

Integrating Traditional Tools to Support Rapid Ideation in an Augmented Reality Virtual Environment

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(ABSTRACT)

This paper presents a design, implementation, and evaluation of an augmented reality virtual environment to support collaborative brainstorming sessions. We specifically support brainstorming in the form of ideation on sticky notes, a common method to organize a large number of ideas in space with sticky notes on a board. Our environment allows users to integrate physical pen and paper used in a brainstorming session with the support of augmented reality headsets, so that we can support further interaction modes and remote collaboration as well. We use an AR HMD to capture images containing notes, detect and crop them with a remote server, then spawn the detected notes in to enable virtual viewing and manipulation. We evaluate our input method for generating notes in a user study. In doing so, we attempt to determine whether traditional input tools like pen and paper can be seamlessly integrated into augmented reality, and see if these tools improve efficiency and comprehensibility over previous augmented reality input methods.

Integrating Traditional Tools to Support Rapid Ideation in an Augmented Reality Virtual Environment

Tam Phan

(GENERAL AUDIENCE ABSTRACT)

Collaborative brainstorming sessions often involve rapid ideation and outputting those ideas on physical sticky notes with others. We built a virtual environment, IdeaSpace, to support collaborative brainstorming in augmented reality head-mounted devices. To support the activities of rapid ideation and creating notes to express those ideas, we developed an input method for creating virtual note objects for augmented reality collaborative brainstorming sessions. We allow users to use traditional tools like pens and sticky notes to write out their notes, then scan them in using device cameras by uttering a voice command. We evaluated this input method to determine the advantages and disadvantages it brings to rapid ideation in augmented reality, and how it affects comprehensibility compared to existing gesture-based input methods in augmented reality. We found that our pen and paper input method outperformed our own baseline gesture input method in efficiency, comfort, usability, and comprehensibility when creating virtual notes. While we cannot conclude that our experiment proved that pen and paper is outright better than all gesture-based input methods, we can safely say pen and paper can be a valuable input method in augmented reality brainstorming for creating notes.

Dedication

*I dedicate this work to my parents and my grandmother for always keeping an eye on me
and checking in while I worked far from home.*

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Contents

- List of Figures x

- 1 Introduction 1**
 - 1.1 Collaborative Brainstorming and AR 1
 - 1.2 IdeaSpace and Utilizing Physical Traditional Tools 6

- 2 Related Work 9**
 - 2.1 Tangible AR 9
 - 2.2 Collaborative Brainstorming 12
 - 2.3 General Input Modalities in XR 16
 - 2.4 Related Works Conclusion 18

- 3 Design Goals 19**

| | | |
|----------|--|-----------|
| 3.1 | Allow Efficient Creation of Notes to Enable Rapid Ideation | 19 |
| 3.2 | Support Comprehensibility of Virtual Notes | 21 |
| 4 | Software Design and Architecture | 23 |
| 4.1 | IdeaSpace HoloLens Application | 23 |
| 4.2 | Pen and Paper Note Generation | 24 |
| 4.3 | Sticky Note Detection | 26 |
| 4.4 | Remote Server | 28 |
| 5 | Research Method | 30 |
| 5.1 | Baseline Input Method | 31 |
| 5.2 | Experimental Design | 33 |
| 5.3 | Data Collection | 37 |
| 6 | Results | 39 |

| | | |
|----------|--|-----------|
| 6.1 | Task Completion Time | 39 |
| 6.2 | System Usability Scale | 41 |
| 6.3 | Partner-Rated Comprehension | 42 |
| 6.3.1 | External Judge Rated Comprehensibility | 44 |
| 6.4 | Post Experiment Interviews | 46 |
| 6.4.1 | Pen and Paper Input Method is Easier to Use | 46 |
| 6.4.2 | HoloLens 1 System Keyboard Was Troublesome | 47 |
| 6.4.3 | Pen and Paper Input Method Could Result In Blurry Images | 48 |
| 6.4.4 | Summary | 49 |
| 7 | Discussion | 50 |
| 7.1 | Results and Research Questions | 50 |
| 7.2 | Limitations | 52 |
| 7.3 | Design Implications | 54 |

| | |
|---|-----------|
| 7.4 Future Work | 55 |
| 8 Conclusions | 57 |
| Bibliography | 59 |
| Appendices | 65 |
| Appendix A Data Collection Materials and Consent Forms | 66 |
| A.1 User Study Consent Form | 66 |
| A.2 COVID-19 Consent Addendum | 71 |
| A.3 Pre-Experiment Survey | 74 |
| A.4 Partner Ratings Form | 78 |
| A.5 Post-Experiment Interview | 82 |

List of Figures

| | | |
|-----|--|----|
| 1.1 | An example outcome of a physical brainstorming session (Weprin, 2016) . . . | 2 |
| 1.2 | An example online brainstorming session on the platform Miro (Latour, 2020). | 2 |
| 1.3 | Hand gestures used to interact on the HoloLens 1 (Bricknell and Yee, 2020). | 4 |
| 1.4 | The HoloLens 1 standard virtual keyboard. Users point their gaze cursor at keys and perform the tap gesture to click them, with behavior similar to mobile keyboards. | 5 |
| 1.5 | IdeaSpace, with the cork board filled up with virtual notes scanned in with our pen and paper input method. | 7 |
| 2.1 | metaDESK, part of the Tangible Bits project. An instrument used to calibrate scaling and rotation is labelled, as well as "phicons" representing entities on a virtual map application (Ishii and Ullmer, 1997). A passiveLENS (transparent optical lens) is overlaid on the table while an activeLENS (LCD screen) is arm-mounted and movable over the table for viewing. | 10 |

| | | |
|-----|--|----|
| 2.2 | Billinghamurst, Kato, and Poupyrev’s Tangible Augmented Reality project - these Tiles were marker-based augmented reality on physical objects (Billinghamurst et al., 2008). This figure shows usable virtual instruments attached to these physical Tiles. | 11 |
| 2.3 | WordPlay, a tabletop interface that supports ideation and decision making. It utilizes speech recognition or multi-touch keyboard to create the text entities displayed (Hunter and Maes, 2008). | 13 |
| 2.4 | MindMap, a prototype mobile application to support spontaneous brainstorming sessions (Lucero et al., 2010). Users could generate notes in the visualized tabletop workspace and connect to other devices. | 14 |
| 4.1 | The process of creating a virtual note in IdeaSpace outlined as a flowchart. | 25 |
| 4.2 | IdeaSpace architecture. Each user in the Photon Unity Networking Room can send RPC (Remote Procedural Calls) to others in the room, which keep track of movement and manipulation of objects and let us tell other clients to download images from the Flask server. Clients communicate with the Flask server via HTTP request. | 29 |
| 5.1 | An example of our baseline input method. The buttons on the right of the board can be utilized with the Air-Tap gesture. When Create Note is pressed, a virtual note object is generated in front of the user, shown on the left in this figure. | 32 |

| | | |
|-----|---|----|
| 5.2 | Diagram showing how participants rated each others' notes. Authors created the sticky notes, and readers would explain their interpretation of the note. Readers would rate how easy it was to comprehend the note (1), and authors would rate how well they thought the reader comprehended the idea based on explanation (2). | 36 |
| 5.3 | Timeline of each trial and how we recorded task completion time. | 37 |
| 6.1 | Box plots for the average time it took to complete tasks for each respective input method. | 41 |
| 6.2 | Box plots of the average ratings for how easy it was for reader partners to comprehend a note for each respective input method. | 43 |
| 6.3 | Box plots of the average ratings for how well authors of notes thought their partners comprehended their note for each respective input method. | 44 |
| 6.4 | Box plots of the average ratings for how easy it was for external judges to comprehend a note for each respective input method. | 45 |

List of Abbreviations

AR Augmented Reality

HMD Head Mounted Display

VR Virtual Reality

XR Extended Reality

Augmented Reality is a type of experience integrating the real-world environment with virtual objects or enhancements.

Head Mounted Displays are devices worn over the head that display some visual content to the user.

Virtual Reality is fully immersive digitally generated virtual environments that users can view and interact with.

Extended Reality includes all virtual environments and experiences generated by digital devices.

Chapter 1

Introduction

1.1 Collaborative Brainstorming and AR

A collaborative brainstorming session often involves participants writing out ideas on sticky notes and placing them on a physical board to analyze with a group and draw connections from (Kawakita, 1991). Figure 1.1 shows an example of several ideas on sticky notes generated in a traditional collaborative brainstorming session. While users may be comfortable using physical tools alone, augmented reality headsets can be used to improve collaborative brainstorming, bringing valuable benefits to the table.

Firstly, by using a digital computing interface it becomes significantly easier to preserve the environment and all notes taken during a session. Rather than needing to preserve the original notes or take a photo of a board containing the notes, digitally created sticky notes can be stored, loaded, and searched. This allows for individual users to return to the virtual environment and continue where they left off or observe much more easily.

Secondly, there are several limitations with modern remote collaboration which can be addressed with AR. While using physical tools and collaborating over video, the lack of



Figure 1.1: An example outcome of a physical brainstorming session (Weprin, 2016)

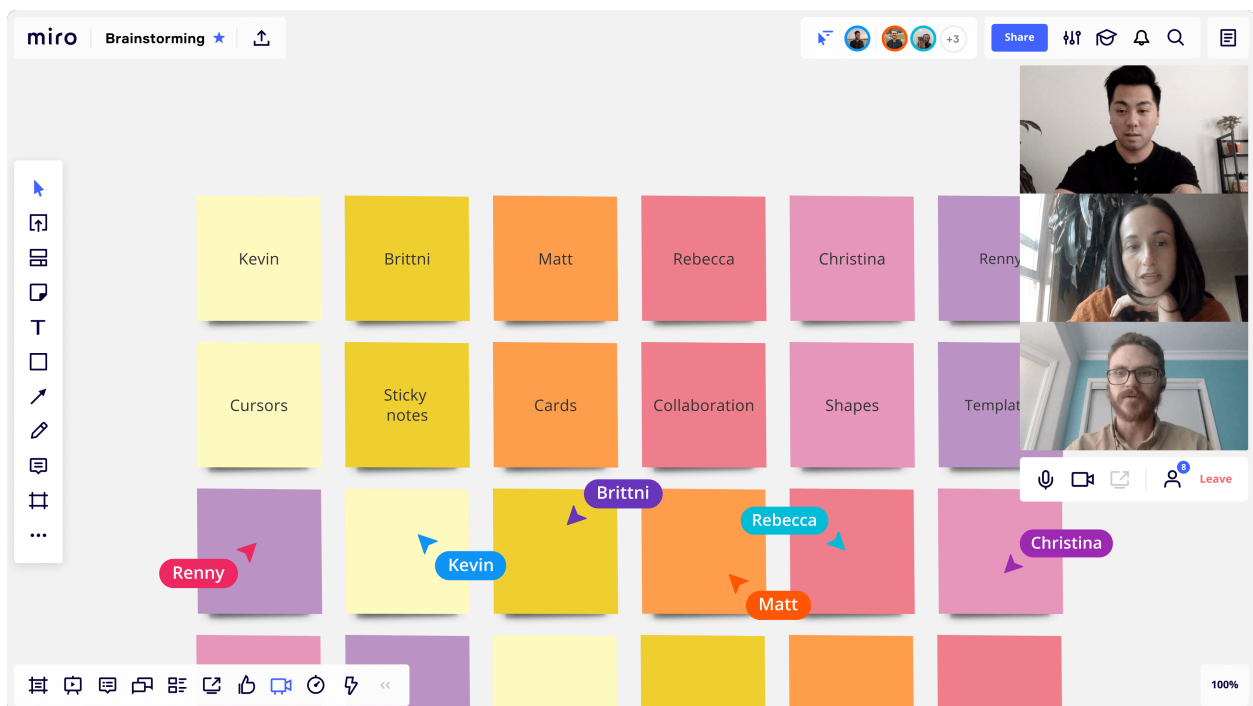


Figure 1.2: An example online brainstorming session on the platform Miro (Latour, 2020).

shared spatial context for remote users makes collaboration difficult (Billingshurst and Kato, 2002). By sharing a virtual environment, each user can fully visualize and interact with notes in their environment, updating in real time for other users as well.

Research has found that collaboration on physical tasks generally involves a number of gestures for pointing at and representing physical objects and interactions for other collocated workers (Fussell et al., 2004). Collaborators cannot gesture directly to others to help show spatial relationships of objects when working remotely. Virtual gaze cues in AR can help to replace pointing gestures that would be used in physical collocated settings (Fussell et al., 2004, Piumsomboon et al., 2017).

Figure 1.2 shows an online brainstorming session, where users utilize a web interface to generate notes. While remote collaboration and visual cues can be supported in this manner, we lose the advantages of 3-dimensional spatiality when interacting over remote video calls (Fussell et al., 2004, Kraut et al., 2002). AR or VR virtual environments preserve our real world spatiality by utilizing immersive virtual environments that users can traverse or interact with 3-dimensionally.

In a VR remote collaborative environment, users can utilize a fully immersive virtual space with others, but not take advantage of their physical surroundings safely. An AR remote collaborative environment improves upon this, as users can utilize the physical environment including physical tools (i.e. pen, paper) and the room itself (Billingshurst and Kato, 2002).

Thirdly, digital interactions can enable users to do much more when interacting with notes than physical interactions. When physically interacting with notes, users have to be

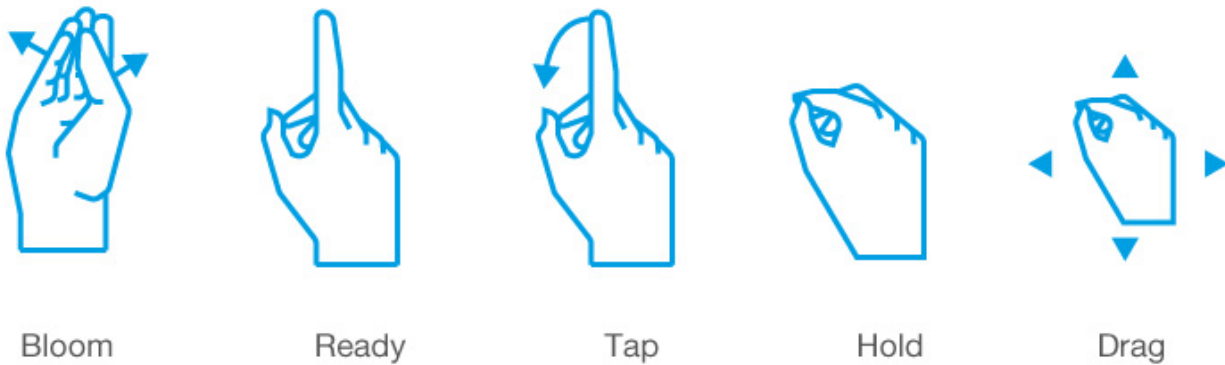


Figure 1.3: Hand gestures used to interact on the HoloLens 1 ([Bricknell and Yee, 2020](#)).

within arm's reach, and distant notes can be harder to read. By utilizing virtual objects in AR, users can resize notes for their own viewing, and distant interactions beyond arm's reach can be performed too. Even unrealistic interactions can be made comfortable and intuitive for users as long as they have a distinct and explainable behavior ([Hilliges et al., 2007](#)).

All of these benefits and more help to build the case for how designing an augmented reality environment for collaborative brainstorming would be useful.

However, input techniques in augmented reality can be slow, hindering the ability to create virtual objects which could impact a collaborative brainstorming session for users ([Lee et al., 2019](#)).

Generally, augmented reality headsets depend on gestures to perform tasks - a popular modern AR headset used in enterprise, the Microsoft HoloLens 1, uses gestures as input ([Mamaylya, 2020](#)). A list of these gestures is depicted in Figure 1.3. Current limitations on hand tracking can make gestures unintuitive to use and can make idea expression difficult,

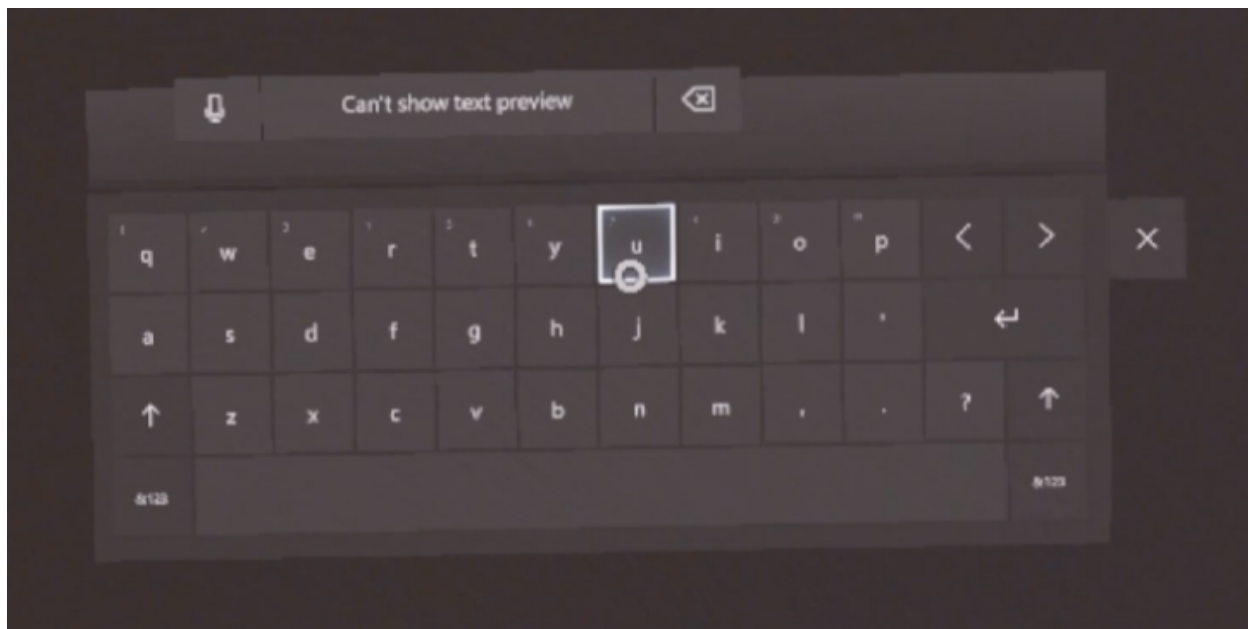


Figure 1.4: The HoloLens 1 standard virtual keyboard. Users point their gaze cursor at keys and perform the tap gesture to click them, with behavior similar to mobile keyboards.

especially when performing tasks that require precise input. To input text for notes and annotations, virtual keyboards are often used - these generally either utilize a cursor or require hand tracking (Lee et al., 2019). Gaze cursor keyboards like the standard HoloLens 1 keyboard are far too slow compared to real keyboards, and hand tracked virtual keyboards suffer from the lack of haptic feedback (Lee et al., 2019). Existing input methods like virtual keyboards are limited to text creation and editing.

Other expressive means like sketching and drawing diagrams are not well supported with these input methods, as opposed to traditional tools like pen and paper. Sketching, a crucial task in collaborative brainstorming and early design stages for products, can be difficult to implement with hand tracked gestures. Freehand 3-dimensional sketching in AR has been explored in earlier research (Dudley et al., 2018). These researchers explored three different input methods, evaluating accuracy and speed, finding that continuous hand-tracked

drawing was the fastest for completing tasks (though not the most accurate). Freehand 2-dimensional sketching, on the other hand, has not seen as much research in AR. While exploration of the use of pen and tablet devices in AR or VR has been a field of research, freehand sketching without additional devices is not well-explored. It is crucial to support 2-dimensional sketching when creating 2-dimensional content like in the form of sticky notes in brainstorming sessions.

1.2 IdeaSpace and Utilizing Physical Traditional Tools

A proposed solution to the augmented reality input technique issue is to integrate physical traditional tools into the augmented reality environment. We designed and implemented IdeaSpace (Figure 1.5), a virtual environment to support collaborative brainstorming in augmented reality integrating physical objects as tools to generate virtual objects. IdeaSpace enables users to participate in collaborative brainstorming sessions using an augmented reality headset with the benefits of digital collaborative brainstorming. IdeaSpace also allows users to use the benefits that integrating physical traditional tools can bring to an augmented reality environment. We implemented a pen and paper physical and virtual input method to accomplish this. Users can write notes using physical pens and sticky notes, and capture them into the virtual environment of the augmented reality headset using voice commands. These notes appear for all users in the same collaborative brainstorming session, and can be manipulated using gestures supported by the HoloLens 1.

In this paper, we present an approach for integrating traditional physical pen and paper into an AR virtual environment. We describe our algorithm and software architecture to



Figure 1.5: IdeaSpace, with the cork board filled up with virtual notes scanned in with our pen and paper input method.

support scanning physical sticky notes into a virtual environment in AR. We then evaluate the effectiveness of this system against regular augmented reality input techniques in brainstorming and ideation tasks.

We answer the following research questions:

RQ1: What are the advantages and disadvantages of utilizing traditional tools as an input method in an augmented reality virtual environment?

RQ2: How does the use of traditional tools help to improve comprehensibility over existing augmented reality input methods (i.e. gestures and virtual keyboard)?

To answer these questions, we present the design and implementation details for IdeaSpace as well as a user study and evaluation for our pen and paper input method.

In our user study we found that our pen and paper input method performed more efficiently, and was more comfortable and easy to learn than our own implemented gesture-based input method. While we could not provide conclusive evidence for whether gesture-based input methods are suitable or not for AR brainstorming, we found that our pen and paper input method performed well enough for AR brainstorming. We also help to provide further design implications for pen and paper input methods in AR.

Chapter 2

Related Work

In this chapter, we present an overview of related literature in HCI research that is particularly relevant to IdeaSpace. This literature helped to influence design decisions made in the development of IdeaSpace. First, we describe related research in input modalities in AR (and VR for further context in virtual environments) to understand how tangible interfaces can be utilized to increase productivity. Then, we provide a brief look at other computing systems built for collaborative brainstorming and problem solving.

2.1 Tangible AR

Our own research explores the benefits of using tangible pen and paper as interfaces for creating content in AR. In this section, we present literature related to input modalities in augmented reality, generally involving tangible physical interfaces for interaction.

In 1997, Ullmer and Ishii presented Tangible Bits, introducing interactive surfaces, coupling of virtual and physical objects, and ambient media for background awareness ([Ishii and Ullmer, 1997](#)). In particular, in one system introduced they introduced, metaDESK,

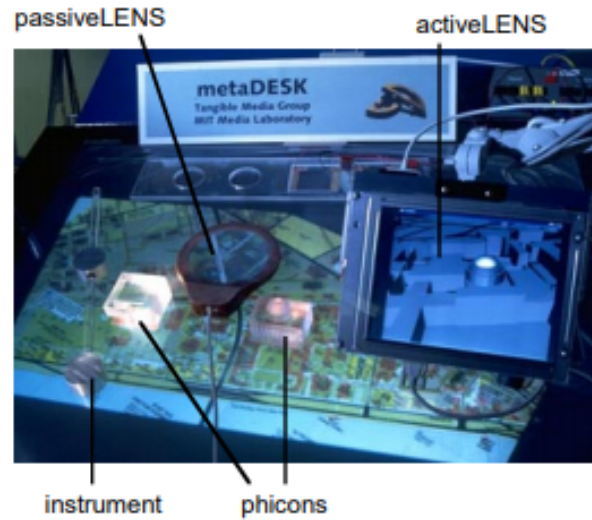


Figure 2.1: metaDESK, part of the Tangible Bits project. An instrument used to calibrate scaling and rotation is labelled, as well as "phicons" representing entities on a virtual map application (Ishii and Ullmer, 1997). A passiveLENS (transparent optical lens) is overlaid on the table while an activeLENS (LCD screen) is arm-mounted and movable over the table for viewing.

virtual objects are instantiated using physical interfaces and have their interaction tied to physical objects as well (Ullmer and Ishii, 1997). The metaDESK system borrows from the GUI (Graphical User Interface) metaphor and translates it to TUI (Tangible User Interface) on a surface. Windows on a desktop are represented by a physical "lens" which can be held, mounted, or placed on a surface. Icons for files are represented with "phicons" or physical icons. Menus and handles on windows are replaced with "trays" and "phandles" (physical handles). GUI controls like scales and scrollbars are controlled via physical instruments. A snapshot of metaDESK running an application Tangible Geospace is seen in Figure 2.1. These systems are generally limited to non-portable interactive surfaces and environments, requiring a number of physical objects to function fully. We build upon their work by using tangible interfaces (pen and paper) and integrating them into portable AR HMDs, and also allowing the creation of novel content with our virtual sticky notes.

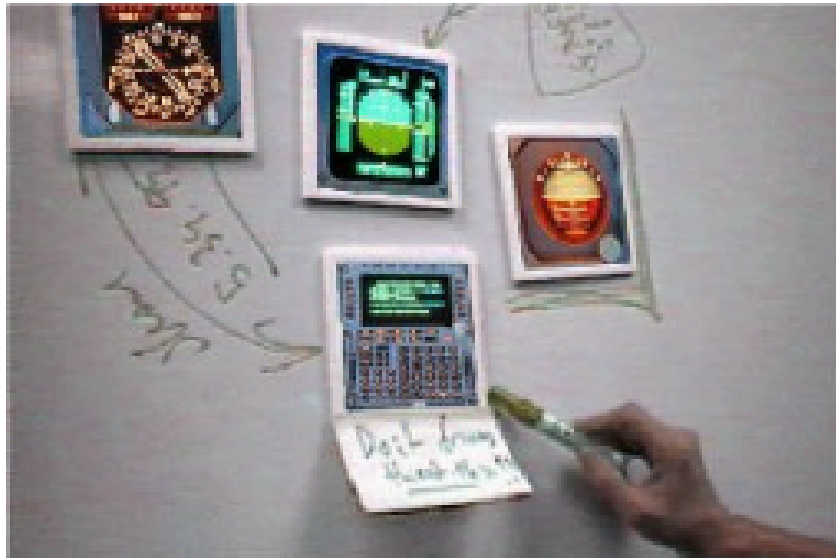


Figure 2.2: Billingham, Kato, and Poupyrev’s Tangible Augmented Reality project - these Tiles were marker-based augmented reality on physical objects (Billingham et al., 2008). This figure shows usable virtual instruments attached to these physical Tiles.

Billingham, Kato, and Poupyrev presented Tangible Augmented Reality, defining design guidelines and prototypes for a mixture of virtual and physical objects (Billingham et al., 2008). They assign a virtual object to a corresponding tangible object for intuitive manipulation. Part of this work was Tiles, where they utilized small cardboard cards with marker-based computer vision as a medium to manipulate virtual objects (Poupyrev et al., 2002). While our system does not currently support the manipulation of virtual objects via physical medium, we could see future work in our virtual environment allowing for these interactions, anchoring virtual notes to the physical notes we used to create them.

Regenbrecht and Wagner presented an augmented reality system MagicMeeting that supports multiple participants manipulating virtual objects via tangible media (Regenbrecht et al., 2002). MagicMeeting was designed to help support meetings discussing product design using 3D virtual models in AR. They integrated the work from Billingham et al’s work for

multiple users and also connected their system to 2D desktop applications ([Billingham et al., 2008](#)). Our work focuses on emulating physical collaborative brainstorming in AR, but the use of 3D models in brainstorming could prove useful in future work.

Mackay and Fayard investigated the use of augmented reality integrated with paper and ink in the workplace ([Mackay and Fayard, 1999](#)). They use physical paper to interface with desktop computers, utilizing video cameras and projectors to translate physical interactions to virtual. Our work is similar in that we put value in the affordances given with paper as a physical medium, and we build further upon their systems with a modern AR HMD to support manipulation and visualization. Rather than augmenting physical reality, in our case, we import artifacts from physical reality to the augmented reality environment as virtual objects. This allows us to manipulate these virtual objects while utilizing our physical affordances as we would traditionally.

Haller et al. developed an augmented tabletop with a digital pen to combine real and virtual information visually, connecting their own personal computers to the server powering their tabletop ([Haller et al., 2006](#)). They similarly focus on brainstorming and early stage ideation with their system, but focus on exploring hardware devices to integrate with an augmented tabletop.

2.2 Collaborative Brainstorming

Our application IdeaSpace was specifically built to support collaborative brainstorming and rapid ideation on virtual notes. In this section, we present literature on collaborative brain-

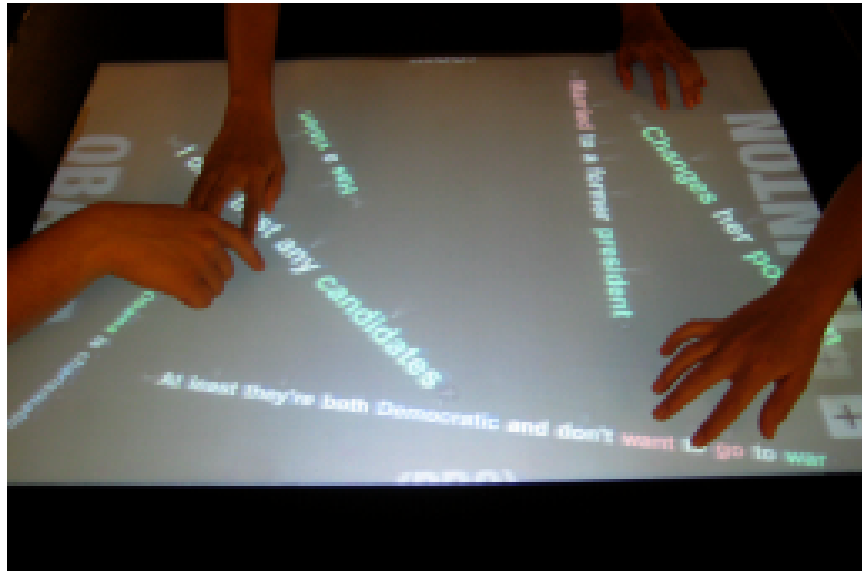


Figure 2.3: WordPlay, a tabletop interface that supports ideation and decision making. It utilizes speech recognition or multi-touch keyboard to create the text entities displayed (Hunter and Maes, 2008).

storming, more specifically the design of applications that help integrate digital tools into collaborative brainstorming sessions.

Hunter and Maes developed WordPlay, a tabletop interface for generation, organization, and exploration of ideas (Hunter and Maes, 2008). For rapid generation of ideas, they utilized speech recognition and a screen-based keyboard. Ideas generated this way could be intuitively sorted around on the tabletop and manipulated with rotation and scaling via touch interface. Our work extends upon this by allowing ideas to include any form of free sketching on notes, and movement using hand gestures with an AR HMD. By including the ability to sketch in our design rather than relying solely on text content, we allow users to reach deeper into the design process, sharing and visualizing potential prototypes in a group.

Lucero, Keränen, and Korhonen built a prototype for MindMap, a mobile application

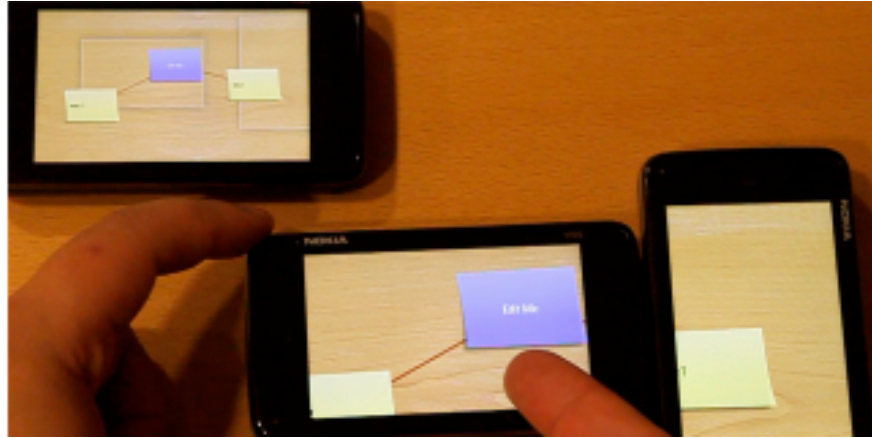


Figure 2.4: MindMap, a prototype mobile application to support spontaneous brainstorming sessions (Lucero et al., 2010). Users could generate notes in the visualized tabletop workspace and connect to other devices.

for spontaneous collaborative brainstorming sessions (Lucero et al., 2010). MindMap is built with mobile phone AR, placing virtual notes onto real tabletops in a multi-user space. Notes were generated via touch screen, where a long press would create a note in that region of the table, and users could type text onto their note. As a mobile AR system, MindMap is quite similar to IdeaSpace, but does not utilize traditional pen and paper tools to generate notes and interactions are performed intuitively for small mobile devices and limited to the space of a table. IdeaSpace on the other hand takes advantage of traditional pen and paper tools in collaborative brainstorming and builds a virtual environment on top of them, with room-scale spatial interactions.

Shih et al. developed GroupMind, a system designed to support collaborative brainstorming in collocated or remote settings (Shih et al., 2009). Designed for tablet PCs, GroupMind allows users to contribute to a single workspace by inserting, editing, deleting, copying, or grouping elements together. With a tablet PC, users can distribute files or images directly from their filesystem or from the web to visualize in the workspace. They combine it with a large shared display to enable collaboration and ensure that users can all

direct their focus to the same element. The ability to distribute files or images from the web in a collaborative brainstorming session is especially of note - future research with AR HMD interaction could consider looking at seamless methods to pull web content into virtual environments for viewing.

Hilliges et al. designed a brainstorming application with an interactive table and wall display, comparing with a traditional brainstorming session as its baseline in a user study (Hilliges et al., 2007). From the results of their experiment, they gathered a set of design guidelines for collaborative creative systems in interactive environments. These guidelines are as follows: pseudo-physicality, meta-physicality, seamless social transitions, and visibility of social interaction.

”Pseudo-physicality” is accomplished through making virtual elements resemble real world objects and the way we interact with them - in our own design, by scanning in physical sticky notes we help to emphasize this physicality (Hilliges et al., 2007).

”Meta-physicality” is the principle that if virtual objects have a distinct and explainable behavior then users will accept and adapt to this behavior despite being unrealistic in a physical environment (Hilliges et al., 2007). In our own application, this is reflected in how we drag the virtual sticky notes around the virtual environment with hand gesture tracking, even across long distances.

”Seamless social transactions” are provided by allowing users to transition between collaborative and individual activities without interruption (Hilliges et al., 2007). Users at any point may scan in or write on physical sticky notes in IdeaSpace, without interruption - while we utilize voice commands to trigger scanning, this is due to limitations in the

HoloLens' available input techniques. Future work involving scanning in physical notes via computer vision and AR HMDs could see other, less interruptive methods to trigger the generation of notes compared to speech input.

"Visibility of social interaction" is the ability to see other users' input actions and output - we provide visual gaze rays and a head representation to show where users are looking, and notes that users create can be instantly seen in IdeaSpace for all users (Hilliges et al., 2007).

Overall, looking at the design considerations that Hilliges et al presented, IdeaSpace manages to meet expectations for all of these on a modern AR HMD platform.

2.3 General Input Modalities in XR

Our work explores general input modalities in AR, including gesture-based freehand input methods. In this section, we present literature related to general input modalities in XR like virtual keyboards and gestures.

Arora et al. explored sketching in VR without use of physical surfaces, but with a digital controller (Arora et al., 2017). They performed two experiments. The first experiment helped them to conclude that a lack of physical surfaces hindered accuracy when sketching in immersive VR. Their second experiment lead them to conclude that additional visual cues could lead to more accurate strokes but can be detrimental to the aesthetic quality. In our work, rather than using digital devices or controllers, we attempt to preserve traditional physical sketching and import these artifacts into virtual environments instead. Drey et al.

also explored sketching in VR, looking at usage of tracked pen and tablet for 3D sketching in virtual environments (Drey et al., 2020). They look at combining 3D mid-air sketching with 2D surface-based sketching. They discovered that each of these were used for different types of tasks - 2D surface-based metaphors were used for drawing lines and flat objects while 3D mid-air metaphors were used for sketching 3D volumes.

Lee et al. explored improvements to virtual keyboards in AR on the HoloLens (Lee et al., 2019). The authors looked at how to reduce screen space of virtual keyboards while still allowing reasonable text entry speeds. Their system, HIBEY, reduces screen space of keyboards by 62.80% compared to the standard HoloLens keyboard while keeping up in words-per-minute efficiency. Chen et al. also looked at text entry in VR, running early pilot experiments comparing VR controller text entry and a touchscreen keyboard text entry method (Chen et al., 2019). They found that the VR controller text entry method was preferable and more performant for their implementation, on average performing at 16.4 words-per-minute while the touchscreen method performed at 9.6 words-per-minute. Knierim et al. explore the usage of physical keyboards in virtual reality, attempting to address the challenge of how real world devices and users' hands may not be visible in immersive VR. They created visualizations of users' hands on their physical keyboard when typing, finding that experts reached similar performance to that outside VR and inexperienced typists only performed 5.6 words-per-minute slower. Our work attempts to compare our own pen and paper input method against existing gesture-based input methods, so understanding some of the state-of-the-art text entry methods in XR and similar research is important for context.

2.4 Related Works Conclusion

Like our pen and paper input method in IdeaSpace, tangible input methods have been utilized for interacting with AR virtual environments or applications in prior research ([Billinghurst et al., 2008](#), [Ishii and Ullmer, 1997](#), [Regenbrecht et al., 2002](#), [Ullmer and Ishii, 1997](#)). Tangible interfaces tend to provide a more familiar, natural way of interaction with virtual objects in AR. However, tools for content creation that involves utilizing tangible physical interfaces like pen and paper are not as well explored as tools for manipulating existing content. Our own work with IdeaSpace attempts to dive into this area, exploring the advantages and disadvantages of doing so with brainstorming as the primary task.

Brainstorming in AR HMDs has not been broadly explored in previous literature. Several systems have been built for newer platforms like tabletop and mobile phone brainstorming ([Haller et al., 2006](#), [Hilliges et al., 2007](#), [Hunter and Maes, 2008](#), [Lucero et al., 2010](#), [Shih et al., 2009](#)). On the other hand, AR HMDs are a more recent platform that enterprise is beginning to adopt and so research should be done for designing platforms like IdeaSpace in AR. Thus, our own research to find input methods to better support rapid ideation is valuable for the future of AR collaborative brainstorming systems.

Chapter 3

Design Goals

In this chapter, we outline the design goals that we used to guide our decision making when building our pen and paper input method in IdeaSpace. With our design, we aimed to preserve the ability to support brainstorming sessions in both digital systems built for this purpose and in traditional physical settings. Thus when creating virtual notes we needed to ensure that these benefits would not be sacrificed and that users could be just as productive in IdeaSpace as they would in either a physical or virtual environment.

3.1 Allow Efficient Creation of Notes to Enable Rapid Ideation

Brainstorming sessions are generally meant to bring out a great quantity of ideas, and a rapid flow of ideas is important to reach this goal. One view of brainstorming sessions looks at them as a mixture of two processes: idea generation and idea exchange ([Wang et al., 2011](#)). Idea generation is a cognitive process, where participants develop ideas by building off of prior knowledge. Concept retrieval from prior knowledge is crucial, and ideas can be inspired by ideas that have been previously exchanged in a session or through other inspirations. Idea

exchange is a social process, where participants express their ideas and share them with their fellow collaborators. The cycle between these processes occurs iteratively, but there are issues that can reduce productivity in a brainstorming session that are a product of the system or method of brainstorming.

One such issue is called "production blocking" (Nijstad et al., 2003, Paulus and Dzindolet, 1993). In common literature, production blocking is defined as the issue of when group members in brainstorming must take turns, causing a productivity loss (Nijstad et al., 2003, Paulus and Dzindolet, 1993, Shih et al., 2009). However, Nijstad, Stroebe, and Lodewijkx found that longer delays between idea generation caused the generation of categorically related ideas to be disrupted (Nijstad et al., 2003). Thus, we would see fewer ideas generated in a session if the delay between idea generation was increased. Therefore, if the idea exchange phase took up too much time, we would see an increased delay between idea generation and thus a decrease in count of ideas generated, indicating a decrease in productivity. In the context of idea exchange here, it can be split further into two parts: generating or writing notes, and comprehending or reading notes.

Thus, since we would like to avoid any hindrances to productivity that may be encountered when generating notes in IdeaSpace, the ability to quickly create notes that are highly comprehensible is crucial to improve efficiency in idea exchange. Existing methods for inputting text in augmented reality (i.e. virtual keyboards) would not be sufficiently fast for our use case (Lee et al., 2019). Time efficiency for freehand AR sketching is not as well explored as text entry in AR. Comparative studies using freehand AR sketching exist, but generally do not have direct comparisons with pen and paper sketching (Dudley et al., 2018). Virtual note objects should be possible to create within only marginally greater time than in a physical traditional collaborative brainstorming session. Therefore, efficiency (time to

create notes) is our first design principle we looked at in our research and optimized for our input method in IdeaSpace.

3.2 Support Comprehensibility of Virtual Notes

As mentioned in the preceding section, idea generation and idea exchange are two primary processes that go into brainstorming sessions. Documenting the idea itself (writing the idea on paper) is a part of idea exchange. Idea exchange can be seen as crucial for sparking ideas in other collaborators when in a group brainstorming session. A creative and well-explained idea can trigger others to pull different ideas from their own memory and apply them to solve the problem ([Siangliulue et al., 2015](#)).

Sketches can help to further explain ideas and diagram them for other collaborators. In AR, sketches without a physical object as guidance can be less accurate than those with a physical surface ([Wacker et al., 2018](#)). When sketching an idea for a group brainstorming session, then, accuracy of sketching should be important so that fewer mistakes are made and ideas are more comprehensible. With an accurate method to support sketching, we hypothesize that ideas will be more comprehensible for other participants in the session, and a result of that will be an improved idea exchange process.

This issue with the level of comprehensibility extends to the limitations of text input in AR. We also hypothesize that participants would express their ideas with significantly smaller bodies of text to describe them if text input was slower via virtual keyboard ([Lee et al., 2019](#)). Thus, a virtual keyboard would not be sufficient for supporting a highly

comprehensible note generation method in our use case.

Thus, our second design principle is to create our input method to support highly comprehensible note generation, to improve the idea exchange process.

Finally, our third design principle was to have the physical notes seamlessly integrated into the virtual environment. We would like to require as simple of an interaction as possible from the user, while retaining the information from the physical notes as best as possible. Overly complex interfaces that would require the user to exert more effort can impede the efficiency of the input method and would make learning to use it more difficult, so ideally having most of the process automated is best.

Chapter 4

Software Design and Architecture

In this chapter we present the software design and architecture that supports our pen and paper input method on the HoloLens device.

4.1 IdeaSpace HoloLens Application

We built the virtual environment for IdeaSpace using Unity version 2019.4 with the HoloLens 1. We utilized the Unity XR SDK and Mixed Reality Toolkit from Microsoft for Unity components and scripts. We utilized Photon Unity Networking for synchronization of objects in the virtual environment. Photon is a library that supports peer-to-peer communication between other users running the same application in the same “room”, similar to a multiplayer server.

Upon starting the application, the virtual environment contains a large, stationary corkboard in front of the user. A sample sticky note is attached to the corkboard in front of the user. An example of the corkboard filled with notes is shown in Figure 1.5. Any user may manipulate the position of the sticky note by grabbing it with the tap gesture (seen

in Figure 1.3) and holding, and the sticky note will follow the motion of the hand while staying perpendicular to the user so that they may view it clearly. Notes can be attached to the board simply by moving them within close proximity, and they will orient themselves parallel to the board for visibility. When other participants join the virtual environment, for all other users a cyan sphere shows their head position and a cyan gaze ray from their head shows where they are looking. Below the corkboard is a "Delete All Notes" button which we implemented specifically for our user study, to remove clutter from the board. Far behind the user is a "Toggle Console" button which us researchers use to toggle the visibility of a TextMeshPro object that shows all debug statements and exceptions (defaulted to invisible).

Figure 4.1 shows the flow of how a virtual note is created in the IdeaSpace virtual environment for all users with our pen and paper input method.

4.2 Pen and Paper Note Generation

To create notes with our pen and paper input method, users first have to create the physical note with their pen and paper as tools. Then, users have to approach the physical sticky note in real life, look at it with their HoloLens headset, and utter the phrase "Capture". When this phrase is uttered, text appears in front of the user, showing a 3-second countdown and then the HoloLens captures an image. This image is converted to a raw byte format then encoded to PNG and sent to a remote server via HTTP POST request. This server handles detecting the sticky note using OpenCV since the HoloLens does not have direct support for using the OpenCV library in Unity. If the sticky note detection is successful (the algorithm for which is described in the following section), a JSON is returned containing the ID of the

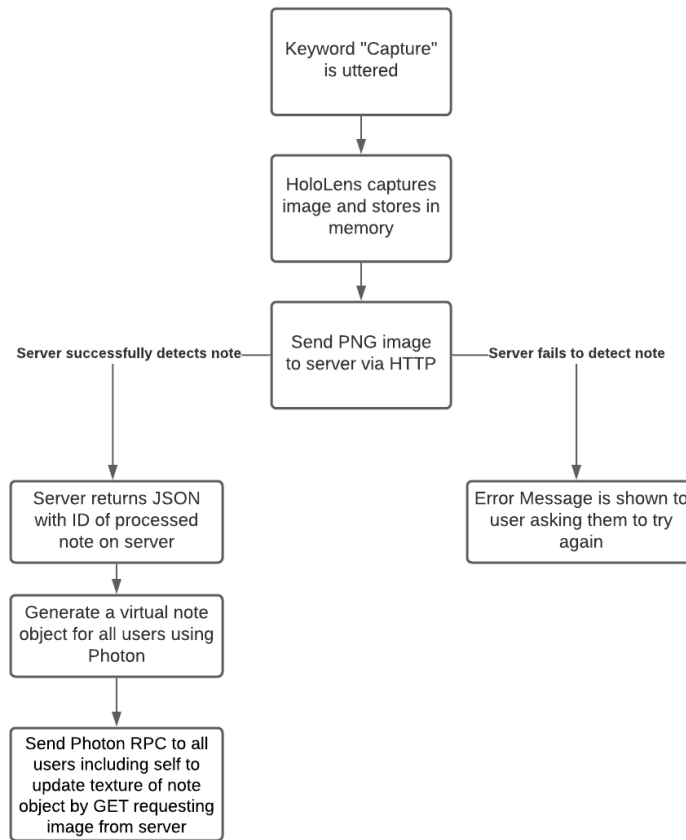


Figure 4.1: The process of creating a virtual note in IdeaSpace outlined as a flowchart.

note in the database on our remote server. Then, a sticky note prefab is spawned in front of the user who captured the note, and the sticky note is updated with the image from the server. If the sticky note detection fails, text appears in front of the user saying that the note was not successfully detected and they should try again.

Our alternative input method for generating notes via gestures is explained in our Research Method section further. It utilizes white canvas boards on the left and right of the virtual environment, which users can sketch on by holding the tap gesture and moving their hand, and also supports virtual keyboard input for text starting from the top of the canvas.

4.3 Sticky Note Detection

To actually detect physical sticky notes in images, we used Python with `opencv-python`, a wrapper hosted via PIP for OpenCV functions containing pre-built OpenCV binaries ([Bradski, 2000](#), [OpenCV, 2021](#)). To detect sticky notes, we pre-process images through multiple stages.

Our algorithm is focused on detecting rectangular or similar objects of a reasonable size, as we direct users to scan in sticky notes at a reasonable enough distance for the HoloLens camera to capture without being unreadable or blurry. Firstly, we resize the image to downsample it so that edge and curve detection later would exclude artifacts.

Secondly, we try to remove shadows from the image. We use an algorithm explained in the top answer in this StackOverflow question ([Mašek, 2017](#)). Basically, we dilate the image with a 7x7 kernel such that we find the image with just the background shadows, then we subtract this image from the original image to negate these shadows. We then normalize the image so that the intensity of the lines in the image is recovered, and threshold the image further to remove any artifacts from the dilation. As an adjustment to the original algorithm, we did this with the image split into its Red, Green, and Blue components (RGB) and then merge the results so that the algorithm works for our colored images.

The next few steps were also gathered from a solution in StackOverflow ([Jones, 2020](#)). We blur the image with a Gaussian filter with kernel size 5x5 to reduce artifacts further. We then run canny edge detection on the image, and find all curves in the image (“contours” in OpenCV) ([Bradski, 2000](#)).

Then, we filter down to polygons between a lower and upper limit on the number of edges, and take up a minimum percentage of the area in the image. In our application, we consider polygons having between 4 and 8 edges in case that sticky notes are creased or not fully flattened against surfaces. We filter generously to polygons taking up 3 percent of the whole image, simply to avoid obvious false positives. We find the largest polygon matching these criteria and crop the image by simply taking the lower and upper x and y bounds of the polygon's vertices. With these lower and upper x and y bounds, we upscale them to the original image size and crop out the sticky note so that the quality of the original image is preserved.

While we considered taking other approaches like utilizing connected components detection or even machine learning object recognition models for object detection, we decided that this model would be the simplest to implement with less edge cases to consider. We could further improve its success rate by setting up our research environment to make scanning successful as often as possible, by utilizing brighter sticky notes with a black poster paper as the backdrop for subjects to place their sticky notes on.

Future work to improve our pen and paper input method could utilize either of the above suggested approaches so that sticky note detection may be more consistently successful in different settings.

4.4 Remote Server

To handle image processing and storage, we used a remote Ubuntu 18.04 server running Python with Flask-SQLAlchemy with PostgreSQL to store our processed notes. To keep the server running throughout all experiment sessions, we used Gunicorn configured with systemd and proxied requests via Nginx ([DigitalOcean, 2018](#)). To hit the server we provided a static URL and port number in our Unity application's code that it would hit. Our server could handle POST requests to different URLs, one to request sticky notes to be processed, cropped and stored, and another for when notes were already processed and simply needed to be stored. The second was used in our application with the baseline input method, as we simply wanted to store the image on the canvas itself without performing our sticky note detection on it so other users in the Photon room could access it.

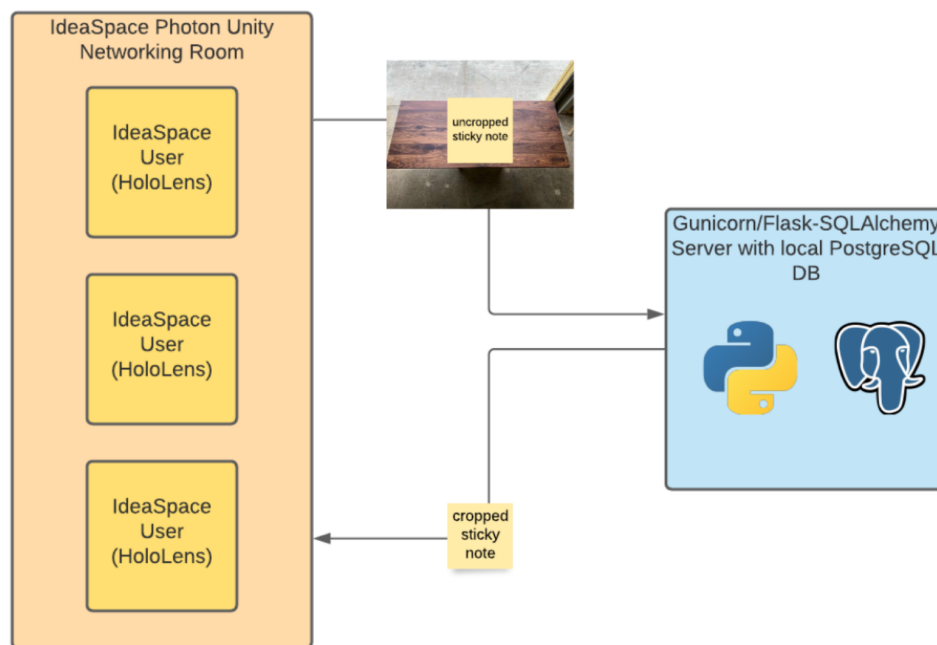


Figure 4.2: IdeaSpace architecture. Each user in the Photon Unity Networking Room can send RPC (Remote Procedural Calls) to others in the room, which keep track of movement and manipulation of objects and let us tell other clients to download images from the Flask server. Clients communicate with the Flask server via HTTP request.

Chapter 5

Research Method

In this chapter we explain our research method, how we prepared our user study and gathered data to answer our research questions.

To answer our research questions, we designed and carried out a user study to determine the accuracy of our hypotheses and evaluate the results. Our goal was to compare our own pen and paper input method against baseline augmented reality input methods, and so in IdeaSpace we also implemented a baseline method for sketching and writing text in augmented reality. With this baseline, users could generate the same note objects that our own pen and paper input method allowed for, and manipulate them the same way as other note objects allowed. We then carried out a user study where we analyzed data within-subject, exposing subjects to both our pen and paper input method and the baseline for real world brainstorming tasks.

5.1 Baseline Input Method

In this section, we describe the baseline input method we implemented to compare with our novel pen and paper input method in IdeaSpace. The baseline input method utilized a canvas plane with UI buttons to the side, where users could access a virtual keyboard to write text on the canvas, and could sketch on the canvas. Users would sketch by using the HoloLens' manipulation gesture to begin sketching with the origin of a line starting at the HoloLens head gaze pointer, and the line would continue to follow the hand position of the manipulation gesture projected onto the canvas plane.

There are 5 buttons that the user interacts with to change the contents of the canvas - Edit Text, Undo Sketch, Clear Text, Clear Sketch, and Create Note. These buttons are interacted with via head gaze raycast and the HoloLens' select gesture. Edit Text opens the keyboard to allow editing of the current text contents (which would display from the top of the canvas from left to right, line by line), Undo Sketch allows the user to undo their last stroke, Clear Text clears all text on the canvas, and Clear Sketch clears all lines on the canvas. Create Note actually generates the note object in front of the user, which would be visible to all users in the session. To avoid having both participants in a session immediately seeing the contents of a note unintentionally when creating the note, we have canvases on both sides of the virtual environment for each participant to use separately.

We considered that connecting a wireless keyboard or drawing tablet to draw content through a web server would be an effective baseline to test against, but we chose to exclude any additional digital devices and limit our input to the HoloLens and traditional tools as general users may not be prepared with these additional devices.



Figure 5.1: An example of our baseline input method. The buttons on the right of the board can be utilized with the Air-Tap gesture. When Create Note is pressed, a virtual note object is generated in front of the user, shown on the left in this figure.

For text input on the HoloLens, virtual keyboards are the most prevalent medium. We utilized the `MixedRealityKeyboard` component in the `MixedRealityToolkit` from Microsoft in Unity. This resembled the standard HoloLens 1 keyboard that would be used in other applications for the HoloLens 1. The text cursor showing where users were currently typing on the canvas would be represented by an underscore (“_”). Users could type text and then close the keyboard using the “Enter” key as we instructed them. Notably, there is an “X” button to hide the keyboard, but we instructed users not to use this key and use Enter instead because a callback function `OnHideKeyboard` in the `MixedRealityKeyboard` component would not trigger when clicking this button to hide the keyboard which would lead to bugs in the application. These instructions were given verbally to participants and also specified on a slip of paper for the users to view during the session, that showed additional tips for using the HoloLens keyboard.

Sketching went through a few iterations. We ran small pilot studies in our lab evaluating

the sketching technique. Our first iteration used gaze-tracking only, following the Microsoft HoloLens cursor, but we found it to be tiring for the user and unnatural. Dudley, Schuff, and Kristensson described input methods for sketching in 3D with the Microsoft HoloLens, and we decided to practically mimic their “Freehand” 3D drawing technique and project it onto our 2D canvas plane (Dudley et al., 2018). We chose this method because of its strong performance in planar drawing, and because it had the greatest speed and comfort questionnaire scores in their study (Dudley et al., 2018). Basically, this input method would require the user to perform a tap gesture to begin drawing a line. This would then track the position of the user’s hand and follow it while drawing the line, until the user performs another tap gesture to stop drawing.

We made a few adjustments - firstly, since we were not attempting to draw 3D objects we needed to project the coordinates of where the cursor and subsequent lines would be drawn onto the 2D canvas plane. Secondly, we required that users hold the tap gesture rather than pressing it once at the start and end of a sketch to avoid user errors that might occur with multiple uses of the Air-Tap gesture on unfamiliar users.

5.2 Experimental Design

In this section, we describe how we prepared our user study and the tasks involved that we used to gather data. We invited community members and students to participate in this study, with two participants per session of the experiment. We gathered metrics from partner evaluations in a brainstorming task, in-application logs and manual annotation of video recordings of the session. We also used a post-experiment interview to gather more

observational information to support our results.

From the pre-experiment survey, we gathered some demographic information. We had 21 participants between the ages of 18 and 24 years old, and 8 participants between 25 and 34 years old. The remaining participants did not fill out this question. 16 participants identified as male, 13 identified as female, and 1 identified as non-binary. One participant did not fill out the question.

The pre-experiment survey included prompts for participants to evaluate their own ability to express and comprehend ideas via sketches and texts. The questions were stated as follows:

1. How would you rate your own ability to express an idea through drawing a sketch? (1 meaning you have difficulty expressing in a sketch, 5 being strong sketching skills)
2. How would you rate your own ability to express an idea through written text? (1 meaning you have difficulty expressing thoughts on paper, 5 being strong writing skills)
3. How would you rate your own ability to comprehend an idea through seeing a sketch? (1 meaning you have difficulty comprehending, 5 being strong comprehensive skills)
4. How would you rate your own ability to comprehend an idea through reading? (1 meaning you have difficulty comprehending, 5 being strong comprehensive skills)

We intended to use this data to make observations within subjects, to help frame their performance in the tasks during the experiment and understand any anomalies in the scoring they receive in the task. The experiment itself consisted of each participant being given a

task, then evaluating the other participant's result in a web form. Participants used both our own pen and paper input method and a baseline input method using a virtual keyboard. The task was to brainstorm an idea to solve a problem that we gave to the participants - these problems were referenced from Teevan and Yu's work ([Teevan and Yu, 2017](#)). We chose to use these problems because of their basis in previous literature as a well-formed open brainstorming question. They are listed below:

Power strip problem - Have a look at the power strip under your desk (participants were shown an image of a crowded power strip instead). How many of its outlets are being used? How many of them would you like to use, but you can't, because a giant power brick (transformer) in the adjacent outlet is blocking it? How could you fit all the different plugs in all the outlets?

Cup problem - When we finish washing cups and glasses, we have to either spread them out individually, but then they take up all the counter space. Alternatively, we can stack them, but then the cups never dry completely and it is hard to separate them from each other later. How can you dry many cups quickly so that they don't take up too much space and moisture doesn't get trapped between them?

Participants were presented with the cup problem and then the power strip problem. We asked them to think of a new idea to solve each problem and create a note with a sketch and text explaining the idea. We asked participants to include both text and sketch when describing their idea because both tasks are crucial in traditional brainstorming sessions and

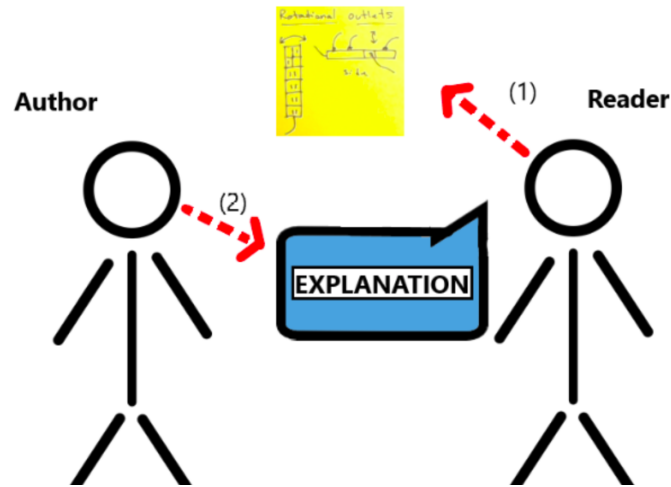


Figure 5.2: Diagram showing how participants rated each others' notes. Authors created the sticky notes, and readers would explain their interpretation of the note. Readers would rate how easy it was to comprehend the note (1), and authors would rate how well they thought the reader comprehended the idea based on explanation (2).

early design phases for describing ideas.

Then, the participants would look at the other person's note, and attempt to comprehend it. We asked them to verbally explain back what their comprehension of the other person's note was. After their explanation, the participants would both answer a question in a web form. The reader was asked to rate the author's note on how easy it was to comprehend on a scale of 1-10. The author was asked to rate how well they thought the reader comprehended the idea that they portrayed on the note on a scale of 1-10. The rating process is further explained in Figure 5.2.

Participants would do this task twice with each input method. The order of the input methods used was randomized (i.e. traditional input method then baseline input method or vice versa), while the problem order was constant. After two rounds with either input method, participants would fill out a System Usability Scale Questionnaire for that input

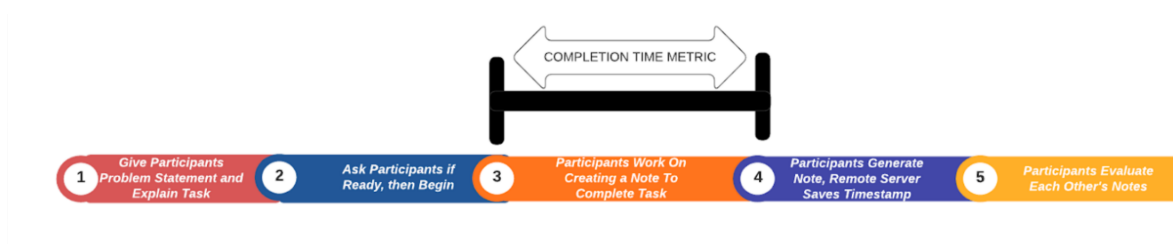


Figure 5.3: Timeline of each trial and how we recorded task completion time.

method as well. Finally, at the end of the entire experiment, a structured interview was carried out with the participants together with the following questions:

1. Which input method did you find more satisfying to use and why?
2. Which input method did you feel was easier to learn and why?
3. Which input method did you have an easier time conveying your ideas with?
4. Did you have any issues with either input method, and if so what were they?
5. Any other questions about this experiment?

5.3 Data Collection

To gather data, we looked at video recordings, our experimental task survey, and the System Usability Scale Questionnaire. We also looked at recordings of the sessions and system logs and recorded the duration that participants spent on performing tasks (explained in Figure 5.3).

When analyzing data, we looked at comparisons between input methods as a whole, and analysis of differences within-subjects. We determined that framing our study within-subject made the most sense since we were comparing our two input methods. By analyzing within-subject, understanding how each individual performed with each of our input methods would be most useful.

After the experiments were complete, we gathered a randomly selected subset of notes created by participants, and created another survey. This survey was similar to the survey given to participants during the study - for each note, we would ask how easy it was to comprehend on a scale of 1-10. We sent this survey out to external judges to fill out for us, and took their responses and used them in our results analysis.

Chapter 6

Results

We collected data from 31 participants. Each participant underwent two trials in the baseline input method condition and two trials in the pen and paper input method condition.

6.1 Task Completion Time

In this section, we analyze the task completion time with either input method with statistical analysis and visualizations. We measured efficiency through task completion time by cuing participants when to start, marking that as a starting timestamp, and recording timestamps when the notes were generated for the task from the log files. We first gathered data points for how long each task took with each input method. Some of the data points had to be scrapped or could not be gathered from the logs. There were a few issues - firstly, the HoloLens device itself would sometimes crash entirely and restart. This error was beyond our control and made trials last significantly longer than they would have had the devices not crashed, so we omitted those points. Another issue was with the video recordings - some video recordings were cut off and did not contain some of the trials and so we could not gather proper timestamps from them. Overall, we gathered 56 trials worth of data with the

baseline input method and 47 trials worth of data with the pen and paper input method.

To actually get these data points, we told the participants exactly when to begin working on the task, with a countdown. We listened for this as the starting timestamp, then looked at the system logs for when notes were generated as the finishing timestamp and verified with the video recordings as well. We then subtracted the starting timestamp from the finishing timestamp and found the number of seconds taken per task in each condition.

We took a few approaches in analyzing this data. We were interested in seeing how performance varied between the two input methods within-subject. Thus, we found the average difference between performance in each input method for each participant. To do so, for each participant we calculated the average time across their two trials in each input method. If we were missing data points for either input method we omitted that participant as there was no way to calculate average time, so we ended up looking at 26 participants out of the 31. We then subtracted the average time it took to complete their trials with the pen and paper input method from the time it took for the baseline input method. We also found the ratio by dividing the average time it took to complete their trials with the pen and paper input method by the time it took for the baseline input method.

Considering the averages of all scores in both conditions, the pen and paper input method took 142.04 seconds less on average compared to the baseline input method. To verify the significance of our results, we ran an independent t-test on the data, comparing all of the times in the baseline condition and in the pen and paper condition. Using a p-value of 0.05, we found that there was a significant difference between the efficiency of each condition with our t-test ($p = 3.85 * 10^{-10} < 0.001$).

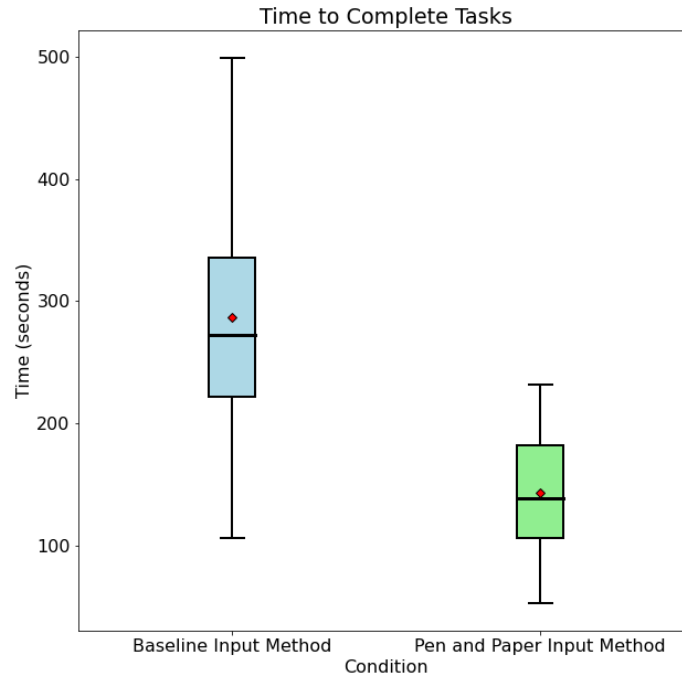


Figure 6.1: Box plots for the average time it took to complete tasks for each respective input method.

The box plots in 6.1 also help to illustrate this relationship, while looking at performance in each condition. This visualization reiterates that the average time to complete tasks with our pen and paper input method is significantly shorter than with the baseline input method.

6.2 System Usability Scale

In this section, we briefly look at the results of our post-experiment system usability scale questionnaire. After each input method was complete (i.e. two trials done), participants would fill out a copy of the system usability scale questionnaire (Affairs, 2013). We introduced this step later in the experiment, so we only recorded ($N = 22$) data points for this metric. Using this usability scale questionnaire, we calculated a score on a scale of 0 - 100 for

the usability of these input methods (Thomas, 2019). For our pen and paper input method, the system usability scale score was 70.79 on average. For our baseline input method, the system usability scale score was 55.23 on average. We performed Mann-Whitney U tests between the System Usability Scale scores for each condition, and found that the differences were significant between each condition ($p = 0.0018 < 0.01$).

6.3 Partner-Rated Comprehension

In this section, we look at the results we collected that would help us to answer our second research question, whether our input method improves comprehensibility over existing methods. We set out to also analyze the pre-experiment survey data where participants rated their own writing and sketching ability and ability to comprehend writing and sketches. However, most participants rated themselves at a 3 (on a scale of 1-5), thus we did not find any meaningful way to split up the data and analyze it. We look at the surveys completed during the experiment, where participants rated each others' notes on how easy they were to comprehend, and how well their partners comprehended their notes. Our surveys were set on a 10-point Likert scale, with the questions shown below:

1. On a scale of 1-10, how easy was it to comprehend the other participant's note? (reader-ratings)
2. On a scale of 1-10, how well do you think the other participant comprehended your note? (author-ratings)

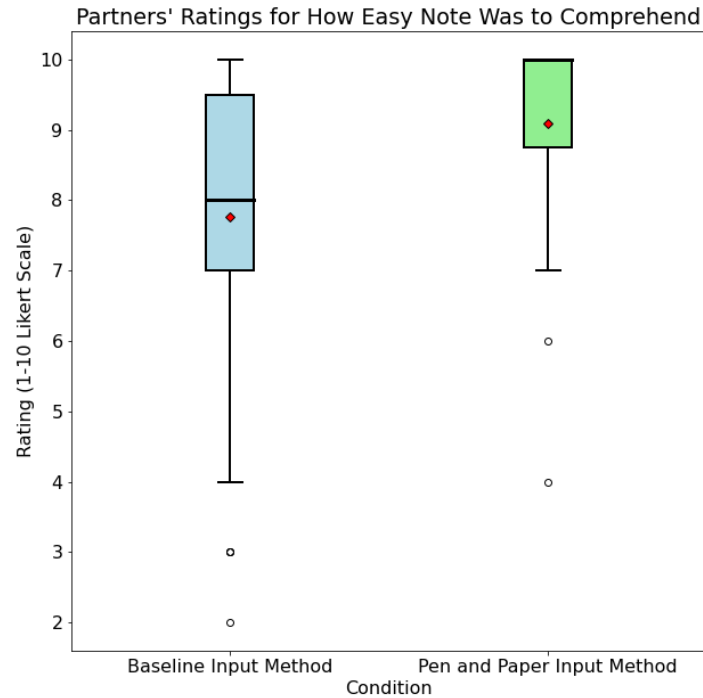


Figure 6.2: Box plots of the average ratings for how easy it was for reader partners to comprehend a note for each respective input method.

For one session, one participant did not show up and so we did not gather these survey results (as they'd need a partner to answer properly). Another session had participants who had to leave early so we lost 2 data points for the pen and paper input method. Overall, we got 22 responses for the pen and paper input method and 24 responses for the baseline input method, for both of the questions above.

For the pen and paper input method, the average score for the reader-ratings was a 9.09, and the average score for the author-ratings was a 9.20. For the baseline input method, the average score for the reader-ratings was a 7.86, and the average score for the author-ratings was a 8.63. These results can be visualized in box plots, with the reader-ratings and author-ratings found in figures 6.2 and 6.3 respectively.

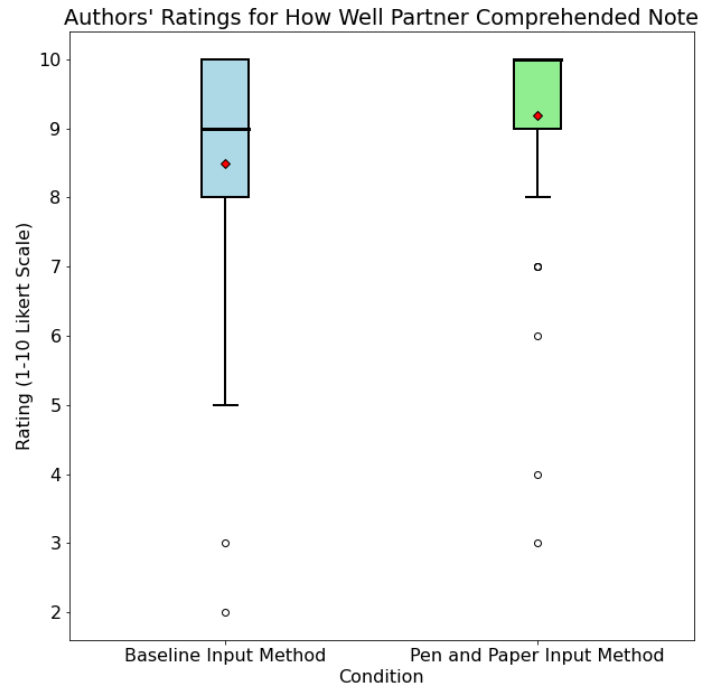


Figure 6.3: Box plots of the average ratings for how well authors of notes thought their partners comprehended their note for each respective input method.

We performed Mann-Whitney U tests between the reader-ratings for each input method (question 1) and the author-ratings for each input method (question 2). We considered a p-value of 0.05 for our null hypothesis. We found that the difference between the pen and paper input method and baseline input method was not significant for self-ratings ($p = 0.0595 < 0.1$). However, the difference between pen and paper input method and baseline input method was significant for partner-ratings ($p = 0.0018 < 0.01$).

6.3.1 External Judge Rated Comprehensibility

In this subsection, we look at the results we collected from our external judges when we compiled a randomly selected subset of notes and created a survey. This survey contained

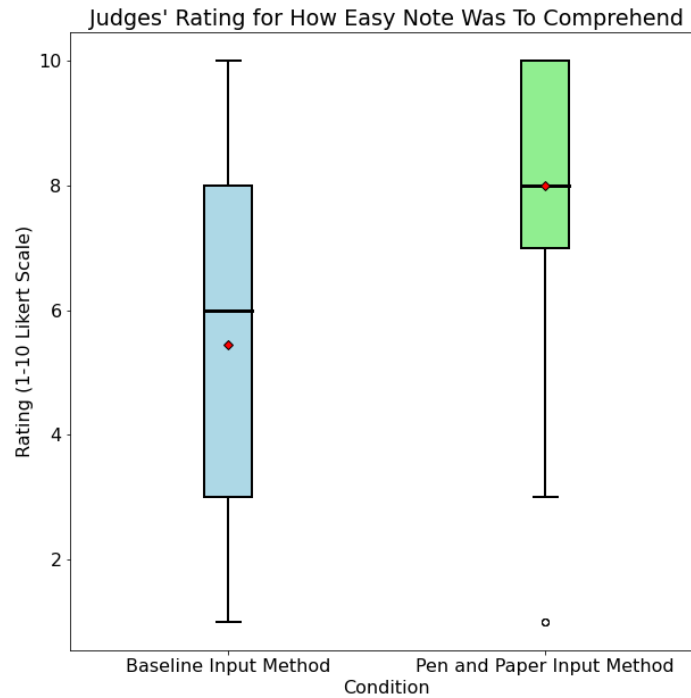


Figure 6.4: Box plots of the average ratings for how easy it was for external judges to comprehend a note for each respective input method.

15 notes in the pen and paper condition and 15 notes in the baseline condition. Note that the survey was not blind, as respondents could easily see the difference between input methods. We had 5 responses to this survey, and analyzed the results in our visualization in Figure 6.4. On average, these results were below the average reader-ratings (when partners were asked to rate how easy it was to comprehend notes). The average score for the pen and paper input method in this metric was a 7.99, while the average score for the baseline input method was 5.44. We ran a Mann-Whitney U test, and found that the difference between the two conditions was significant ($p = 6.87 * 10^{-9} < 0.001$).

6.4 Post Experiment Interviews

From the post-experiment interviews, we gathered some general observations that most participants tended to note.

6.4.1 Pen and Paper Input Method is Easier to Use

Our first, second, and third interview questions asked participants which input method was more satisfying to use, which was easier to learn, and which they had an easier time conveying ideas with respectively. 23 out of 25 participants answered that our pen and paper input method felt more satisfying to use compared to our baseline. The participants who answered otherwise mentioned that their reasoning for saying so was that it felt more fun to draw virtually. Several participants said that the pen and paper input method used writing on paper, something that they were already familiar with, and only added one more step to the process. On the other hand, the baseline method involved using gestures on a keyboard and sketching virtually which most were unfamiliar with. Many participants tended to agree that our baseline method felt slower and more fatiguing to use. Very often, participants would attempt to use the Air-Tap gesture and the device would fail to detect it, without outside intervention helping them to better learn the gesture. Holding up their arms for the duration of the activity ended up being tiring compared to simply writing on physical sticky notes with our pen and paper input method. Here are a few quotes from some of the interviews:

P6: "In terms of having a satisfying feeling, the drawing was fun..."

P8: "It's easier to write with your pen rather than write with your finger." "There wasn't really much to do except say capture..."

P10: "I have X years of experience writing on paper [...] it didn't have the full feature set of pen and paper, and it was slower..."

P11: "It was much easier to write (talking about pen and paper method), but the other one feels much cooler..."

P12: "I loved the AR input, but I'd rather use the sticky note for now [...] for the comfortability..."

P13: "I had less of a headache... (referring to pen and paper input method)"

6.4.2 HoloLens 1 System Keyboard Was Troublesome

Our fifth interview question asked participants if they had any suggestions for ways to improve either input method. Multiple participants recommended an external keyboard be hooked up to the HoloLens device, or a more intuitive virtual keyboard attached to physical surfaces. Text entry involved pointing their gaze cursor at individual keys and performing a gesture, which would sometimes not be detected. Some participants had trouble keeping their head steady and would often mistype a character as a result. Here are a few quotes from the interviews:

P15: "Maybe a keyboard [...] being able to actually type rather than entering keys using the (Air-Tap gesture)..."

P17: "If you could actually type with your hands instead of the hologram... (when asked about ways to improve either input method)"

P27: "We could have voice recording and not convert it to text but put it on the sticky note for playing back..."

6.4.3 Pen and Paper Input Method Could Result In Blurry Images

One significant complaint that we saw about the pen and paper input method was when participants would end up with blurry images. As mentioned with the virtual keyboard, keeping the head steady can be difficult and would result in poorer quality, motion blurred images. The baseline input method is superior in this regard, as a more straightforward system, where what you see on the canvas is exactly what will be output. The delay with the countdown when capturing images and then waiting for computer vision algorithms to compute remotely made retaking the image a cumbersome task to repeat when issues like this came up.

P3: "Maybe have a distance meter or something... if you go too far, it gets blurry..."

P15: "I was looking somewhere else and didn't realize I had to constantly look at my note to capture it..."

6.4.4 Summary

The pen and paper input method outperformed our baseline in almost all of our metrics. Participants completed tasks significantly faster on average with it compared to the baseline. It had a higher system usability scale score, and tended to score higher in our surveys for comprehensibility of notes using each input method (only reaching a significant difference for when partners rated comprehensibility of notes). Participants tended to prefer the pen and paper input method since it only added one more step to the process of creating a physical sticky note. Writing and sketching using virtual keyboard and gestures ended up being fatiguing to participants.

Chapter 7

Discussion

In this chapter, we discuss our results, and talk about limitations in our user study and implementation and potential future work.

7.1 Results and Research Questions

Our goal in this paper was to answer our initial research questions as stated in the preceding chapters and restated below:

RQ1: What are the advantages and disadvantages of utilizing traditional tools as an input method in an augmented reality virtual environment?

RQ2: How does the use of traditional tools help to improve comprehensibility over standard augmented reality input methods?

From our results, we found several pieces of information that help us to answer our first research question. In terms of task efficiency (based on speed), our pen and paper

input method was superior to our baseline input method. By utilizing traditional tools as an input method, an advantage we can potentially see is improvements in performance over existing AR input methods. However, this was when compared to our own implemented baseline, which means that while we have some reasonable evidence for this statement, we cannot absolutely rule out that gesture-based input methods can perform as fast or faster than using pen and paper. Comfort was also superior with our input method, as we saw that participants thought writing on pen and paper was simpler and something they were more familiar with. In contrast, our gesture-based writing and sketching input method ended up causing more fatigue for users and issues with holding the HMD steady made input difficult. A disadvantage that we could see with our pen and paper input method was mentioned from participants in the post-experiment interview: images didn't always come out clearly. Using the camera to capture photos ended up with blurry images for some participants as keeping the AR HMD steady could be difficult.

Our pen and paper input method resulted in notes that tended to have a higher comprehensibility rating from other users in our experiment, and from external judges in our later survey. The post experiment interviews mentioned that it was much faster to write text on physical notes than virtual keyboard input, and sketching was much easier with pen and paper compared to gesture-based sketching. The system usability scale questionnaire score for our pen and paper input method was also greater than our baseline input method. These were likely a major factor in why notes were more comprehensible, and also shows that our pen and paper input method improves comprehensibility as participants felt both writing and sketching were easier on pen and paper.

7.2 Limitations

A significant limitation with our work and trying to compare with existing AR-based input methods was our technology.

The HoloLens 1 has a very small field of view for rendering objects. This may limit immersion in the virtual environment compared to a physical brainstorming session, as virtual objects needed to be within this field of view to be seen. One result of this was that we often had users "lose" the notes and have to find them again with this limited field of view, something we would not see in a physical brainstorming session.

Another large limitation that also restricts what we can conclude from our research was our baseline input method. While we did iteratively improve this interface for usability so that our participants could utilize it as best as possible, we cannot for certain say this represents the state-of-the-art in gesture based input methods. There are many UX improvements that could be made to our baseline input method, or other undiscovered possibilities for gesture-based input methods that could perform better. Several potential issues with our baseline could be brought up and improved - for example, the thickness of the lines was not adjustable when sketching and the text entry was limited to being positioned on the top of the notes. These limitations alone make it so that we cannot use our results with the baseline input method to prove that gesture-based methods are unsuitable for brainstorming.

An additional limitation with our user study was that we asked participants to use both text and sketches when creating notes in both input methods. We wanted to evaluate both text entry and the ability to sketch as both are crucial in early design phases and

brainstorming, but constraining participants to perform both does not reflect the reality of brainstorming sessions. In future experiments, isolating text entry and sketching processes would be better for understanding the differences between pen and paper and gesture-based methods in both tasks.

Another issue is the general mode of interaction with the HoloLens 1: users must point their gaze cursor at objects of interest, and perform hand gestures within view of the device cameras. This disadvantage made performing gestures difficult for participants in our user study, and not as intuitive as they may be in well hand-tracked environments. Users that had shakier heads struggled much more with the virtual keyboard and virtual sketching because of this.

Another significant limitation was the number and demographic of participants. Almost all participants had no familiarity with the HoloLens or any AR headset in general, so they had to entirely learn how to perform gestures during the session. This had a significant effect on results with our baseline input method, as we saw in recordings participants had difficulty in moving around virtual notes or drawing or typing. If we could have run the user study longer and with more participants that were familiar with AR HMDs, we could find more interesting information about how gesture-based methods perform when users are already familiar with gestures.

One final limitation of our experiment was imposed by the COVID-19 pandemic and conditions surrounding it. Our user study was only able to handle two participants, and had to have a particular format to allow us to gather data. This made it so that our experiment was far more structured, rather than allowing us to really create a virtual brainstorming session in IdeaSpace. If we could have worked with a larger group, then we could see how

a real collaborative brainstorming session may actually work in IdeaSpace. Then, we could more intuitively see how comprehensibility and efficiency vary for participants when given a task for brainstorming in general rather than in our structured methodology.

7.3 Design Implications

In this section, we describe some of the design implications we discovered during our user study and while designing our pen and paper input method.

Firstly, our own implementation only captured a single image and checked for whether it contained a sticky note. This made it so that the likelihood of a false negative and error rate would be higher, compared to if we took several images. Future implementations of our system or any pen and paper input method could consider taking several pictures and searching among all of them for sticky notes.

Another useful improvement would be to allow users to utilize other surfaces like whiteboards or regular paper for generating notes. Since our implementation was limited to computer vision detection of sticky notes and cropping them from images, it would not function properly on other types of surfaces - approaches like marker-based detection could be useful here.

Another discovery we found during our experiments was that often, participants would lose track of their notes when they were generated. The notes spawned in front of the user when they were successfully detected, but with a limited field of view on the HoloLens they

could be lost easily. Stronger visual cues for when generating virtual content from physical pen and paper should be a necessity.

Finally, our UI for the pen and paper input method was not very thorough - we simply displayed text prompts to the user telling them they'd begun capturing notes. More assistance for users to provide good quality images when scanning in physical notes would help to reduce the amount of false negatives and error rate.

7.4 Future Work

Collaborative brainstorming in AR HMDs is an under-explored area and leaves much room for further research and experiments that could use IdeaSpace.

Using the HoloLens 1 ended up being difficult and restrictive due to the mode of interaction. Implementing input methods on newer devices that have superior hand tracking like the HoloLens 2 could end up having different results where perhaps traditional tools don't improve performance.

Another interesting field to research is how to generate virtual notes in fully immersive VR environments. Our work takes advantage of the physical environment and traditional tooling, but immersive VR may not have these capabilities. Determining the best way to support rapid ideation in an immersive VR collaborative brainstorming environment would be an interesting field for research.

Also, this experiment doesn't help to prove the value of the advantages an AR collaborative brainstorming session has over other settings. Implementing a way to serialize and deserialize the virtual environment, offering remote communication without other technologies, and improving virtual interactions with notes could be possible paths to explore in AR brainstorming. Experiments could be done in the future comparing our own system against physical brainstorming sessions and virtual brainstorming sessions on other platforms. These could help to understand what benefits of both physical and virtual brainstorming sessions that AR collaborative brainstorming could bring, or any disadvantages that come with the platform.

Chapter 8

Conclusions

This paper helps to explore how we can support collaborative brainstorming with AR HMDs. We design an input method integrated with traditional tools to allow for rapid ideation and ease of access. In doing so, we asked what the advantages and disadvantages of doing so were, and how comprehensibility may be affected by this method, in comparison with freehand gesture-based input methods. To answer these questions, we conducted a user study to gather data and make observations.

We found that our input method improved task efficiency (speed to complete tasks) significantly. Users in our experiment also tended to complain more about comfort when using our gesture-based input methods than our own pen and paper input method. Our pen and paper input method scored higher in a basic system usability scale questionnaire as well, and notes created with it tended to be more comprehensible than those with the gesture-based input method. Users tended to also state that the pen and paper input method was easier to convey ideas with than the gesture-based input method, and so comprehensibility was superior with it. A disadvantage of our input method was with issues like blurriness of images as a disadvantage compared to WYSIWYG gesture-based input methods. Further exploration could be made with other technology like the HoloLens 2 for exploring how devices with better gesture input may have improved performance.

We must express caution in assuming that pen and paper is outright superior to gesture-based input methods in general - we only had our in-house implementation of a gesture-based input method to compare to, and there is absolutely room for improvement there. However, we feel that it is safe to say that pen and paper is a viable input method for support rapid ideation, with the metrics we gathered for our pen and paper input method in terms of efficiency and comprehensibility, and in qualitative observations in comfort and ease of learning.

In conclusion, while collaborative brainstorming in AR has several steps to take before being adopted widely, we help to expand our knowledge by determining that traditional tools can assist us significantly in generating notes in AR for rapid ideation.

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Appendices

Appendix A

Data Collection Materials and Consent Forms

A.1 User Study Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Consent to Take Part in a Research Study

Title of research study: Evaluating Input Techniques for Generating Notes in Augmented Reality

Principal Investigator: Sang Won Lee sangwonlee@vt.edu (540)231-4857

Other study contact(s):

- Doug A. Bowman dbowman@vt.edu (540) 231-2058
- Tam Phan tphan25@vt.edu (240) 994-0672

Key Information: The following is a short summary of this study to help you decide whether or not to be a part of this study. More detailed information is listed later on in this form.

We would like to invite you to participate in a research study using augmented reality (AR) headsets, pens, and paper. We are planning to investigate the usage of pen and paper in augmented reality, and your participation would be a great help. We will use the Microsoft HoloLens device and perform some tasks while taking video recording of the tasks as you complete them. We will use a recorded Zoom call to record audio in the session and record video with the HoloLens for the entire duration of the experiment, up to 60 minutes.

Detailed Information: The following is more detailed information about this study in addition to the information listed above.

Who can I talk to?

If you have questions, concerns, or complaints, or think the research has hurt you, talk to the research team at tphan25@vt.edu / (240) 994-0672

This research has been reviewed and approved by the Virginia Tech Institutional Review Board (IRB). You may communicate with them at 540-231-3732 or irb@vt.edu if:

- You have questions about your rights as a research subject
- Your questions, concerns, or complaints are not being answered by the research team
- You cannot reach the research team
- You want to talk to someone besides the research team to provide feedback about this research

How many people will be studied?

We plan to include about 16 people in this research study.

What happens if I say yes, I want to be in this research?

The study will take place in the Usability Lab 133 (D, E, F) (102 McBryde Hall) or in the Corporate Research Center at 2202 Kraft Drive. and will take approximately 60 minutes. When you arrive, you will be greeted and asked to read and sign the informed consent form after your questions (if any) are answered. Then you will be asked to clarify you have normal vision (glasses or contacts are fine). Next you will be provided with written or verbal instructions for the

Consent to Take Part in a Research Study

experiment, and familiarized with the lab and the equipment they will be using. You will wear an augmented reality (AR) headset such as the Microsoft HoloLens. Using the devices, you will then complete a series of interaction tasks in AR and in real world, using one or more 3D interaction techniques. Tasks will involve physical movements including looking around the environment, pointing to objects, manipulating virtual objects, writing on pen and paper, and capturing images using the HoloLens via voice command. After each block of tasks, you will be interviewed by the investigator to gather qualitative feedback. Breaks will be given after each usability questionnaire. After all tasks are completed, you will be interviewed about the entire experience. The entire session will be audio recorded.

To thank you for your participation, we will give out \$12 electronic gift card at the end of the study.

What happens if I say yes, but I change my mind later?

You can leave the research at any time, for any reason, and it will not be held against you.

If you decide to leave the research, contact the investigator so that the investigator can terminate current experiment session. Any data collected by far will be disregarded and will not be used for further study. There will be no follow-up procedures afterwards.

Withdrawing from the experiment does not affect receiving \$12 gift card compensation.

Is there any way being in this study could be bad for me? (Detailed Risks)

Using AR technology can produce symptoms of sickness or discomfort in some users. These symptoms are usually mild, and may include dizziness, nausea, eye strain, headache, or disorientation. During tasks involving physical movement, there is also some risk that you could collide with obstacles in the physical environment.

You will be given the option to take a break or quit the experiment at any time. To mitigate the risk of sickness and discomfort, we will adjust the display properly, keep task sessions short, provide frequent breaks, and ask you after each set of tasks how you are feeling. To mitigate the risk of physical obstacles and cabling, we will clear the area of obstacles, show you where the boundaries of the space are.

What happens to the information collected for the research?

We will make every effort to limit the use and disclosure of your personal information, including research study and medical records, only to people who have a need to review this information. We cannot promise complete confidentiality. Organizations that may inspect and copy your information include the IRB, Human Research Protection Program, and other authorized representatives of Virginia Tech.

All data collected during this study will be done so anonymously and stored in a password protected computer. No names, contact information, or any other identifying information will be attached to your responses to an investigator's questions or to your results from the provided tasks. At no time will the researchers release identifiable results of the study to anyone other than individuals working on the project without your written consent. However, you may be asked to perform tasks in a public space and bystanders could recognize you.

Consent to Take Part in a Research Study

If identifiers are removed from your private information or samples that are collected during this research, that information or those samples could be used for future research studies or distributed to another investigator for future research studies without your additional informed consent.

The results of this research study may be presented in summary form at conferences, in presentations, reports to the sponsor, academic papers, and as part of a thesis/dissertation.

Can I be removed from the research without my OK?

The person in charge of the research study or the sponsor can remove you from the research study without your approval. Possible reasons for removal include technical issues.

What else do I need to know?

We will not offer to share your individual test results with you. You may accept or decline these results.

Consent to Take Part in a Research Study

Signature Block for Capable Adult

Your signature documents your permission to take part in this research. We will provide you with a signed copy of this form for your records.

Signature of subject

Date

Printed name of subject

Signature of person obtaining consent

Date

Printed name of person obtaining consent

A.2 COVID-19 Consent Addendum

Protocol #21-095

Principal Investigator Name and Contact Information Sang Won Lee (sangwonlee@vt.edu)

**Additional COVID-19 Information Related to
Consent to Participate in In-Person Research at Virginia Tech**

You have agreed to participate in a research study at Virginia Tech. The research study involves in-person contact or procedures. Here are some things you should know about in-person research while COVID-19 remains a risk:

Risks related to COVID-19:

If you choose to participate in this study, the risk for COVID-19 are about the same as those posed by similar activities while the virus is still spreading in your community. Similar activities could include grocery shopping, having your car repaired, or getting a haircut.

In addition, participation might increase risk to your family, the community, and the research team.

You should not participate if you have any conditions or risk factors that could make a COVID-19 infection more serious. Risk factors for severe illness include having other medical conditions such as asthma, diabetes, heart problems, or any other illness. Certain populations might also be at increased risk or unknown risk, including people aged 65 and older, people with disabilities, women who are pregnant or breastfeeding, people who are experiencing homelessness, and people who are part of racial and ethnic minority groups.

The information on people who need to take extra precautions is being updated regularly. We encourage you to check for the latest information before you decide whether to participate. Please visit <https://www.cdc.gov/coronavirus/2019-ncov/need-extra-precautions/index.html> for the most up to date information.

What we are doing to reduce risk to you:

Each lab or study has developed a process for conducting the research as safely as possible, given current knowledge about COVID-19. This process has been reviewed by the Human Research Protection Program at Virginia Tech. You will be given a sheet with information specific to your study. You should review this information and ask any questions before you agree to participate.

We will not conduct the study during times of increasing community spread or if we cannot obtain the necessary disinfecting supplies and equipment to reduce the risk of exposure.

Everyone working on the study has been instructed to stay home if they have any symptoms that could be related to COVID-19. If someone on the research team tests positive for COVID-19 and you have been exposed, someone will notify you. We will maintain a contact tracing log that is separate from your data and other details about your participation, and we will provide this log to the New River Health District (540 267-8240) who will conduct contact tracing in the case of a positive test. We will destroy this log 60 days after your last visit.

Protocol #21-095

Principal Investigator Name and Contact Information Sang Won Lee (sangwonlee@vt.edu)

What you can do to reduce risk to us and to the community:

Do not participate if you have had any symptoms of COVID-19 in the past 14 days or have been in contact with someone who has symptoms. Symptoms include, but are not limited to, cough, shortness of breath or difficulty breathing, fever, chill, repeated shaking with chills, muscle pain, headache, sore throat, and new loss of taste or smell.

Do not participate if you have tested positive for COVID-19 in the past 21 days, even if you have not shown any symptoms.

Do not participate if you know you have been exposed to anyone who has tested positive for COVID-19 in the past 21 days.

Let us know if you test positive for COVID-19 within the next 14 days. We will provide your contact tracing log to university or public health authorities who will use the tracing log to contact others who may have been exposed during your visit.

Wash your hands frequently and observe current guidance on avoiding virus spread from the Centers for Disease Control.

Wear a mask or a cloth face covering over your nose and mouth. Depending on the study, another method may be used, such as physical distancing, a face shield, or Plexiglas barrier.

For the latest information on COVID-19 please visit:

<https://www.cdc.gov/coronavirus/2019-ncov/index.html>

Signature Block

Your signature documents that you have read and understand the information outlined in this document and all of your questions have been answered. We will provide you with a signed copy of this consent addendum for your records.

| | |
|---|---------------|
| _____ Signature of subject | _____ Date |
| _____ Printed name of subject | |
| _____ Signature of person obtaining consent | _____ Date |
| _____ Printed name of person obtaining consent | |

A.3 Pre-Experiment Survey

Evaluating Input Techniques for Generating Notes in Augmented Reality

What is your gender?

- Male
- Female
- Non-binary
- Transgender
- Intersex
- Prefer not to say
- Other... (editable short answer field)

What category best describes you?

- White (Eg: German, Irish, English, Italian, Polish, French, etc)
- Hispanic, Latino, or Spanish origin
- Black or African American
- Asian
- American Indian or Alaska Native
- Middle Eastern or North African
- Native Hawaiian or Other Pacific Islander
- Some other race, ethnicity, or origin

What is your age?

- <Type a numeric answer here>

How familiar would you consider yourself to be with Augmented Reality headsets?

- Extremely familiar
- Very familiar
- Moderately familiar
- Slightly familiar
- Not at all

How familiar would you consider yourself to be with the Microsoft HoloLens?

- Extremely familiar
- Very familiar

- Moderately familiar
- Slightly familiar
- Not at all

Have you ever participated in an affinity diagramming session before?

- Yes
- No

How would you rate your own ability to express an idea through drawing a sketch? (1 meaning you have difficulty expressing in a sketch, 5 being strong sketching skills)

- 1
- 2
- 3
- 4
- 5

How would you rate your own ability to express an idea through written text? (1 meaning you have difficulty expressing thoughts on paper, 5 being strong writing skills)

- 1
- 2
- 3
- 4
- 5

How would you rate your own ability to comprehend an idea through seeing a sketch? (1 meaning you have difficulty comprehending, 5 being strong comprehensive skills)

- 1
- 2
- 3
- 4
- 5

How would you rate your own ability to comprehend an idea through reading? (1 meaning you have difficulty comprehending, 5 being strong comprehensive skills)

- 1
- 2
- 3
- 4
- 5

A.4 Partner Ratings Form

User Study Comprehension Ratings

In this survey, one participant will look at the other person's note, and try and understand it without explanation. Then, they will attempt to explain their understanding of the note to the other person, who will then rate how well they believe they understood the intent of the note.

1. Which participant is this?

Mark only one oval.

- Participant 1 *Skip to question 2*
- Participant 2 *Skip to question 3*

User Study Comprehension Ratings:
Own Comprehending

Please rate the other participants' note on how easy it was to comprehend.

2. On a scale of 1-10, how easy was it to comprehend the other participant's note?

Mark only one oval.

| | | | | | | | | | |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |

User Study Comprehension Ratings:
Partner Comprehending

Please rate how well you think the other person comprehended your idea on your note.

- 3. On a scale of 1-10, how well do you think the other participant comprehended your note?

Mark only one oval.

1 2 3 4 5 6 7 8 9 10

User Study Comprehension Ratings:
Own Comprehending

Please rate the other participants' note on how easy it was to comprehend.

- 4. On a scale of 1-10, how easy was it to comprehend the other participant's note?

Mark only one oval.

1 2 3 4 5 6 7 8 9 10

User Study Comprehension Ratings:
Partner Comprehending

Please rate how well you think the other person comprehended your idea on your note.

- 5. On a scale of 1-10, how well do you think the other participant comprehended your note?

Mark only one oval.

1 2 3 4 5 6 7 8 9 10

User Study Comprehension Ratings:
Own Comprehending

Please rate the other participants' note on how easy it was to comprehend.

6. On a scale of 1-10, how easy was it to comprehend the other participant's note?

Mark only one oval.

| | | | | | | | | | |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |

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A.5 Post-Experiment Interview

Evaluating Input Techniques for Generating Notes in Augmented Reality

Which input method did you find more satisfying to use and why?

Which input method did you feel was easier to learn and why?

Which input method did you have an easier time conveying your ideas with?

Did you have any issues with either input method, and if so what were they?

If you have any way to improve either input method, what would you suggest?

Any other questions about this experiment?