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Scaling Objects: Implementation and Evaluation of Scaling Techniques for the ARPen System

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Media Computing Group
Prof. Dr. Jan Borchers
Computer Science Department
RWTH Aachen University

by
Farhadiba Mohammed

Thesis advisor:
Prof. Dr. Jan Borchers

Second examiner:
Prof. Dr. Torsten Kuhlen

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Mohammed, Farhadiba

Name, Vorname/Last Name, First Name

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Abstract

Using Augmented Reality, users can create and manipulate virtual models within the real environment by applying fundamental transformations like translation, rotation, or scaling. Researchers are increasingly using smartphones to display Augmented Reality. Nevertheless, modeling in 3D, while interacting with a 2D touchscreen is complicated by limited screen size and reduced depth information. Attempts to overcome these issues include pen-like input devices for mid-air interaction. The ARPen System conforms to such a system by combining a 3D-printed pen with a smartphone for precise 3D input. Previous studies have already evaluated the translation and rotation of virtual objects with this bimanual system. To complete the set of transformations, in this Bachelor's thesis, we aim to identify the most effective and user-friendly scaling technique, utilizing the ARPen system for 3D modeling. We designed six techniques using touch input and pen input provided by the system, which we later evaluated within a user study. The final results show a preference for touchscreen interaction and a ray-casting method requiring the pen.

Überblick

Mit Hilfe von Augmented Reality können Nutzer jetzt virtuelle Modelle in der realen Umgebung erstellen und manipulieren, indem sie grundlegende Transformationen wie Translation, Rotation oder Skalierung anwenden. Heutzutage werden Smartphones zunehmend zur Darstellung von Augmented Reality eingesetzt. Die Modellierung in 3D durch Interaktion mit einem 2D-Touchscreen wird jedoch durch eine begrenzte Bildschirmgröße und reduzierte Tiefeninformationen erschwert. Zu den Versuchen, diese Probleme zu überwinden, gehören Stift-ähnliche Eingabegeräte für die Interaktion in der Luft. Das ARPen-System entspricht einem solchen System, indem es einen 3D-gedruckten Stift mit einem Smartphone, für präzise 3D-Eingaben, kombiniert. Frühere Studien haben bereits die Translation und Rotation virtueller Objekte mit diesem bimanuellen System evaluiert. Um die Reihe der Transformationen zu vervollständigen, wollen wir in dieser Bachelorarbeit die effektivste, intuitivste und komfortabelste Skalierungstechnik ermitteln, welche das ARPen-System für 3D-Modellierung einsetzt. Dazu haben wir sechs Techniken entworfen, welche sowohl den Touchscreen, als auch den Stift zur Interaktion verwenden. Zur Bewertung unserer Techniken führten wir eine Benutzerstudie durch. Die Endergebnisse zeigen eine Präferenz für die Touchscreen-Interaktion und einer Ray-Casting-Methode mit dem Stift.

Acknowledgements

First, I would like to express my thanks to Prof. Dr. Borchers and Prof. Dr. Kuhlen for examining this thesis.

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Also, I want to thank my family and friends, who always support me.

Finally, I'd like to thank all participants who spared an hour of their free time participating in my user study.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

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

`myClass`

The whole thesis is written in American English. The first person is written in the plural form. Unidentified third persons are described in female form.

Chapter 1

Introduction

Augmented Reality (AR) has been gaining increasing attention within the last decade. With Augmented Reality, we describe the possibility to enrich the real environment with virtual content in a matter that both appear to coincide in the same space [Azuma et al. [2001]]. Nowadays, there are numerous fields of applications that benefit from this technology. Several research projects have primarily focused their interest in creating and manipulating three-dimensional (3D) models in mid-air using AR [Peng et al. [2018], Bai et al. [2012, 2014]].

AR superimposes virtual content upon the real environment, hence enhancing 3D modeling capabilities.

One way to display virtual content is by using a Head-Mounted Display (HMD). HMDs have been used for this purpose since the 1960s [Sutherland [1968]] and are still used in the majority of projects for AR today (e.g., Microsoft's HoloLens[1]). Still, the acquisition can be costly, and the overall bulkiness of these devices might not appeal to less tech-savvy consumers [LLP [2018]]. An alternative to HMDs are handheld AR (HAR) devices, such as smartphones, which use frameworks like Google's ARCore[2] or Apple's ARKit[3] for their AR applications. Smartphones can make AR more accessible to people, as the ma-

Handheld AR makes AR more accessible to people.

[1] `https://www.microsoft.com/en-us/hololens` *(Accessed: 20.09.20)*

[2] `https://developers.google.com/ar` *(Accessed: 20.09.20)*

[3] `https://developer.apple.com/augmented-reality/arkit/` *(Accessed: 20.09.20)*

Touchscreen interaction has some limitations.

jority of the population owns a smartphone already. The touchscreen thereby provides the main source of input. However, touch input has limitations, especially for applications including 3D interaction. Experiencing 3D content through a 2D screen reduces depth information, making it difficult for users to specify a 3D point at a specific depth [Kruijff et al. [2010], Mossel et al. [2013], Wacker et al. [2019]]. Additionally, the small screen size only offers limited space for manipulation, and precision suffers under an ambiguous selection point (i.e. fat finger problem) and finger occlusion [Le et al. [2017], Wigdor et al. [2007], Siek et al. [2005], Vogel and Baudisch [2007]].

Pen-input can increase accuracy.

To address these issues, researchers are developing trackable pen-similar input devices [Wu et al. [2017], Jackson and Keefe [2016], Seidinger and Grubert [2016], Arora et al. [2018]]. Similarly, Wacker et al. [2019] introduced the ARPen system, a bimanual system that combines an iPhone with a 3D-printed pen. The goal is to offer users an accessible tool for 3D modeling and personal fabrication, which is intuitive to use even for non-expert users.

We propose six scaling techniques for the ARPen system, which we evaluated within a user study.

To model in 3D, users require certain operations. The three main 3D operations to transform a virtual object are translation, rotation, and scaling. Former studies have already focused on analyzing suitable translation and rotation techniques for the ARPen system [Klamma [2019], Wacker et al. [2019]]. To complete this set of essential transformations, this Bachelor's thesis focuses on developing and analyzing scaling techniques for this bimanual system. We developed six different scaling techniques, which we evaluated to identify the most effective and user-friendly technique for users within a user study. As there are several input methods provided by the ARPen system, our techniques not only focus on using the ARPen for mid-air manipulation but also use the touchscreen for input. Therefore, we are specifically interested in investigating how well mid-air pen input performs against the standard touch input or if a combination of both works best.

1.1 Outline

In the following chapter, we provide some background information about Augmented Reality. We present the history and developments, and discuss various applications. Next, we examine the ARPen system we have based our techniques on.

Then in chapter 3, we look into related work. There we identify existing trackable, pen-like input devices, and further describe previously conducted studies using the ARPen system. Finally, we introduce scaling techniques that researchers have evaluated in similar research projects.

In chapter 4, we define our scaling techniques based on the findings from the Related Work section.

Chapter 5 deals with the user study we conducted to investigate the differences in our six techniques' performance and the participants' subjective ratings. Here we explain the measurements we have recorded and the task we asked our users to perform. Furthermore, we describe the experimental design and study procedure. Finally, we present the results and discuss them.

We conclude our thesis with a summary of the overall thesis and results, and propose future research possibilities in chapter 6, Summary and Future Work.

Chapter 2

Background

2.1 Augmented Reality

We can trace back Augmented Reality's beginning to the 1960s when Ivan Sutherland [1968] created the first Head-Mounted-Display (HMD), the 'Sword of Damocles'. Later in 1975, Krueger et al. [1985] established an artificial reality lab called VIDEOPLACE. Cameras captured users' body figures and projected them onto a screen. But only in the early 1990s, former Boing researcher Thomas P. Caudell first coined the term Augmented Reality, when he designed a heads-up display headset to assist workers with the manufacturing of aircraft [Caudell and Mizell [1992]]. In 1997, Azuma [1997] then proposed a widely accepted definition of the term Augmented Reality. He stated that an AR system should provide three properties: (1) Firstly, it should join real and virtual objects together in a real environment. (2) Secondly, it should allow user interaction and run in real-time. (3) Finally, it should be registered in 3D space. Since then, more researchers began focusing their work on the idea of superimposing virtual content upon the real environment.

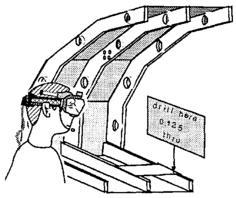


Image from Caudell and Mizell [1992]

Caudell and Mizell's HMD for manufacturing assistance.

Though Augmented Reality is still at its initial phase, the technology has undergone rapid developments within the last two decades. In 1994, Julie Martin presented the first AR theater production, 'Dancing in Cyberspace' [Cipresso

AR has many applications.

et al. [2018]]. Thereupon AR entered the field of entertainment and has been employed for multiple applications since. AR has enriched the game industry with games like ARQuake [Thomas et al. [2000]], ARTennis [Henrysson et al. [2006]] or more recently, PokemonGo[1]. Also, it served more practical purposes, including education [Bacca et al. [2014], Nincarean et al. [2013], Azuma et al. [2001]], medicine [Sielhorst et al. [2008], Azuma et al. [2001], IGD], sightseeing [Furata et al. [2012], Alkhamisi et al. [2013]] and commerce [IKEA, Azuma et al. [2001], Alkhamisi et al. [2013], Pereira et al. [2011]]. Besides the variety of applications already listed, 3D geometry modeling is another area that benefits from Augmented Reality. Users can now create virtual models conforming to the surrounding physical objects within the real environment [Arora et al. [2018]].

Smartphones are increasingly used to display AR.

There exist different possibilities to experience AR content. We can classify the main AR displays into three categories: HMDs, handheld displays (HHD), and spatial displays [Carmigniani et al. [2011]]. As an HMD, we describe a device that is worn on the head. Mostly, HMDs are attached to goggles or helmets. This way, users' hands are potentially free to interact with virtual content. HMDs are extensively used for displaying Virtual Reality as well. Virtual Reality, is an environment fully surrounded by computer-generated images [Steuer [1992], Burdea and Coiffet [2003]]. Hand-held displays describe portable computing devices such as tablets or smartphones, which require users to hold the device in their hands. Tablets are unwieldy and too heavy to use single-handedly. On the other hand, smartphones require one hand to hold the smartphone leaving the other hand free for interaction. Finally, spatial displays do not require the user to hold or wear any display. They experience Augmented Reality through the projection of virtual content onto physical surfaces. Therefore spatial displays are generally static and not mobile as HMD or HHD. Nowadays, more research is moving towards the employment of AR on handheld devices, especially smartphones. Similarly, researchers at the Media Computing Group of the RWTH Aachen developed a handheld AR system for 3D modeling.

[1] `https://www.pokemongo.com/en-us/` *(Accessed: 20.09.20)*

Figure 2.1: The ARPen, a 3D-printed, interactive stylus with three buttons connected to a Bluetooth chip for transferring signals to the device. The box on top shows six trackable arUco markers.

2.2 The ARPen System

The ARPen system combines a smartphone with a 3D-printed, interactive pen.

The ARPen system presents a combination of a smartphone with a 3D-printed, pen-shaped input device, the *ARPen*. This device represents a pen-shaped stick with three buttons, located close to the pen's tip, and a cubical box placed at the top [Schäfer [2020]]. Each face of the cube thereby represents one of six arUco markers (see Figure 2.1). The pen uses Bluetooth to communicate the current button states to the device.

To use the ARPen, Wacker et al. [2019] developed an open-source iOS application[2] that uses Apple's ARKit[3] framework and SceneKit[4] to create the AR experience. Figure 2.2 visualizes how the app calculates the pen's position. When starting the app, the AR world is constructed, and its origin is set to a predefined, fixed location. ARKit enables tracking the device camera's location relative to the AR world's origin at any time. The marker tracking provided by the arUco framework empowers the calculation of the marker's loca-

[2] `https://github.com/i10/ARPen` *(Accessed: 20.09.20)*

[3] `https://developer.apple.com/augmented-reality/arkit/` *(Accessed: 20.09.20)*

[4] `https://developer.apple.com/documentation/scenekit` *(Accessed: 20.09.20)*

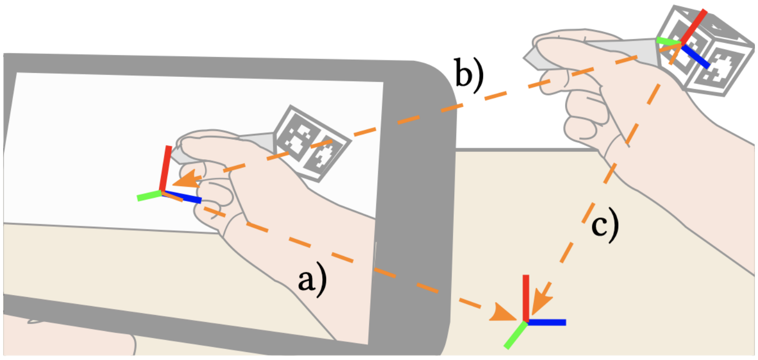


Figure 2.2: Calculation of the ARPen's 3D position. (a) ARKit assists in computing the camera's position relative to the AR world's origin. (b) arUco identifies the marker's position relative to the camera. (c) Combining these positions enables the calculation of the marker's position within the AR world. Image from Wacker et al. [2019].

tion in camera coordinates. Finally, the marker's position relative to the AR world's origin is determined by combining these features. Based on this, the pen tip's 3D position can be specified. As the computation depends on the markers' visibility, they must remain in front of the camera during the interaction. If the markers are outside the camera view, the system struggles to specify the pen tip's position, although users can still perceive the pen tip on the screen. If multiple markers are visible simultaneously, the system averages all calculated pen tip positions.

The markers' visibility limits the calculation of the pen's position.

Given its bimanual nature, the system provides several input methods. The most familiar form of interaction is with the touchscreen. Users benefit from haptic feedback provided by the screen. So far, the touchscreen was used to switch modes or adjust settings, but researchers have also evaluated its use for selecting and manipulating virtual objects [Klamma [2019], Nowak [2019], Wacker et al. [2019]]. The device creates another form of interaction, as changes in the viewport can be applied to the model. Finally, the ARPen encourages mid-air interaction with the in-build buttons.

The ARPen system provides several input methods.

Chapter 3

Related work

This thesis aims to identify the most effective and user-friendly scaling technique using the ARPen system. Therefore in the following chapter, we focus on existing studies dealing with similar research questions in the field of AR and VR. We first present other pen-like input devices used for 3D modeling and sketching. Next, we recall the findings obtained from former studies on the ARPen system. Ultimately, we introduce existing scaling methods implemented for handheld AR systems.

3.1 Pen Input in Augmented and Virtual Reality

AR offers new opportunities for 3D modeling and especially *in-situ* modeling. With in-situ modeling, we describe the creation of models in the exact location we desire them to be finally placed. Besides transformations like the translation, rotation, or scaling of objects, sketching in mid-air helps create models. The most intuitive and natural tool for us to sketch is a pen. Therefore, researchers increasingly design pen-like input devices, similar to the ARPen, to investigate their performance for 3D modeling in Augmented Reality.

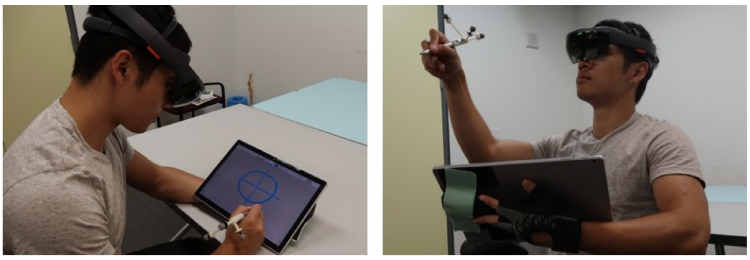
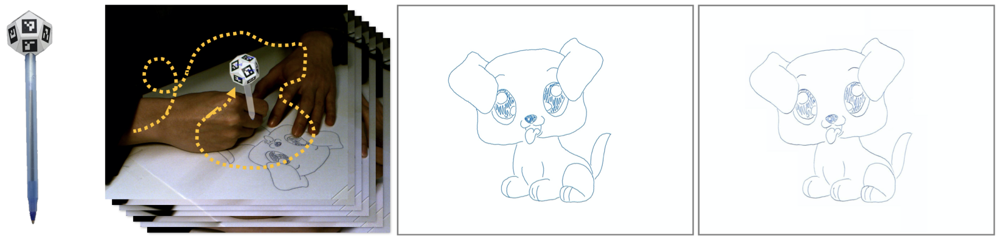


Figure 3.1: User drawing with a motion-tracked pen on the tablet (left) or mid-air (right). Image from: Arora et al. [2018].

Figure 3.2: Creation of sculptures with *Lift-Off*. (a) The user prepares a sketch on paper and (b) imports this sketch into the VR application. (c) The user can now lift lines from the imagery into the 3D environment and insert surfaces between them (c) to design a 3D sculpture (c). Image from: Jackson and Keefe [2016].

Using curved canvases, SymbiosisSketch combines 2D and 3D sketching.

Arora et al. [2018] have analyzed the performance of a hybrid sketching system that combines mid-air 3D interaction with 2D surface interaction . They call it *SymbiosisSketch*. The ability of 3D modeling to create life-sized, immersive models, and the haptic feedback and precise interaction in 2D were combined to enable in-situ 3D designs. The system consists of an AR capable HMD, a tablet for 2D drawing with a mouse attached to its back for triggering the interactions, and a motion-tracking digital pen (see Figure 3.1). Users can draw several strokes mid-air to define a curved drawing canvas whose orthographic projection is shown on the 2D tablet.



(a) DodecaPen (b) Monocular video (c) DodecaPen tracking (d) Ground-truth scan

Figure 3.3: The Dodeca system uses the (a) DodecaPen, a passive stylus with markers for tracking, and (b) requires only a single camera to achieve (c & d) high accuracy. Image from: Wu et al. [2017].

With *Lift-Off*, Jackson and Keefe [2016] propose another approach to achieve precise 3D models with 2D sketches. They present a 3D immersive modeling system for VR. Here users start by sketching the desired model on a paper, which they then import into VR. Now they can select lines of the imagery and lift them off to position them in mid-air or can draw 3D curves freehand in space. After defining the curves, they insert surfaces to create 3D virtual sculptures (see Figure 3.2).

Lift-Off enables 3D sculpture creation from 2D sketches.

Wu et al. [2017] have introduced the *DodecaPen*. The DodecaPen is a passive stylus that can be applied for 2D and 3D drawing and general object manipulation in VR and AR. The goal was to design an easy-to-construct system that enables real-time six degrees of freedom (6DoF) tracking. The system only requires one external, monocular camera. Similar to the ARPen, the DodecaPen is a 3D-printed tool with several binary square markers from the arUco library used to compute the pen's position relative to the camera. The authors claim to achieve a precision of 0.4 mm. Figure 3.3 presents the DodecaPen and the image users created with it.

The DodecaPen uses fiducial markers and a single camera for accurate tracking.

While the previously presented research projects focus on 3D sketching rather than 3D object manipulation, Seidinger and Grubert [2016] designed a passive stylus that enables users to directly interact with and transform virtual objects. The author's goal was to design a prototype for 3D character customization in mobile-based AR games. Unlike the ARPen or DodecaPen, the *MarkerPen* consists of a

The MarkerPen consists of markers representing different transformation modes.

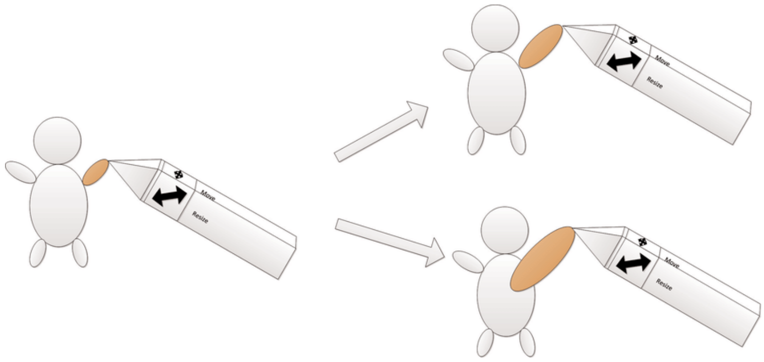


Figure 3.4: Scaling with the MarkerPen. The MarkerPen consists of markers which communicate the current manipulation mode. Image from: Seidinger and Grubert [2016].

foam board marker cube with four markers whereby each marker represents a manipulation mode. These modes include the translation, rotation, and scaling of objects. Therefore, to perform a manipulation, users have to rotate the pen. The corresponding marker is visible for the camera, and the user then confirms the manipulation mode by pressing a lock button on the touchscreen. Figure 3.4 visualizes the interaction steps for scaling a characters arm. When activating the scaling mode, the object's hull is attached to the pen tip throughout the entire manipulation process. The user moves the pen tip closer to decrease the object's size while a movement away scales it up. The results of the performance evaluation underline the hedonic qualities of pen-based input. However, efficiency can still be improved.

3.2 Related Work on the ARPen System

Since the introduction of the ARPen in 2018, researchers have focused on evaluating the ARPen system's potential for different modeling tasks.

The *pinkie grasp* is used to hold the smartphone.

First, Wacker et al. [2019] investigated which phone orientation and grasp works best for this system. Here the results showed that a *pinkie grasp*, where the phone is placed

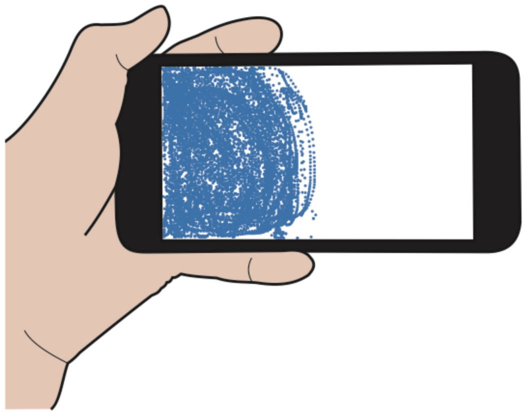


Figure 3.5: The *pinkie grasp* used for studies with the ARPen System. Image from: Wacker et al. [2019].

horizontally on the non-dominant hand's pinkie such that the camera is not occluded, covers the largest touchscreen area and should thus be employed for future studies (see Figure 3.5). Using this information, they further analyzed suitable selection and translation techniques. They implemented three pen-based selection methods besides the traditional touchscreen selection, which they evaluated in a one-handed and two-handed variant. Pen selection required the user to directly select the object by positioning the pen tip inside it. They analyzed this technique with and without providing visual assistance. The remaining technique would cast a ray through the pen's tip such that the first target behind it is selected. As a consequence, users could position the pen tip in front of the object as well. The results show that mid-air selection with the ARPen is not ideal as users struggle to find the correct depth in 3D. Still, the ray-based method delivered good results for both selection and translation tasks and ranked high on user preference. A hybrid technique, combining touchscreen selection and pen translation, was also evaluated and received good user feedback within the translation study. The authors encouraged further investigations of such combinations. Later, Klamma [2019] conducted a similar study to evaluate rotation methods for the ARPen system. She compared five rotation methods, including the device, the touchscreen, and the pen for input. All in all, the rotation method, pro-

A ray-based method performed best for selection and translation.

A device-based method should be used for rotation.

jecting the device's rotation onto the object, proved itself to be a reliable rotation method.

3.3 Scaling Techniques in Related Work

Physical objects cannot be scaled, so no natural scaling gesture exists.

Within our real environment, we can translate and rotate physical objects. However, scaling objects lies beyond our possibilities. Augmented and virtual environments enhance us with this capability and allow us to create accurately scaled models. Although there are no predefined, real-world metaphors we can familiarize with, we still develop an intuitive idea on how to scale a virtual object if we encounter one. Given the various input methods provided by the ARPen system, we want to identify which types of gestures other researchers have perceived suitable for scaling tasks and which input methods have already been employed and were most intuitive for users.

We start by looking at traditional touch-based scaling methods. However, before studying concrete implementations, we understand which user gestures are intuitive for scaling 3D Objects from touch input. Cohé and Hachet [2012] have investigated this research question and proposed some design implications based on their findings. In the process of understanding how users perceive a 3D manipulation task and which gesture they intuitively associate with it, the authors have observed, amongst other aspects, the number of fingers used to perform the manipulation. They identified that most users tend to use two or four fingers for scaling, while only a few found it natural to use one finger Many participants performed a pinch gesture to scale the object and stated that it felt familiar through zooming functionalities on other applications. Therefore, the final design principles for an easy and widely used scaling strategy suggest employing this gesture.

A pinch gesture is intuitive for scaling.

Indeed, lots of researchers have used a pinch gesture for scaling. Bai et al. [2012] have compared a touch-based interaction approach to a finger gesture-based method. Thereby the touch-based method used a freeze mode for more stability. In both techniques, users perform a two-finger pinch gesture to scale the object uniformly. Moving the fingers closer together decreases the size while moving them apart, scales the object up. The results revealed that the touch-based method was much faster and more precise. Still, users enjoyed the gesture-based interaction considerably more.

Similarly, Mossel et al. [2013] have integrated a two-finger pinch approach for scaling with the touch-based method *3DTouch* and the device motion-based technique *HOMER-S*. The goal was to introduce intuitive six-degree-of-freedom (6DoF) manipulation techniques, meaning intuitive techniques that allow translation along and rotation around all three manipulation axes. Users first select the scaling mode through a menu before scaling. A scaling operation is always performed non-uniformly along one axis at a time. To overcome the restriction to a 2D interaction space provided by the touchscreen, 3DTouch divides the 6DoF into 3DoF tasks. Subsequently, the object's local coordinate system appears. To access the desired manipulation axis, users adjust the camera such that the target axis is visible on the screen. They can then apply the pinch gesture parallel to the axis to adjust the size of the object along that axis. The other approach was to decouple the entire interaction from the touchscreen and use the device itself to manipulate the object. The HOMER-S algorithm calculates the difference between the original and updated positions of the device and uses it to compute the scaling factor. Moving the device along the positive direction of an axis would scale the object up in that dimension. Similarly, a movement along the negative direction of an axis would compress the object. The results after comparing both approaches show that experienced users could complete the scaling task significantly faster with 3DTouch than with HOMER-s, while the others also were faster but not significantly. In the subjective ratings, both experienced and non-experienced participants favored 3DTouch over HOMER-S for scaling. Therefore, the authors concluded that the touch-based method should be preferred over the device-based method if scaling is required.

Touch-based 3DTouch performed better than device-based HOMER-S.

Another approach for scaling found in literature follows the metaphor of directly grabbing an object and pulling it

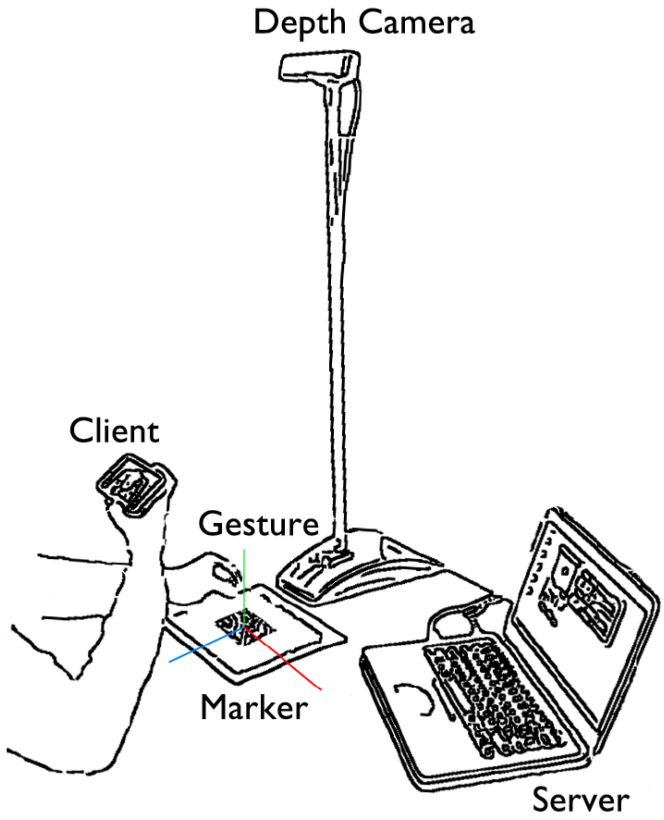


Figure 3.6: The setup for detecting free-hand gestures used by Bai et al. [2014]

Gesture-based approach follows a 'grab&drag' kind of interaction which is comparable to the resizing of 2D images.

to scale it. We have already seen a comparable implementation with Seidinger and Grubert's MarkerPen. Likewise, Bai et al. [2014] have used this form of scaling in their 3D gesture interaction study. The authors associate this interaction with press-holding a button on a mouse and then dragging it, as it is implemented in different desktop applications for resizing 2D images. Figure 3.6 presents the required setup used for gesture recognition. Within the study, the authors have compared the gesture interaction to a similar form of touchscreen interaction. Users used one finger on the touchscreen to exactly adapt the gesture-based approach. The task completion time indicates that the touch-based method was significantly faster than the gesture-based variant. But regarding the naturalness of the interaction, the direct gesture interaction had significantly higher ratings. Also, users felt the gesture interaction was easier to learn and use than the touchscreen method. Some argued that the non-intuitiveness for the touch-based variant resulted from using a single finger while a two-finger pinching approach was already familiar.

All in all, we have identified a multitude of different scaling techniques. Nevertheless, none of the above studies compared scaling techniques using traditional input methods to scaling techniques using a pen for interaction. Our study provides such an analysis by comparing the performance of different pen-based techniques to touch-based techniques for scaling.

None of the studies compare different pen-based techniques for scaling.

Chapter 4

Description of the Scaling Techniques

This chapter discusses the design and implementation of the scaling techniques we have developed based on the related work chapter's insights. As initially defined, the ARPen system offers various interaction methods. The goal was to design techniques using multiple methods to enable an omnifarious evaluation and identify the most effective and user-friendly technique. As device scaling did not achieve good results in related work, we decided to focus on using the remaining input methods of the ARPen system. Therefore, our designed techniques include touchscreen interaction as well as mid-air interaction requiring the ARPen. To understand our selection of techniques, we first elaborate on our motivation for the general design and continue with a detailed description of each method.

Our techniques use the touchscreen and pen for interaction.

To evaluate the techniques comparably, we first defined the general characteristics of the scaling techniques. We identified that there exist two possibilities on how scaling can be applied to an object. The model can either be scaled concerning its center or concerning a fixed corner. Both variants are presented in Figure 4.1. The type of scaling does not impact the interaction. Therefore either could be implemented. The majority of our techniques follow the metaphor of grabbing a corner and dragging it for scaling, similar to the mid-air gesture-based approach we pre-

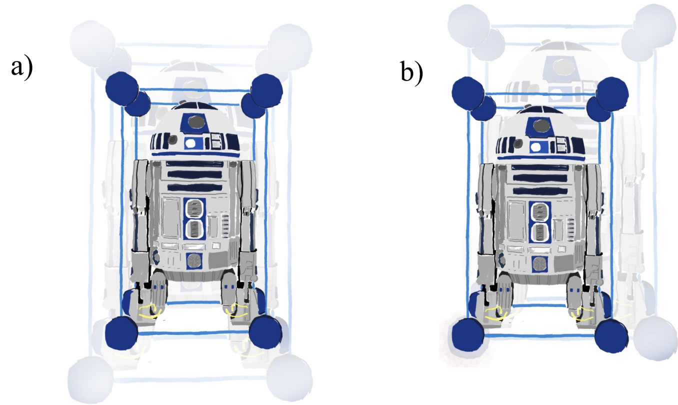


Figure 4.1: Two types of scaling. We can scale a model either concerning a) the center or (b) a corner.

The virtual object is scaled uniformly with a corner as the anchor point for scaling.

sented in the related work section. Therefore, we decided to mostly implement the second approach for our study, as we considered it to be more intuitive and flexible. Upon selecting a corner, the corner located at the opposite end of the connecting diagonal becomes the scaling anchor point. Generally, an object can only be scaled if a corner is selected. Another decision we made was to implement our techniques to perform uniform scaling. Our primary focus is on evaluating the interaction using our techniques. To fulfill this purpose, it was not necessary to include non-uniform scaling yet. However, all techniques can still be adapted to perform center scaling and non-uniform scaling in the future, if desired. A pre-selection of an axis could assist in defining the desired scaling dimension for non-uniform scaling. Depending on our technique, we have employed a different type of selection best suited for the interaction. For touch-based interaction, it is only reasonable to use the touchscreen for selection as well. Therefore, users tap the object's projection on the screen to select it. As the results of the ARPen selection study suggested the implementation of the pen ray selection, we use this form of selection for the majority of our pen-based techniques. All of our defined techniques interact with the bounding box of the model.

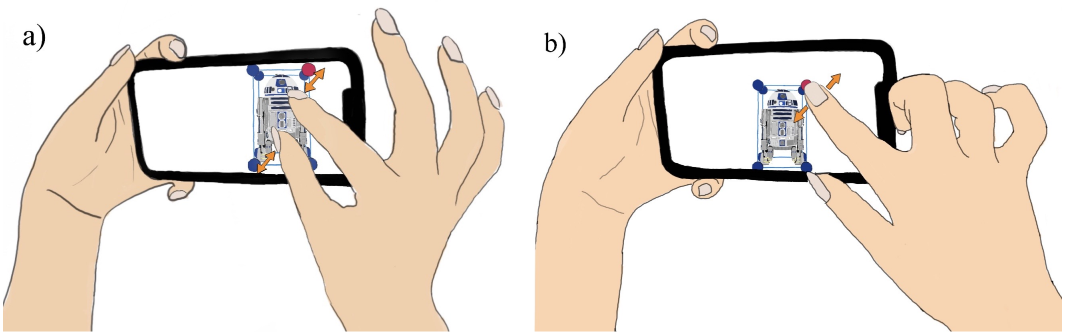


Figure 4.2: Touch-based scaling techniques. a) *Pinch* and b) *Scroll*

4.1 Definition of the Scaling Techniques

We developed six scaling techniques.

In total, we developed six different techniques for the ARPen system: (a) Scaling using a Pinch Gesture (*pinch*), (b) Scaling using a Scroll Gesture (*scroll*), (c) Direct Pen Scaling (*direct pen*), (d) Pen Ray Scaling (*pen ray*), (e) Touch Selection And Pen Scaling (*touch&pen*), and finally (f) Distance Scaling (*distance*).

(a) *Scaling using a Pinch Gesture.* We wanted to include the pinch gesture in our evaluation, as in most literature, this technique was repeatedly used for scaling and claimed intuitive for users. However, we have slightly adapted the implementation from the related work to match our predefined general characteristics. So, users first select a corner on the touchscreen to define the scaling direction. Then they perform a two-finger pinch gesture across the touchscreen to scale the object (see Figure 4.2). The scaling factor is determined by the distance between the fingertips and is applied to the object. An increase in distance implies an increase in size and vice versa.

(b) *Scaling using a Scroll Gesture.* We pay particular interest in evaluating how touch-based techniques perform against pen-based techniques. So, we wanted to include a touch-based technique mirroring the same 'grab&drag' interaction on screen, which we implemented for most pen-based techniques. Users press-hold one finger on the projection of a corner on the screen to select it. By moving their finger, they can carry the selected corner along (see Figure 4.2).

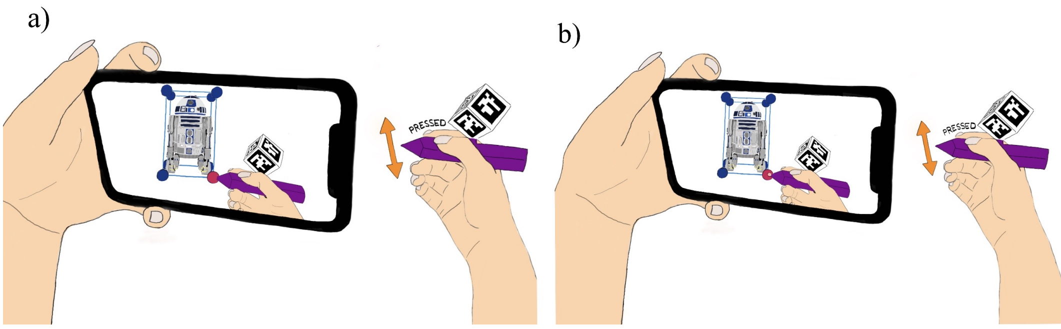


Figure 4.3: Pen-based scaling techniques: a) *Direct pen* and b) *Pen ray*

The size of the object increases or decreases analogously to the movement of the finger on the screen. A movement away from the anchor point increases the size. A movement towards it decreases the size.

(c) *Direct Pen Scaling*. We wanted to adapt the gesture-based metaphor of grabbing a corner to manipulate the object. However, with the ARPen system, we cannot directly interact with an object using gestures. Instead, we use the ARPen for mid-air interaction. Therefore, we implemented a technique where users have to directly grab a corner with the ARPen by positioning the pen tip inside the corner and press-holding one of the integrated buttons. Upon pressing the button, the corner gets selected and is attached to the pen tip. The user moves the pen away from the initial corner position to scale the object up. Moving it towards it scales the object down. To support the users in finding the corner, we provided visual feedback. As soon as they manage to place the pen tip inside a corner, the corner is highlighted.

(d) *Pen Ray Scaling*. As the results of the selection and translation studies with the ARPen favored a method using ray-casting, we also included this scaling approach. Here again, users do not need to place the pen tip inside the corner as it suffices to place it in front of it. Then upon pressing the button, a ray is cast through the pen tip and selects the first corner behind it. The selected corner then mirrors the pen tip's movements, despite the depth offset between pen and corner, and the entire object is scaled.

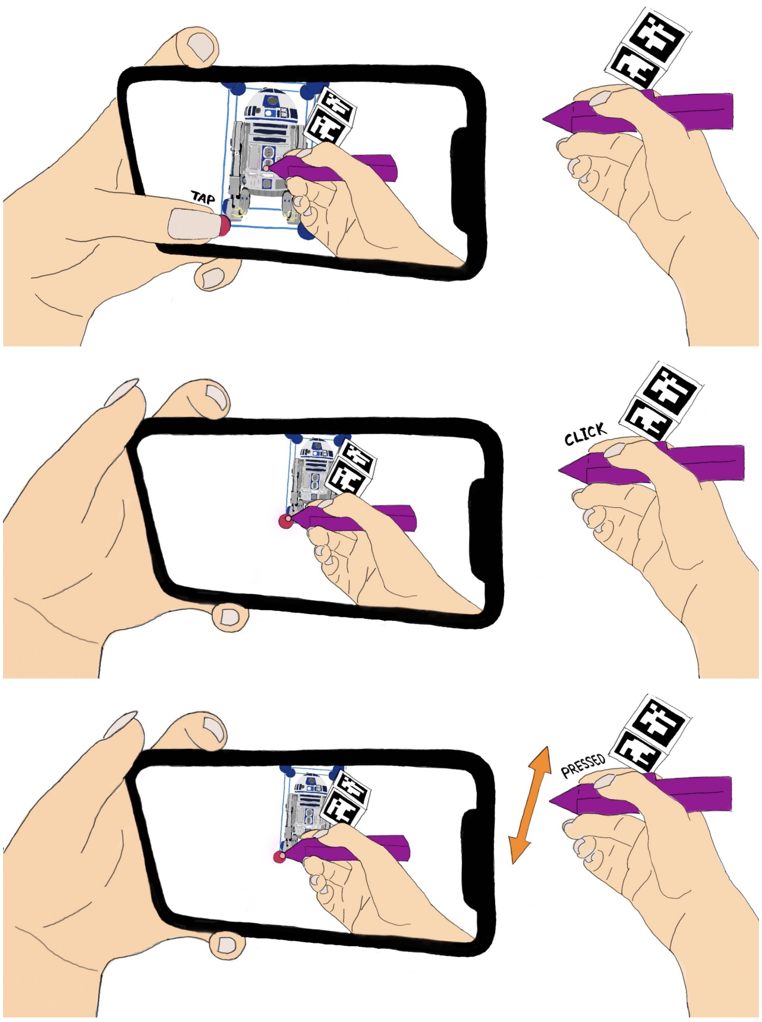


Figure 4.4: Scaling with *Touch&pen*

(e) *Touch Selection and Pen Scaling*. Wacker et al. [2019] encouraged analyzing combinations of the touchscreen and pen further, as implemented for the translation study. Consequently, we also integrated such a combination. Users select a corner by tapping it on the touchscreen. Meanwhile, they can place the tip of the pen at the approximate target location, which they want the selected corner to assume after the scaling operation is completed. Upon pressing the button, the corner jumps to the position of the pen tip. Press-holding the button allows the user to fine-tune the final scale similar to the previous pen-based methods

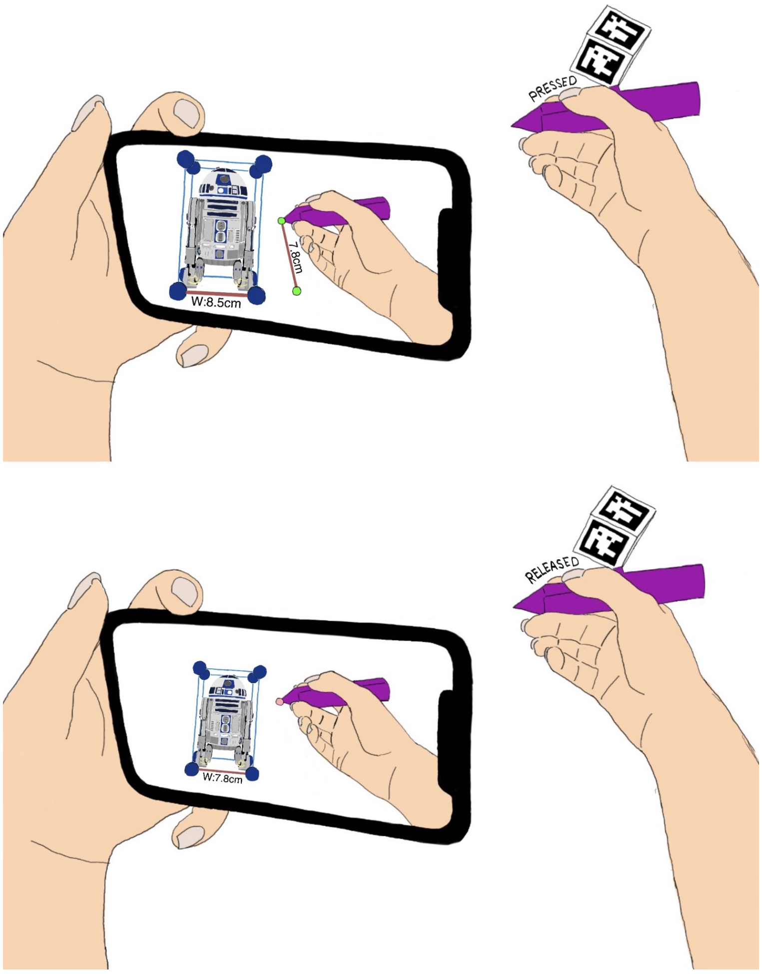


Figure 4.5: Scaling with *distance*

(see Figure 4.4).

(f) *Distance Scaling*. With this technique, we propose a novel attempt for scaling. Initially, the idea was to allow users to define a space within the real world, in which the model should be positioned and fit in. To develop a technique that is still comparable to the previously defined methods and focuses only on scaling rather than scaling and translating the object, we adapted the idea so that the object remains at its initial position and only is scaled corresponding to the defined space. The determined space can only describe one dimension at a time. Therefore, it is essential first to communicate which dimension should be defined by the space. To realize this concept with our system, we use the ARPen for mid-air interaction. Users indicate the target dimension by selecting an edge representing the width, height, or length of the object using the pen ray selection. Then, by holding down an additional button, they can draw a line anywhere in mid-air. On button release, the line disappears and the model is scaled such that the selected edge's size equals the value of the distance, defined by the starting point and endpoint of the drawn line, respectively, the length of the line. The other dimensions are scaled according to the same scaling factor to guarantee uniformity (see Figure 4.5).

Chapter 5

User Study

We have created a plugin for each of our six techniques within the ARPen project. Details about the implementation are provided in Appendix A. This chapter deals with the user study we conducted to evaluate the effects of variant scaling techniques on overall performance and users' subjective preferences. First, we formulate our motivation and goal for the study. Next, we introduce the measurements we recorded. Based on this, we describe the task and study procedure we executed and finally present and discuss the results we obtained.

5.1 Aim

Goal: Identify the most effective and user-friendly scaling technique.

Our goal was to discover the most effective and user-friendly scaling technique for the ARPen system. We defined an effective technique as a technique that allows the user to complete the scaling task quickly and precisely, while not needing to perform many corrections. The technique should be easy to understand and use and meet the user's expectations to be user-friendly. Also, users should not feel mental or physical stress throughout the scaling process and enjoy using the technique. Generally, we want to identify a technique that adequately fulfills its purpose without being unnecessarily complex for the scaling task.

5.2 Measurements

We measured effectiveness through *interaction time*, *deviation*, *scale attempts*, and user-friendliness through subjective ratings.

To measure the effectiveness of a technique as previously defined, we first recorded the *interaction time* in seconds needed to complete the task, i.e., the time between the first selection and the last scaling operation applied to the model. To measure the precision, we recorded the *deviation* in millimeters from the target scale. Additionally, we noted the number of *scale attempts* required. We increased the counter for every scale correction performed. We provided a questionnaire to evaluate the user-friendliness of a technique, amongst other qualities. Our questionnaire (Appendix B "Study Material") is an adapted version of the System Usability Scale (SUS). Therefore, our scores only have a meaning within our study and cannot be compared to scores retrieved from the original SUS. We use the same calculation to obtain a score. First, we compute all item scores. For items 1,3,5,7 and 9, the score contribution is the scale position minus one. Items 2,4,6,8 and 10 are negatively connoted, so the contribution is five minus the scale position. This guarantees all items that a high score is better than a low one. After this, we sum up all item scores and multiply this number by 2.5 to achieve a score range of 0 to 100. Thereby each item's score contribution ranges from 0 to 4. The questionnaire contains ten items that evaluate the techniques' usability, comfortability, and efficiency. Users rate the items on five-level Likert Scales. We chose four items which we analyzed separately in addition to the overall scores:

1) I thought the system was easy to use (*ease of use*)

2) It was exhausting to use this technique (*stress*)

3) I was able to complete the task precisely using this system (*precision*)

4) I found the system unnecessarily complex (*suitability*)

Finally, we asked the users to rank the *scaling techniques* and provide comments.

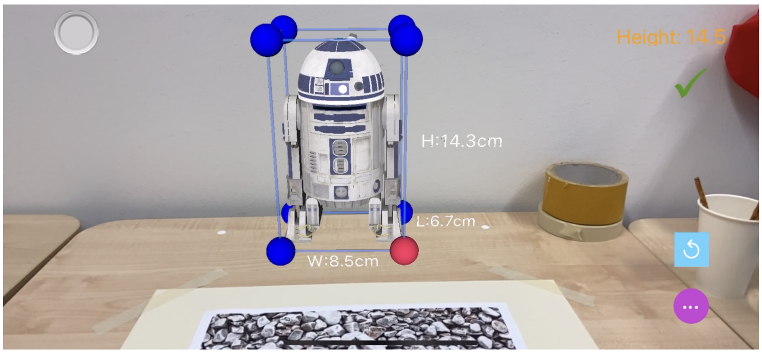


Figure 5.1: User study task and interface. The upper right-hand corner shows the target size and the target dimension. Below is the green checkmark users use to confirm their results and enter the next trial. The blue undo button resets a trial if needed. Users scaled a model, picturing R2-D2.

5.3 Task

We displayed a randomly computed target value and target dimension, i.e., width, height, or length. The participants were asked to scale a model, picturing R2-D2, to reach this target size quickly. The model was thereby positioned in mid-air. We allowed them to correct their results as often as they pleased. Once they were satisfied, they confirmed their results by clicking the green checkmark on the touch-screen. Then the object was reset to its original scale, and a new target size was generated. We recorded six trials of each of the participants. Figure 5.1 shows the interface of the application.

Task: Quickly scale to target size. In total, we recorded six trials.

5.4 Experimental Design

As we wanted to identify each participant's subjective preferences, we used a within-group design for our study. The order of the techniques we counterbalanced with a Latin Square.

5.5 Apparatus

Our study's smartphone was an iPhone 11 with a 6.1-inch (diagonal) multi-touch display. The iPhone weighs 194g and has a size of 150.9mm x 75.7mm x 8.3mm. The camera has a 12-megapixel resolution, while the display has a resolution of 1792 x 828 pixels. It uses the A13 chip from Apple.

5.6 Study Procedure

The study set up included cameras for recording, the ARPen system, and a visual marker on a table to guarantee the same model position and orientation for every participant. Snacks and drinks were provided during the study. To comply with the safety measures during the pandemic, the equipment was disinfected before and after the use of a participant. In addition, the conductor and participants wore masks throughout the study and disinfected their hands at the beginning and the end.

At first, we welcomed the participant and allowed her to take her seat. The smartphone, ARPen, and consent form (Appendix B "Study Material") were already placed in front of her. The participant intently read the consent form, which was additionally explained by the conductor, and signed it. Also, she filled out the first page of the questionnaire. Then the conductor stated the motivation behind the study and introduced the ARPen system. The conductor further explained the interface and the task the participant had to perform. Moreover, the conductor reminded the participant that she could take breaks if she wanted to but could not interrupt a trial. After the short introduction, the conductor set the user ID and the first technique and handed over the smartphone to the participant. The conductor named the technique, explained the interaction and demonstrated the *pinkie grasp*, the participant should hold the smartphone with. The participant could get acquainted with the interaction first as long as she pleased. Once she was ready, she pressed a record button on the touchscreen to leave the training session and enter the first trial. Then she performed the previously defined task. The conductor encouraged the participant to think aloud while she was completing the task. After the last trial, the green checkmark disappeared and the system communicated to the participant that she had completed the first technique. The conductor took the smartphone and asked the participant to fill out the questionnaire for the technique. Meanwhile, the conductor saved the data and made sure that everything was recorded correctly. Afterward, she prepared the next technique. The procedure was repeated for all six techniques. Once the participant completed all techniques, she ranked them. Finally, the conductor interviewed the participant informally and asked her to share her thoughts and provide feedback or improvements.

5.7 Results

In the following, we present the results we obtained through our study. First, we discuss the quantitative data we recorded, which includes the *interaction time*, the *deviation* from the target size, and the total number of *scale attempts* on the one hand. And on the other hand, the items of the questionnaire evaluating the *ease of use*, *stress*, *precision* and *suitability*, we regarded separately. Here, we also present the scores and ranking for the *scaling techniques* we retrieved from the questionnaire. In the second part, we describe the qualitative data we gathered through the participants' comments within the questionnaire or during the interview. For our study, we recruited 24 participants (11 female, 20-26 years, M:21.96, SD: 1.46, no left-handed). As we asked each of our participants to complete six trials for each of the six techniques, we recorded 864 trials. We analyzed all of our variables using repeated-measures ANOVA. The data we analyzed with the ANOVA included one representing value for each of the participants. We averaged the measurements for the six trials to gain this representing value. For the post-hoc tests, we used multiple paired t-tests with a Bonferroni correction.

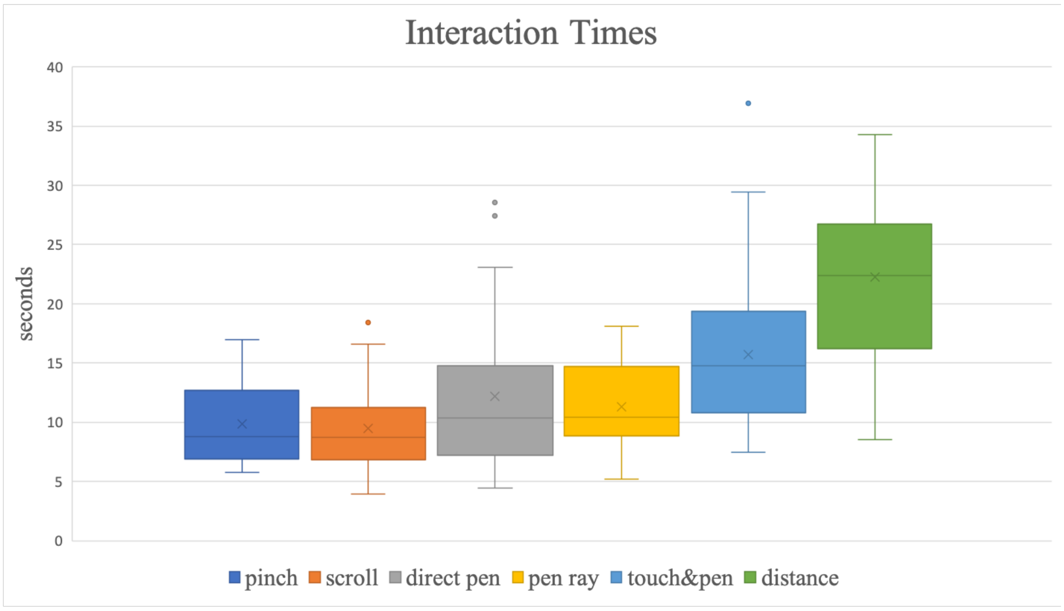


Figure 5.2: Box plots showing the average interaction times. Interaction time describes the time interval measured in seconds between the first selection and the last scaling operation applied to the object. Highest performances are achieved for *scroll* and *pinch* while *distance* requires the longest time.

5.7.1 Quantitative Results

Interaction time. As Figure 5.2 shows, performance is highest for *scroll* (M = 9.47, SD = 3,65) and *pinch* (M = 9.85, SD = 3,26) and decreases for *pen ray* (M = 11.31, SD = 3.58), *direct pen* (M = 12.17, SD = 6.56), *touch&pen* (M = 15.74, SD = 7.05) and *distance* (M = 22.26, SD = 10.49), in that order. The assumptions for sphericity were not met, therefore we used the Greenhouse-Geisser adjustments to correct for violations. The repeated-measures ANOVA shows statistically significant effects of *scaling technique* on *interaction time* (F(3.0, 68.99) = 17.61, p<.001, partial η^2 = .43). Bonferroni-adjusted post-hoc analysis indicates significant differences between *pinch*, *scroll* and *pen ray*, and *distance* and *touch&pen*. There is no significant difference found between *direct pen* and the other techniques except for *distance*.

Pinch, *scroll* and *pen ray* are significantly faster than *distance* and *touch&pen*.

Deviation. *Touch&pen* has the least deviation from the target size (M:0.01, SD:0.03) followed by *pinch* (M:0.02, SD:0.05). *Distance* provides the greatest deviation com-

No significant differences for *deviation* were found.

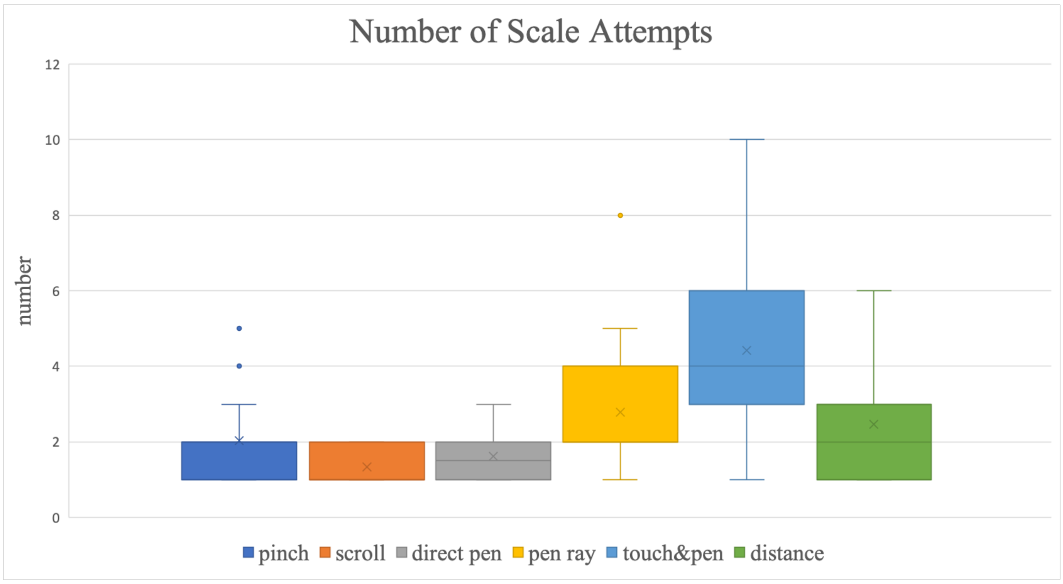


Figure 5.3: Box plots providing the average number of scale attempts. *Touch&pen* needs the most scaling attempts. Numbers for *Pinch*, *scroll* and *direct pen* are best.

pared to the other conditions (M:0.04, SD:0.05). We could not find any statistically significant effect of *scaling technique* on *deviation* (F(3.44, 79.03) = 2.1, p = 0.10, partial η^2 = .08).

Scale attempts. The repeated-measures ANOVA with a Greenhouse-Geisser correction determined that *scaling technique* has a statistically significant effect on measurements of *scale attempts* (F(3.09, 70.95) = 16.07, p < .001, partial η^2 = .41). The subsequent post-hoc tests underline that *touch&pen* requires significantly more corrections compared to all the other techniques. (M:4.42, SD:2,39). *Scroll* (M:1.33, SD:0.48) and *direct pen* (M:1.62, SD:0.71) further have a significantly better performance compared to *pen ray* (M:2.79, SD:1.67).

Touch&pen needs significantly more corrections than all the other techniques.

We tested if there was a correlation between *interaction time* and *deviation*, *deviation* and *scale attempts* or *interaction time* and *scale attempts*. Using the Pearson correlation, we could only identify a significant correlation (p< .001) between *interaction time* and *scale attempts*.

Now we proceed with the results of the questionnaires. We analyzed the first four items of our questionnaire which

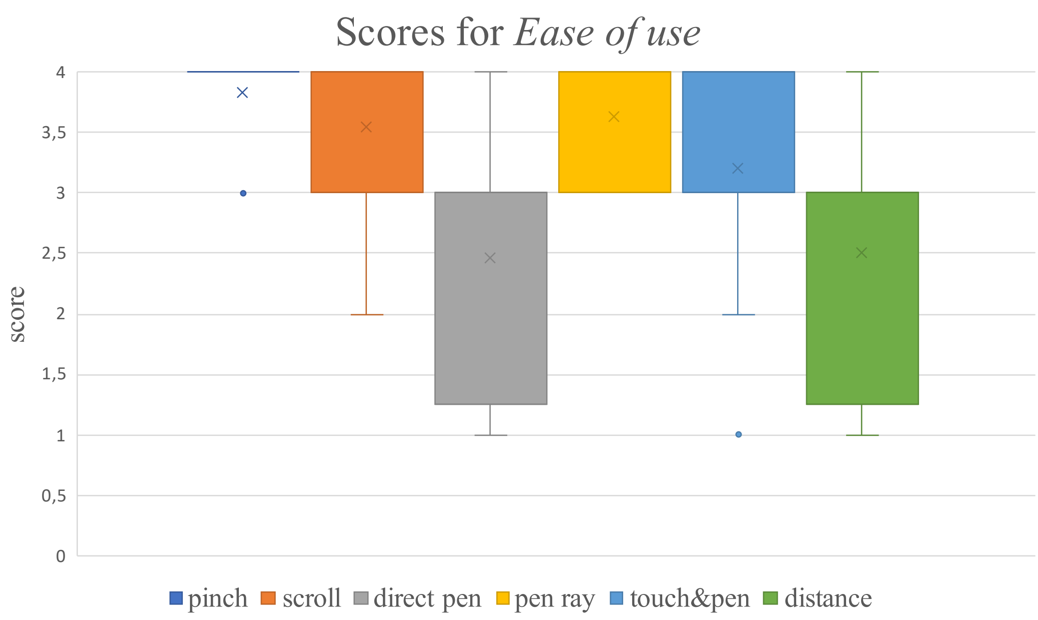


Figure 5.4: Box plots showing the average scores evaluating *ease of use*. *Pinch* is easiest to use, followed by *scroll* and *pen ray*. *Direct pen* and *distance* have the lowest scores.

evaluate *ease of use*, *stress*, *precision* and *suitability* of the techniques, seperately. Again, we used a repeated-measures ANOVA and multiple paired t-tests with a Bonferroni correction.

Pinch, *scroll* and *pen ray* are significantly easier to use than *direct pen* and *distance*.

Ease of use. We corrected sphericity violations with Greenhouse-Geisser and found out that *scaling technique* shows a statistically significant effect on *ease of use* ($F(3.55, 81.6) = 13.79$, $p < .001$, partial $\eta^2 = .38$). The post-hoc tests reveal that *pinch* (M: 3.83, SD: 0.38), *scroll* (M: 3.54, SD: 0.59) and *pen ray* (M: 3.62, SD: 0.5) are significantly easier to use than *direct pen* (M: 2.46, SD: 1.06) and *distance* (M: 2.5, SD: 1.06). *Touch&pen* (M: 3.21, SD: 1.06) shows no statistical difference to any technique.

Pinch, *scroll* and *pen ray* are significantly less stressful than *direct pen* and *distance*.

Stress. Similarly, the choice of the *scaling technique* significantly influences the mental or physical *stress*, participants experienced during the task ($F(5, 115) = 7.57$, $p < .001$, partial $\eta^2 = .37$). The results show that users feel significantly less stressed performing *pinch* (M: 3.54, SD: 0.78), *scroll* (M:

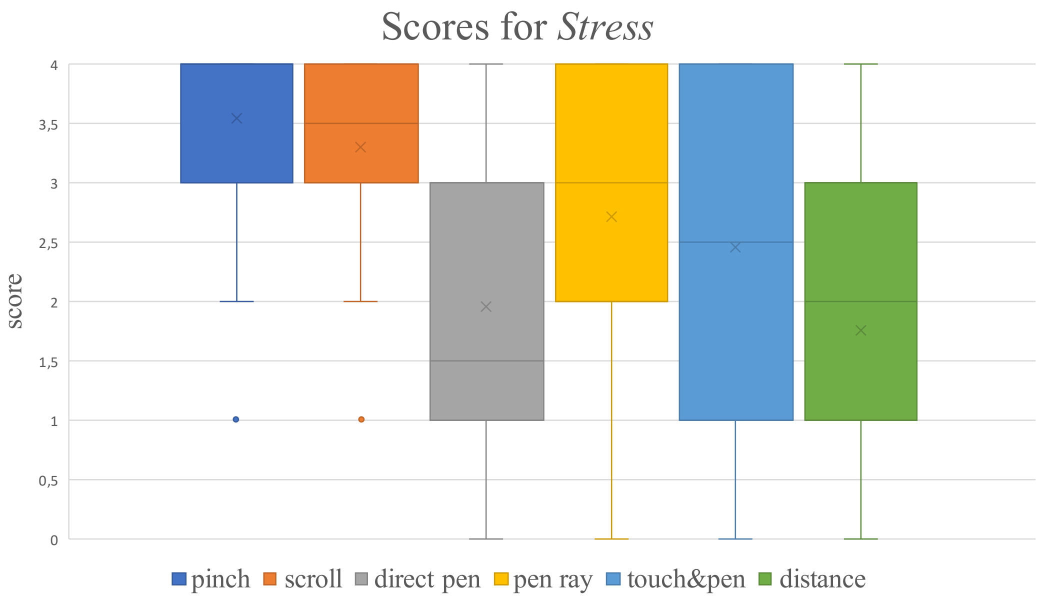


Figure 5.5: Box plots describing the average scores for *stress* (mental or physical). *Pinch* and *scroll* are less stressful than the remaining techniques. *Direct pen* and *distance* cause the most stress.

3.29, SD: 0.86) and *pen ray* (M: 2.71, SD: 1.2) than *distance* (M: 1.75, SD: 1.11) or *direct pen* (M: 1.96, SD: 1.27).

Precision. Though the recorded *deviation* did not show any significant effect for precision, the subjective ratings for *precision* statistically differ between the *scaling techniques* (F(5, 115) = 7.57, $p < .001$, partial $\eta^2 = .25$). The results show that users felt they worked significantly more precisely with *pinch* (M: 3.5, SD: 0.66) than *distance* (M: 2.25, SD: 1.03) or *direct pen* (M: 2.79, SD: 0.93).

Pinch feels significantly more precise than *direct pen* and *distance*.

Suitability. The results state that the participant's perception of a scaling technique to be unnecessarily complex compared to the alternatives, significantly depends on the *scaling technique* performed (F(2.74, 62.97) = 15.27, $p < .001$, partial $\eta^2 = .40$). Users feel that *direct pen* (M: 2.42, SD: 1.25) and *distance* (M: 2.37, SD: 1.31) are unnecessarily complex for the scaling task, whereas *pinch* (M: 3.79, SD: 0.51), *scroll* (M: 3.71, SD: 0.46) and *pen ray* (M: 3.83, SD: 0.38) receive significantly higher ratings for *suitability* than both.

Pinch, *scroll* and *pen ray* are significantly more appropriate for scaling than *direct pen* and *distance*.

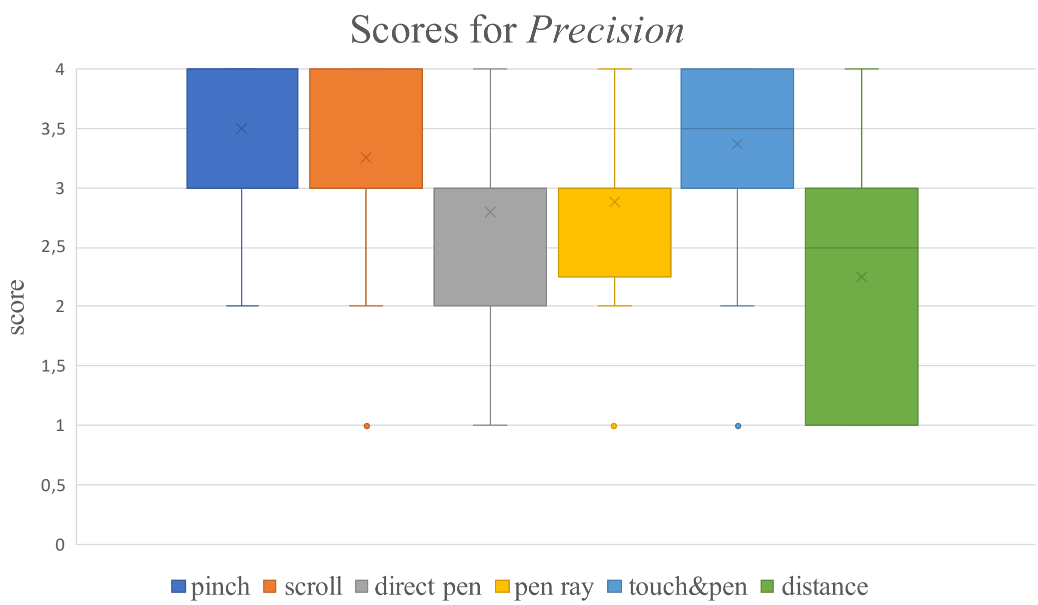


Figure 5.6: Box plots comparing the average scores for *precision*. Touch-based approaches are generally more precise. The highest score belongs to *pinch* and the lowest to *distance*.

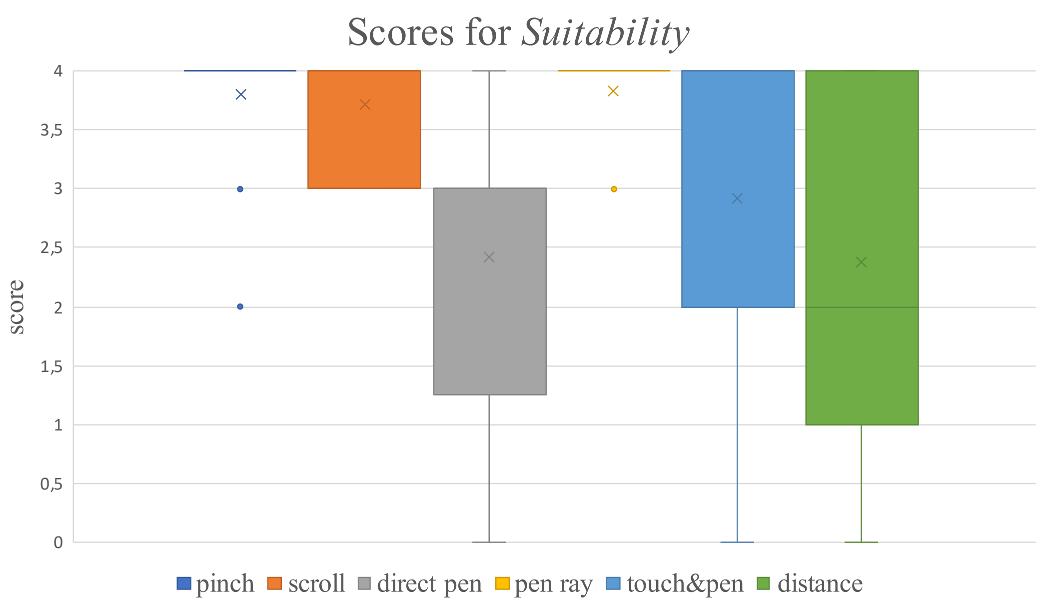


Figure 5.7: Box plots highlighting the average scores for *suitability*. *Direct pen* and *distance* are perceived as unnecessarily complex for scaling, followed by *touch&pen*. *Pinch* and *pen ray* are rated highly suitable for scaling.

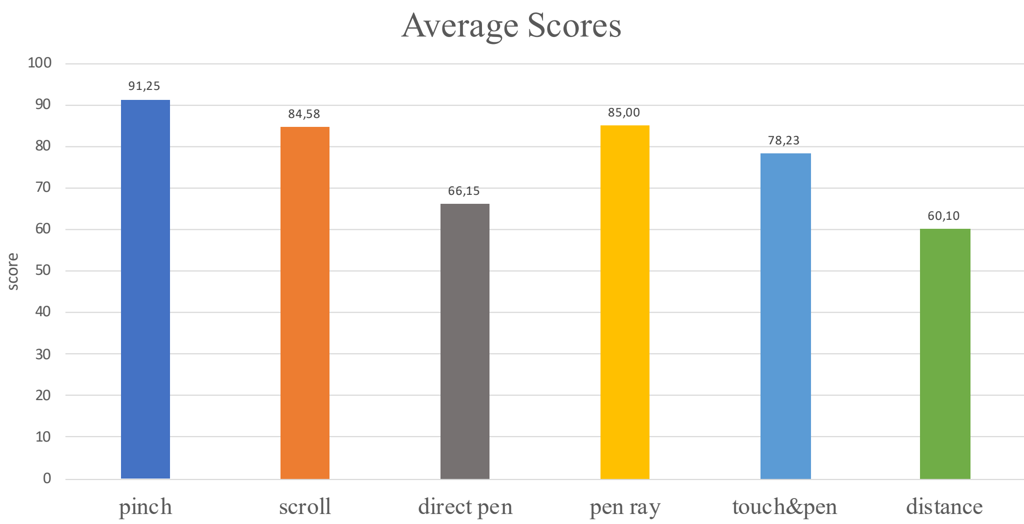


Figure 5.8: Score means calculated from all scores received for each technique. *Pinch* has the highest score, followed by *pen ray* and then *scroll*. *Direct pen* and *distance* receive the lowest scores. *Touch&pen* has an intermediate score.

We computed the total scores from each participant for each technique. Figure 5.8 provides an overview of the score means. *Pinch* receives the highest overall score (M: 91.25, SD: 7.52), followed by *pen ray* (M: 85, SD: 10.27) and *scroll* (M: 84.58, SD: 11.41). The lowest scores belong to *distance* (M: 60.10, SD: 20.5) and *direct pen* (M: 66.15, SD: 20.84). *Touch&pen* has an intermediate score.

Pinch has the highest score, followed by *pen ray*.

Finally, we disclose the ranking of the *scaling techniques*. Figure 5.9 provides an overview of the rank distributions. The results mainly coincide with the scores but do not reveal a clear preference. The majority of participants placed *pinch* and *pen ray* on the first rank. Only a few ever placed *pinch* on the fourth rank or lower. *Pen ray* was also frequently placed on the third or fourth rank but was never placed last. *Scroll* was mainly ranked on the second or third place. *Touch&pen* was more evenly ranked among all placements, but shows a peak for the second rank. Looking at the distributions on the first two ranks, the preferences for *pinch*, *scroll*, *pen ray*, and *touch&pen* seem to be almost equal. The touch-based techniques tend to have a slightly higher preference throughout all ranks. With a decrease in rank position, the occurrence of *distance* increases. *Distance* was

Direct pen and *Distance* rank lowest on user preference.

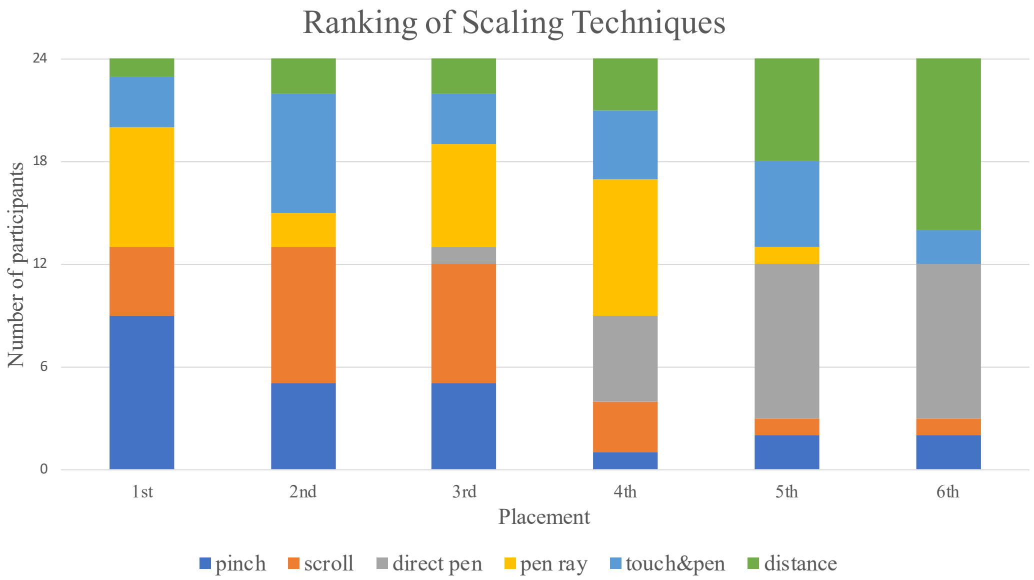


Figure 5.9: Subjective ranking of the scaling techniques. *Direct pen* and *distance* are least preferred. Top ranks do not reveal a clear preference. *Pinch*, *scroll*, *pen ray*, and *touch&pen* seem to be almost equally preferred. Touch-based techniques tend to be preferred slightly more.

ranked last the most. The participants never placed *direct pen* on the first or second rank. Together with *distance*, *direct pen* has the lowest ranking.

5.7.2 Qualitative Results

We proceed with the comments that reached us during the interviews or through the questionnaire and unveil our observations. We provide a summary of the most common remarks about each technique and general pen-based interaction and touch-based interaction. Also, we present improvements proposed by the participants.

Pinch. Participants exclaimed that pinch scaling felt very intuitive to them as they were already used to the gesture from other applications. The majority said that they could work quickly and precisely using this technique. One participant questioned the need for selecting a corner first as she expected a center-scaling when using a pinch gesture.

Scroll. A lot communicated that scrolling felt very intuitive. Still, the issue quite a lot of participants faced was that they struggled to select a corner. Often they thought they had selected the corner, but while dragging it, realized they had not.

Direct Pen. Almost all participants complained that it was challenging to position the pen tip inside the corner for selection. Some shared their concern that this technique would not be efficient from a usability perspective as it forces the user always to stay close to the object and expects a good depth perception. They also said that it consumes much more time to find and select a corner than perform the scaling.

Participants highly struggled to select a corner with *direct Pen*.

Pen Ray. The participants felt much more relaxed using this technique than the *direct pen* scaling. Some claimed that this technique was the best pen-based technique and that they enjoyed using it. Still, there were difficulties in achieving precise results.

Touch&Pen. The opinions about this technique vary among the participants. While some felt that this technique simplified the task as they could perform huge scales with one button click, others did not understand this feature and used the technique like *pen ray*. Due to this, the touchscreen selection felt redundant to them. Only a few participants used their thumb of the hand, holding the smartphone to select a corner. The others always switched their hand from touchscreen to mid-air, as they experienced reachability issues. As a consequence, some of these participants felt annoyed by this repeating switch.

Distance. Except for one participant who ranked this technique as the best technique, all the others had difficulties using it. That participant said it felt like drawing a line on a paper and was therefore very intuitive. Many participants said that the technique was very innovative but not suitable for the scaling task. Few shared that they liked that the scaling was completely independent of the model as they just needed to focus on the line. Others did not understand this technique's purpose if it does not require an interaction with the object. Almost all felt that they could not achieve precise results. Some said it was difficult to select an edge representing the object's depth as it was not always visible unless they adjusted their perspective. They also felt that it was tough to scale the object up to a large target size because they had to draw a long line that exceeded the camera view. So, they were forced to adjust the smartphone's orientation or position while keeping track of the markers' visibility. Therefore, participants complained about physical stress. Most participants were further annoyed that they always had to restart drawing an entirely new line even if they missed the target size by few millimeters.

Touch-based interaction. The participants valued the haptic feedback they received from interacting with the touchscreen. Some said they felt more in control and confident to complete this task and worked much more precisely. Still, others complained about the limited space as they happened to occlude relevant information as the current scale indicators, sometimes. They also recognized the struggle of specifying a precise point on the touchscreen due to the fat finger problem. Besides, few could not interact with the touchscreen well, as they had long fingernails.

Participants were overwhelmed with multitasking.

Pen-based interaction. Participants enjoyed the pen-based interaction more than the touch-based one. Still, after long mid-air interaction and especially after large scale operations, they got a little exhausted. Many participants were entirely overwhelmed by the bimanual nature of the system and struggled with multitasking. They often forgot that the markers had to be visible for the pen to be tracked correctly. So, they had a hard time focusing on keeping the markers in front of the camera and simultaneously scaling the object. Generally, some were not comfortable with the pinkie grasp to hold the smartphone. Another problem they identified was that shaky hands sometimes changed the current scale in the last moment before releasing the button. Consequently, participants felt insecure and frustrated.

Participants suggest the implementation of a precise mode.

Suggestions. Few participants proposed to integrate a precision mode to guarantee precise input for pen-based techniques. One suggested synchronizing the hand movement with the scale updates. That means that as soon as users slow down the movement, more considerable distances cause smaller changes. For example, two centimeters of hand movement does not correspond to two centimeters of scale change anymore but to half a centimeter. Another approach suggested was to use an additional button of the ARPen to signalize the precision mode. Again, within this mode, larger gestures would result in small updates. This way, shaky hands would not falsify the results, they assumed.

5.8 Discussion

We begin with a discussion of the quantitative results presented in the previous section. The scaling techniques scored similar results for deviation. As the participants were allowed to correct their results, they mostly managed to get close to the target size with every technique. Throughout all analyses, *pinch* and *scroll* always scored good results. This indicates the strength of touch-based interaction for scaling. While we recorded a good interaction time and a low rate of scale attempts for *direct pen* as well, this technique scored considerably bad results in the subjective ratings. This inconsistency results from the high selection time required to perform *direct pen* scaling, which we did not record, but which was considered in the subjective ratings and expressed through the comments. As a result, *direct pen* again confirms the difficulties in finding a specific 3D point with reduced depth information through the touchscreen. On the contrary, *pen ray* scaling receives overall good results in all measurements, including the subjective ratings. But *direct pen* needed significantly less scale attempts than *pen ray*. We could argue that this resulted from the participants being closer to the object for selection, as they then tended to rest their arm on the table for the interaction. As a result, they could work more precisely and did not need as many corrections as participants who scaled the object while maintaining distance and without support for their arm. From all the pen-based techniques, *pen ray* scored the best results. This indicates that *pen ray* should be employed for mid-air interaction, as it was already the case for the selection and translation study. Some participants used a strategy for *touch&pen* where they did

Touch-based scaling scores good results.

High selection times for *direct pen* imply difficulties in identifying the correct depth in HAR.

Pen ray scaling should be employed for mid-air interaction.

not use the fine-tune feature but approached the target size step-by-step with button presses, as the selected corner always assumes the pen tip position after each button-press. For this reason, *touch&pen* required an increased number of scale attempts. *Distance* scaling always maintained the lowest scores throughout all measurements. The increased interaction time and scale attempts could have resulted from the lacking possibility to undertake small corrections. Participants always had to redraw the entire line. Additionally, this technique was a novel attempt and completely unfamiliar to all participants. We could argue that the technique might not be suitable for scaling mid-air objects but could receive better results for a different scaling task, e.g., if participants were asked to scale an object to fit between two physical objects. All in all, the quantitative results undermine the strength of the two touch-based techniques and *pen ray*. *Direct pen* and *distance* repeatedly have the lowest scores. Therefore these techniques should not be used for this scaling task. *Touch&pen* has average scores, indicating that the combination of touchscreen and pen offers a reliable alternative but does not surpass the traditional touchscreen interaction. Still, it is the better choice compared to most pen-based techniques, with pen ray as an exception.

Distance could perform better for a different scaling task.

The qualitative results underline the potential of touch-based interaction for scaling. Similar to the related work results, participants exclaimed that *pinch* scaling felt very intuitive to them as they were already used to the gesture from other applications. Participants tend to associate the zooming feature with the scaling of an object. Even though users in related studies exclaimed that a one-finger interaction for scaling is not as intuitive as pinching, our participants liked this technique. Some participants intuitively performed a scrolling gesture once we handed over the smartphone to them. Nonetheless, the results recognize the limitations of touchscreen interaction that we had already identified in chapter 1, such as finger occlusions and the fat finger problem. Participants especially struggled with the selection of a corner using *scroll*. All in all, users still seem to prefer touch-based interaction over pen-based interaction for scaling, though pen-based interaction has an increased fun factor towards touch-based interaction. However, the missing haptic feedback and depth perception difficulties seem to limit quick and precise input.

5.9 Limitations

Unfortunately, a few times, we realized that the record manager failed to record the interaction time properly, showing negative results. Gladly, we filmed the entire study and user interaction to restore the data correctly. If we noticed the issue during the study, we asked the participant to redo the trial. Besides, the application crashed unexpectedly during a record phase, so we needed the participant to repeat the trials of the respective technique. Now and then, the system also had difficulties in tracking the pen tip correctly such that it was not stable on-screen. As a consequence, participants struggled to achieve precise results for these trials.

This study aimed to evaluate the performance of the different techniques and especially compare touch-based interaction to mid-air interaction. The participants sat in a swivel chair with armrest in front of a table throughout the entire study. We observed that they mostly included the properties of the chair and table for interaction. Many participants rested their arm holding the ARPen on the armrest or table and consequently did not feel physically stressed quickly. For *distance*, we observed few participants following a technique, where they drew the line while resting their arm on the armrest and turning within the chair instead of moving the arm. This way, they could easily draw long lines and did not need to put in much physical effort. Therefore, analyzing the techniques with no table and a static chair without armrest could lead to more exact results.

5.10 Conclusion

Considering all these results, we recognize *pinch*, *scroll* and *pen ray* as the most effective and user-friendly techniques for scaling with the ARPen system. All three techniques

We conclude that *pinch* or *pen ray* should be implemented for this scaling task.

generally show good results in all measurements and are favored by users. Among the touch-based techniques, participants struggled more using *scroll* than *pinch*. Therefore we recommend *pinch* as the best touch-based and *pen ray* as the best mid-air scaling approach. On the contrary, *direct pen* and *distance* generally received the lowest results and poor feedback. Therefore these techniques should not be implemented for this scaling task. However, especially *distance* could score better results for a different scaling task, including physical objects.

We put a special interest in comparing touch-based input to mid-air pen input. According to the results, touch-based techniques generally received higher scores than pen-based techniques. Consequently, the implementation of *pinch* over *pen ray* could be recommended. However, considering that the translation and selection study already recommend implementing a similar ray-based technique, we propose to include *pen ray* for scaling with the ARPen as well, as this could simplify compound tasks, including scaling. Furthermore, *pinch* requires users to place the ARPen down for scaling. In compound tasks, including multiple different transformations and frequent use of the pen, this might annoy the user. Nevertheless, a study analyzing this effect needs to be conducted first.

Chapter 6

Summary and Future Work

This last chapter summarizes the key points of this thesis and discusses potential future research topics.

6.1 Summary and Contributions

In this Bachelor's thesis, we presented six different scaling techniques for the ARPen System, which describes a bimanual system utilizing a 3D-printed pen for mid-air interaction. We designed our techniques to use different inputs of this system. Our goal was to identify the most effective and user-friendly technique. Furthermore, we paid particular interest in identifying how pen-based interaction performs against touch-based interaction and what a combination of both input methods would accomplish.

The first section summed up the necessary knowledge to understand the context of our work. We presented the ARPen system and discussed the limitations of handheld AR systems. We then analyzed related work and first looked at existing pen input projects and previous studies regarding the ARPen system, before we identified different gestures that researchers have already implemented for scaling. Based on our findings, we designed six techniques: *pinch*, *scroll*, *direct pen*, *pen ray*, *touch&pen* and *distance* for scaling. We conducted a user study to evaluate the performance. The overall results proved the strength of touch-based techniques towards pen-based techniques in general. The combination of touchscreen and pen provided average results. Throughout all measurements, *pinch*, *scroll*,and *pen ray* scored the best results. Users highly disliked *direct pen* and *distance* for scaling. Considering the overall performance and subjective rankings, we agreed on implementing *pinch* or *pen ray* for the ARPen system. As previous studies using the ARPen system favored pen ray interaction, we would also propose to include *pen ray* for scaling, as this could support compound translation and scaling tasks.

6.2 Future Work

With the knowledge we gained through this thesis, we propose remaining future work on the ARPen system. First, we could integrate participants' proposals regarding a precision mode into the pen-based techniques and conduct an additional study re-evaluating the performance. As we have now evaluated the interaction, we could extend *pen ray* and *pinch* to perform non-uniform scaling.

Now that all fundamental 3D object transformations are evaluated, we require future research to analyze how all transformations can be combined and integrated into the ARPen system to perform compound tasks. Especially, as *pinch* requires the user to put down the ARPen, the performance of this technique and *pen ray* could be re-evaluated for compound tasks to identify whether placing down the ARPen impacts the overall performance or subjective preferences.

In our evaluation we analyzed the scaling of a fixed model in mid-air. Further research should be conducted to evaluate the scaling techniques for additional tasks. This could include scaling the model to fit within a restricted physical space.

Appendix A

Implementation

The complete ARPen project can be accessed on GitHub and encourages interested parties to develop their own modeling techniques. The project's entire code was mainly written in Swift with Xcode as the integrated development environment (IDE). C++ frameworks, including the arUco framework, were imported using Objective-C and Objective-C++. The use of plugins simplifies adding features to the project. Therefore, to implement our techniques, we created a plugin for each of them containing the code for the selection, the scaling, and the user study task. In the following sections, we provide some basic information about the implementation.

As we have already stated at an earlier stage of this thesis, the project benefits from Apple's ARKit and SceneKit. In SceneKit, the scene is structured through `SCNNodes`, which provide useful properties for transformations. To implement the scaling of virtual objects, we utilized its `scale` and `pivot` properties.

We can subdivide the implementation of our scaling techniques into the selection and the scaling process. Upon selection, we need to declare the opposite corner to the selected corner as the scaling anchor point. To achieve this, we utilize `SCNNodes`'s `pivot` property. The `pivot` property describes the transformation between the node's local coordinate system and the one used by its transformation properties, position, rotation, and scale. The scaling process includes the computation of a scaling factor. `SCNNodes`'s `scale` property delivers the current scale of the `SCNNodes` and therewith the scale of the attached model. We calculate the scaling factor by dividing the new height by the old height. Then we apply this scaling factor to the other dimensions. This guarantees uniform scaling. It should be noted that width or length could also be used for computing the scaling factor.

Except for *pinch* and *distance*, all techniques follow the same fundamental procedure:

1. A corner is selected. The user provides touch or pen input and specifies new 3D points while dragging the selected corner.
2. We compute the diagonal of the bounding box that connects the selected corner with the opposite corner.
3. We project each updated 3D input point onto the diagonal using an orthogonal projection. This guarantees smooth interaction and enables the computation of the scaling factor.
4. We can now update all corner positions through the computed point on the diagonal and determine the new height to compute the scaling factor.

For touch-based techniques, we first need to project the diagonal onto the screen and then compute the projection. The computed points on the diagonal are then projected back into the 3D scene to identify the corresponding 3D point on the actual diagonal. Generally, for all techniques, the performance was much smoother if we used screen coordinates.

For *pinch* we determine the scaling factor based on the distance between the fingertips on screen. For *distance* we compute the length of the constructed line and divide this value by the selected edge's original length, to identify the scaling factor.

Appendix B

Study Material

We attached the consent form and the questionnaire, we used during our study to gather subjective ratings on the different scaling techniques.

Einverständniserklärung

Evaluierung der Skalierungstechniken für das ARPen System

STUDIENLEITER	Farhadiba Mohammed Media Computing Group RWTH Aachen University Telefon: (phone) 1234-5678 Email: (email) chat@cs.rwth-aachen.de

Ziel der Studie: Das Ziel der Studie ist es, die effektivste und benutzerfreundlichste Skalierungstechnik zu identifizieren. Die Teilnehmer werden gebeten, ein Objekt auf dem Touchscreen, sowie mid-air zu skalieren. Die Zeit, Anzahl an Korrekturen, sowie die Abweichung zum angegebenen Idealwert werden in der Analyse ausgewertet.

Ablauf: Die Teilnahme an der Studie besteht aus zwei Phasen für jede der insgesamt sechs Techniken. In der ersten Phase dürfen Sie die Technik ausprobieren. In der zweiten Phase wird Ihnen eine konkrete Größe, sowie Breite, Höhe oder Länge angegeben, welche diese Größe annehmen soll. Sie werden gebeten das Objekt auf die Zielgröße zu skalieren. Hierbei werden die Werte aufgezeichnet. Diese Studie sollte etwa eine Stunde dauern.

Nach jeweils der zweiten Phase werden wir Sie bitten, den Fragebogen über die getestete Technik auszufüllen. In diesem Fragebogen werden wir die Bewertung der Technik abfragen.

Risiken/Beschwerden: Es könnte sein, dass Sie die Teilnahme an der Studie ermüdet. Sie werden mehrere Gelegenheiten haben, sich zu erholen; zusätzliche Pausen sind ebenfalls möglich. Es sind keine weiteren Risiken im Zusammenhang mit der Studie bekannt. Sollte die Aufgabe oder der Fragebogen zu anstrengend für Sie sein, können Sie die Bearbeitung sofort abbrechen.

Nutzen: Die Resultate der Studie helfen der Weiterentwicklung des ARPen Systems.

Persönliche Daten: Während der Studie wird eine Bildschirmaufnahme getätigt, sowie eine weitere Bild- und Tonaufnahme von Ihrer Interaktion mit dem System aufgenommen.

Alternativen zur Teilnahme: Die Teilnahme an der Studie ist freiwillig. Es steht Ihnen frei, Ihre Teilnahme zurückzuziehen oder abzubrechen.

Kosten und Entschädigung: Die Teilnahme an der Studie wird Ihnen keinerlei Kosten verursachen. Während und nach ihrer Teilnahme werden für Sie Getränke und Snacks bereitstehen.

Vertraulichkeit: Alle Informationen, die während der Studienphase gesammelt werden, werden streng vertraulich behandelt. Ihre Daten werden nur durch Identifikationsnummern identifiziert. Keine Publikationen oder Berichte aus diesem Projekt werden personenbezogene Informationen über die Teilnehmer beinhalten. Wenn Sie sich bereit erklären, an dieser Studie teilzunehmen, unterschreiben Sie bitte unten.

_____ Ich habe die Hinweise auf diesem Formular gelesen und verstanden.
_____ Man hat mir die Hinweise auf dem Formular erklärt.

Name des Teilnehmers	Unterschrift des Teilnehmers	Datum
	Studienleiter	Datum

Wenn Sie Fragen zu dieser Studie haben, wenden Sie sich bitte an Farhadiba Mohammed unter 01731762451, Email: farhadiba.mohammed@rwth-aachen.de

German Questionnaire ID: ____

Scaling Objects: Implementation and Evaluation of Scaling Techniques for the ARPen System

Geschlecht: ☐ männlich ☐ weiblich ☐ andere ☐ k.A.
Alter: _____
Dominante Hand: ☐ rechts ☐ links ☐ k.A.

Erfahrung mit AR / VR: ☐ keine ☐ wenig ☐ viel
Erfahrung mit ARPen: ☐ keine ☐ wenig ☐ viel
Erfahrung mit 3D Modellierung: ☐ keine ☐ wenig ☐ viel

Mit welchen Geräten/Technologien haben Sie im Bereich VR/AR bereits Erfahrungen gesammelt?

____

Nach der Studie auszufüllen:

Sortieren Sie die Techniken nach Ihren Präferenzen von 1 (beste) bis 6 (schlechteste). Sie dürfen jede Zahl nur einmal vergeben.

Skalierungstechniken:
(a) Pinch - Skalierung
(b) Scroll - Skalierung
(c) Direkte Stift Skalierung
(d) Pen Ray Skalierung
(e) Touch & Stift Skalierung
(f) Punkt Skalierung

Ranking	
1 (beste)	
6 (schlechteste)	

Was gefällt Ihnen an ihrem Platz 1 besser, als an den anderen Techniken?

Technik: **ID: ____**

	Trifft überhaupt nicht zu	Trifft eher nicht zu	Weder noch	Trifft eher zu	Trifft voll zu
Ich fand die Technik einfach zu benutzen					
Es war anstrengend die Technik zu benutzen					
Mit der Technik konnte ich die Aufgabe präzise erfüllen					
Ich fand die Technik unnötig komplex					
Mit der Technik konnte ich die Aufgabe schnell erfüllen					
Ich musste eine Menge lernen, bevor ich die Technik nutzen konnte					
Es hat mir Spaß gemacht die Technik zu nutzen					
Ich habe mich unsicher gefühlt die Technik zu nutzen					
Insgesamt bin ich mit der Technik zufrieden					
Die Technik verhielt sich nicht, wie ich erwartet habe					

Sonstige Kommentare zu der Technik:

Informed Consent Form

(your study name) Evaluating Input Method for Touchscreen Device

PRINCIPAL INVESTIGATOR (The lead experimenter) Chatchavan Wacharamanotham
Media Computing Group
RWTH Aachen University
Phone: (phone) 1234-5678
Email: (email) chat@cs.rwth-aachen.de

Purpose of the study: The goal of this study is to identify the most effective, intuitive and comfortable scaling technique. Participants will be asked to scale an object using touch and mid-air input. We will record the interaction time, the number of scale attempts and the deviation from the target size.

Procedure: Participation in this study will involve two phases for each of the total six techniques. In the first phase, you will be allowed to get acquainted with the technique. In the second phase, a target size and dimension will be displayed to you on the screen and you will be asked to scale the object to reach the target size. In this phase we will record the measures stated above. This study should take about an hour to complete.

After each second phase, we will ask you to fill out the questionnaire about the tested technique. In this questionnaire, we will ask some you to rate the technique.

Risks/Discomfort: You may become fatigued during the course of your participation in the study. You will be given several opportunities to rest, and additional breaks are also possible. There are no other risks associated with participation in the study. Should completion of either the task or the questionnaire become distressing to you, it will be terminated immediately.

Benefits: The results of this study will contribute to the research regarding the ARPen System.

Personal data: During the study, we will video record the screen and your interaction with the system.

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 snacks and drinks for you during and after 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 (PI name) Chatchavan Wacharamanotham at (PI number) 1234-5678 email: (PI email) chat@cs.rwth-aachen.de

English Questionnaire

ID: ____

Scaling Objects: Implementation and Evaluation of Scaling Techniques for the ARPen System

Gender: ☐ male ☐ female ☐ other ☐ N.A.
Age: _____
Dominant Hand: ☐ right ☐ left ☐ N.A.

Experience with AR / VR: ☐ non ☐ little ☐ a lot
Experience with ARPen: ☐ non ☐ little ☐ a lot
Experience with 3D modeling: ☐ non ☐ little ☐ a lot

Which devices/technologies have you already used in the field of AR/VR?

____

Fill out after the study:

Rank the techniques from 1(best) to 6 (worst). Each rank must only be used once.

Techniques:
(a) Pinch Scaling
(b) Scroll Scaling
(c) Direct Pen Scaling
(d) Pen Ray Scaling
(e) Touch & Pen Scaling
(f) Distance Scaling

Ranking	
1 (best)	
2	
3	
4	
5	
6 (worst)	

What do you like better about your first rank compared to the other techniques?

Technique: **ID: ____**

	Strongly disagree	disagree	neither	agree	Strongly agree
I thought the system was easy to use					
It was exhausting to use this technique					
I was able to complete the task precisely using this system					
I found the system unnecessarily complex					
I was able to complete the task quickly using this system					
I had to learn a lot before I could use the technique					
I enjoyed using this technique					
I did not feel confident using the system					
Overall I am satisfied with this technique					
The technique did not perform as I expected					

Comments on the technique:

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