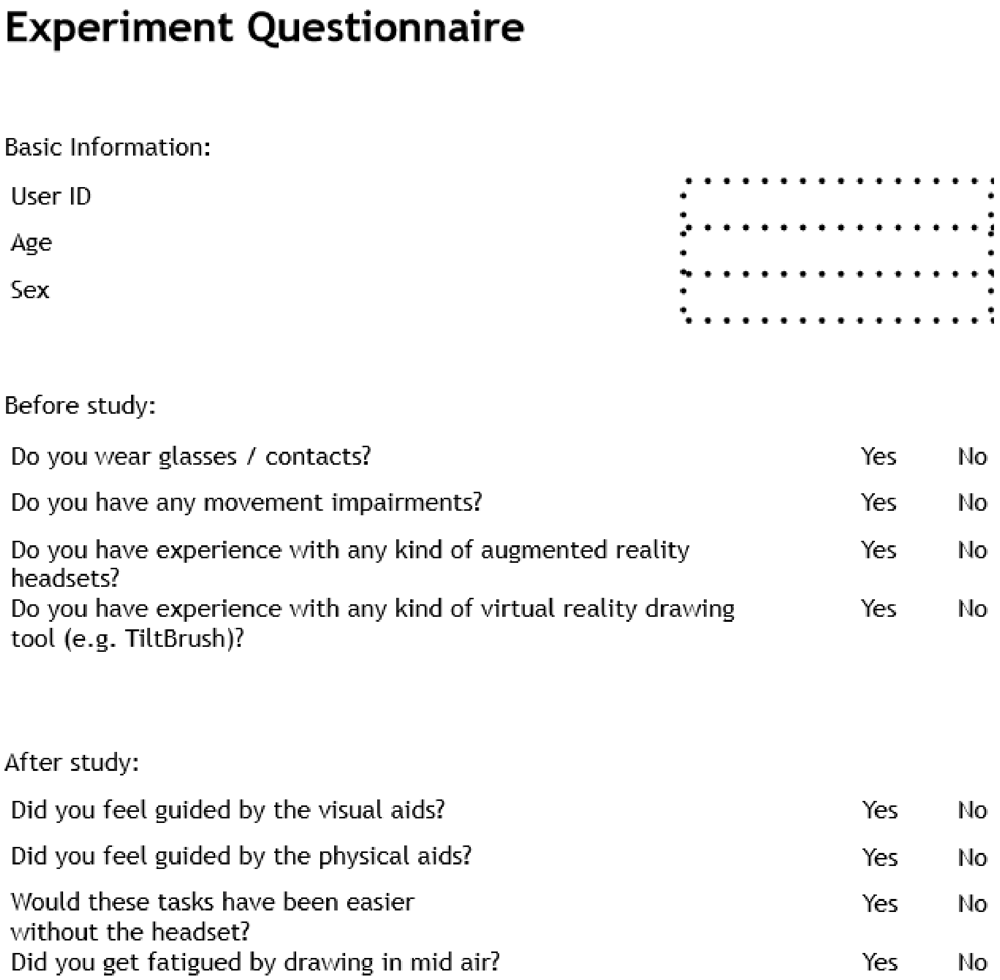
Principal Investigator
Date

If you have any questions regarding this study, please contact Adrian Wagner: adrian.wagner@rwth-aachen.de

Figure A.1: Consent Form

Appendix B

User Study Questionnaire



Experiment Questionnaire

Basic Information:

User ID

Age

Sex

Before study:

Do you wear glasses / contacts?	Yes	No
Do you have any movement impairments?	Yes	No
Do you have experience with any kind of augmented reality headsets?	Yes	No
Do you have experience with any kind of virtual reality drawing tool (e.g. TiltBrush)?	Yes	No

After study:

Did you feel guided by the visual aids?	Yes	No
Did you feel guided by the physical aids?	Yes	No
Would these tasks have been easier without the headset?	Yes	No
Did you get fatigued by drawing in mid air?	Yes	No

Figure B.1: Questionnaire

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abbrv, *see* abbreviation

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