UNIVERSITY OF CALGARY

Exploring User Experience Guidelines for Designing HMD Extended Reality Applications

by

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Abstract

With the rise of Extended Reality (XR) technologies, such as head mounted displays (HMD) for Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR), designers are presented with many unique challenges and opportunities when creating applications. Publications can be found from research and industry that offer insights and ideas surrounding user experience (UX) for XR applications. However, these publications often vary in format and content. Based on a thorough analysis of 68 different resources from research, industry, and 2D design, we present a set of eleven UX guidelines for designing XR applications. Our work serves as a reference to the literature for understanding what others have tried and discovered and provides an integrated set of guidelines. Furthermore, we explore how our work can be utilized by conducting a case study where we used our guidelines throughout the development of an XR application. More specifically, in collaboration with the Alberta Electric System Operators (AESO), we developed an HMD XR app that explores how information from their current control room can be replicated and reimagined in a virtual environment. Based on our experience, we use the knowledge gained to reflect on the guidelines and suggest areas for future research. We see our work as a starting point to better understand how to create and design usable HMD XR applications.

Preface

Some figures and material in this thesis have previously appeared in prior work:

> **Steven Vi**, Tiago Silvia Da Silvia, and Frank Maurer: *User Experience Guidelines for Designing HMD Extended Reality Applications* in: the proceedings of Human-Computer Interaction – INTERACT 2019 17th IFIP TC 13 International Conference (INTERACT 2019), Paphos, Cyprus.

The co-authors have given permission to use parts of the publication for my thesis, which can be seen in Appendix D. More specifically, Chapter 1, 2, 3, 4, and 6 all adapted content from the publication. Furthermore, I wish to stress the importance of the contributions of the many collaborators that had helped me throughout the entire process; without them, the research conducted in this thesis would not have been possible.

Acknowledgements

- To Frank Maurer - To say that I am grateful for all that you have done for me would be an understatement. When I look back at how much I have grown over the past few years, I would have to credit most of it to your reliable guidance and mentorship. Thank you for all the countless opportunities you gave me to grow as an academic researcher, as a computer scientist, and as a person. My skills and confidence have improved exponentially ever since I join the ASE Lab. I have truly been in your care.

- To Tiago da Silva - When you came to Calgary, I did not expect us to become as close as we did. Thank you for joining me in the chaotic journey that was my research. Being new to HCI research, I greatly appreciate having someone with experience that I could struggle with and rely on. Without your help, I am doubtful that I would have ever published the INTERACT paper. Thank you for being a vital part of my research.

- To Bryson, Tarishi, and Dianna - The AESO Immersive Control Room Project was very significant to me, and without your support, the project would have never turned out as well as it did. I am sure it was not easy having a project lead as inexperienced as myself, but you guys were understanding, forgiving, and supportive. Thank you for sticking with me through the highs and lows, and giving your all throughout the project. I truly appreciate your effort, and more importantly, your friendship.

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- To my Family - To my Mom, Dad, and my Sister, I am truly grateful for your unconditional love and support. I cannot even put into words how much you all mean to me. I could not be asked to be raised by a better family. I am who I am because of you all. Thank you for everything.

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List of Figures and Illustrations

List of Symbols, Abbreviations and Nomenclature

Symbol or abbreviation	Definition
XR	Extended Reality
VR	Virtual Reality
AR	Augmented Reality
MR	Mixed Reality
RV	Reality Virtuality
UX	User Experience
HMD	Head Mounted Displays
RtD	Research Through Design
HCI	Human Computer Interaction
MLR	Multivocal Literature Review
AESO	Alberta Eletrical System Operators
FOV	Field of View

Chapter 1

Introduction

Recent developments in Extended Reality (XR) technologies, such as wearable Head Mounted Displays (HMD) for Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR), have yielded affordable hardware for experiencing immersive virtual environments in multidimensional space. 2D displays are limited to showing content on a screen, but XR applications can embed a user in his or her digital information, utilizing a 360-degree view, perceived depth, physical location, and movement tracking to expand what can be experienced in a digital application. Furthermore, continued development in this space has seen additional capabilities, such as haptics, spatial audio, hand tracking, improved sensors, etc., be continually added to XR platforms. While XR provides increased potential for interacting with digital information, it is important to remember that these advancements require an expansion of our current understanding of UX design. Established patterns and guidelines are built around applications running on a 2D screen and do not address the potential additional considerations that come with spatial environments and interactions. As long as existing design lessons are not extended for the capabilities of XR, designers likely face barriers to unlock the full potential of these technologies. (Fig. 1.1)

Figure 1.1: Theses photos showcase the difference in capabilities between 2D displays vs HMD XR headsets. Left shows a traditional 2D display, while the top right shows Google's Tilt Brush and bottom right show a concept of a Mixed Reality application[1]

1.1 Motivation

Recent work from various communities, such as device manufactures, developer blogs, news sites, and academic sources, can be found that provide ideas around designing for XR platforms. These resources vary in content, in supporting evidence, and in format, such as first-hand experiences, proposed guidelines, speculative ideas, prototypes, etc. This provides a diverse wealth of information; however, it also makes it difficult to identify valid patterns that can be beneficial for designers. Inspired by this work, we developed a set of UX guidelines for designing XR applications that aim at integrating various ideas from different XR and UX communities. It should be noted that the guidelines are not meant to present ab-

[1]Picture adapted from `http://climatecentre.org/downloads/images/VR` and `https://insanelab.it/virtual-reality-technology/`

solute rules, but rather to provide in a concise manner a reference for understanding what others have tried and discovered. Our work is targeted towards aiding in the design of applications for wearable HMD XR devices, such as the Microsoft HoloLens, Magic Leap, Meta, HTC Vive, Oculus Rift, etc., that uses stereoscopic imaging, spatial audio, and head tracking to provide users with an immersive experience.

1.2 Research Goals

The primary research problem that inspired this thesis was:

How do we design usable HMD XR applications?

We recognized that the scope of this problem is large and that it in composites various different topics. As such, our work aimed at accomplishing three, more specific, research objectives that ultimately contribute to addressing this problem.

The first objective is to inform XR designers and developers of common XR design considerations. An extensive review of both the literature in academia and resources from industry was conducted to understand the current state of UX recommendations for HMD XR technologies. The second objective was to provide a useful set of guidelines for the design of HMD XR applications to support developers and designers in the creation of XR applications. These guidelines were derived from the results of our literature review. The third objective was to showcase how our guidelines can be used in a development scenario. A case study was conducted that documents the use of the guidelines in the creation of an XR application.

1.3 Research Questions

The research conducted in this thesis can be divided into the following, more specific, questions:

- *Research Questions 1 (RQ1)*: What is the current state of research regarding UX design for XR platforms?

Before we developed our UX guidelines for HMD XR applications, we first needed to understand what work has already been done in this space. With consumer models of XR technologies already available for a few years, we wanted to discern the extent to which others have explored this topic and the relationships between the information found in them. Thus, we conducted a systematic mapping study to understand the state of this research.

- *Research Questions 2 (RQ2)*: What observations can be made from existing resources, to help the design and implementation of XR applications?

With the insight from RQ1 in mind, we conducted a thematic analysis of the related resources to find recognizable reoccurring topics or patterns occurring within the data. The results were used to develop a set of guidelines that reflected the common ideas identified in our findings.

- *Research Questions 3 (RQ3)*: In what ways can HMD UX guidelines aid in the design and creation of future XR applications?

With the guidelines created as a result of RQ2, we took a self design approach, where we used our guidelines throughout the development of an XR application. The aim was to gain insight into how our guidelines can be used and their effectiveness through genuine usage in a development scenario.

1.4 Thesis Contributions

By answering the previously mentioned questions, this thesis makes the following contributions:

- *Thesis Contribution 1 (TC1)*: Provide a guided overview of the existing literature on UX for XR applications in academic research and in industry.
- *Thesis Contribution 2 (TC2)*: Propose a set of guidelines that are encompassing the body of work in a concise and structured manner.
- *Thesis Contribution 3 (TC3)*: Detail a case study that explores how our guidelines are used in the development of an HMD XR application.

1.5 Thesis Structure

Chapter one provided an introduction and overview of our research. The remainder of the thesis will be organized as follows:

Chapter Two: Background and Related works - provides definitions, necessary background knowledge, and an overview of related research.

Chapter Three: The Process – documents the approach of creating and evaluating our UX guidelines. This section will detail the six different stages of our process and how we used and adapted the methodologies described in Chapter Two.

Chapter Four: UX Guidelines for HMD XR Applications – outlines our set of guidelines. For each, we provide a name, definition, explanation, sub guidelines, and references to the original resources they were derived from.

Chapter Five: AESO Immersive Control Room: A Case Study – describes the development of the AESO Immersive Control Room application. We detail how the UX guidelines were used throughout the development process and showcase the resulting XR prototype.

Chapter Six: Reflection and Discussion – discusses the lessons learned from the case study in Chapter Five. Additionally, we reflect on the entire process of creating our UX guidelines to discuss the current state of XR research and the limitations of our appraoch.

Chapter Seven: Conclusions and Future Work – the questions, goals, and contributions are revisited, and a conclusion is made to wrap up the research in this paper. Moreover, we discusses potential opportunities for future research.

Chapter 2

Background and Related Work

In this chapter, we provide an overview of related research and discuss necessary background information for understanding our research. This chapter is divided as followed: 2.1 we discuss the terminologies around extended reality, 2.2 we overview the concepts of user experience guidelines in HCI, 2.3 we recap the academic literature related to XR user experience guidelines, and 2.4 we summaries related methodologies that were adapted throughout our research.

2.1 Extended Reality

As the industries around these platforms develop, so does the terminology. Different definitions have been used in this field, but there have been distinct categories of technologies that have emerged in recent years. For the purpose of this thesis, the following terminology is used to classify Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Extended Reality (XR). VR allows users to be fully immersed in a computer-generated environment while the real world is occluded when the device is in use [46]. AR allows for information to be superimposed around a user without blinding them to their own physical surroundings [96]. Similar to AR, MR overlays information onto the real world, but also

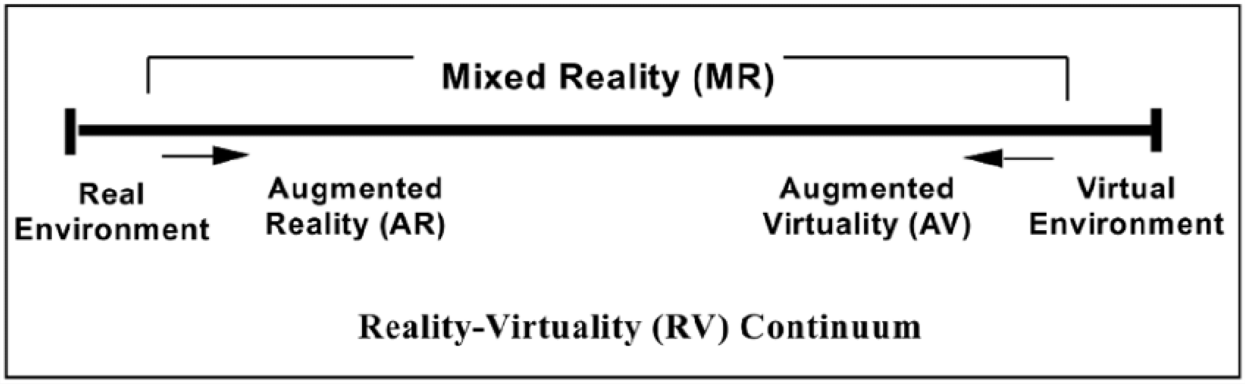

Figure 2.1: Diagram showing a representation of Milgram et al. Reality Virtuality Continuum. [58]

includes the capability to understand and use the environment around the user to show or hide part of the digital content [91]. These definitions differ slightly from the work of Milgram et al., [58]. In his paper, he works on defining AR, VR, and MR, and suggests that these terminologies are closely related. Thus, it is more appropriate to view them as part of a continuum, which he defines as the Reality – Virtuality (RV) Continuum in Fig. 2.1. Milgram et al. uses Mixed Reality (MR) environment to define the broad range of technologies between the extremities of the RV continuum. However, the current use of the term MR, especially in industry, is often used to define its own class of immersive technologies. For example, Fig. 2.2 shows how Magic Leap defines their MR headset (right picture) differently

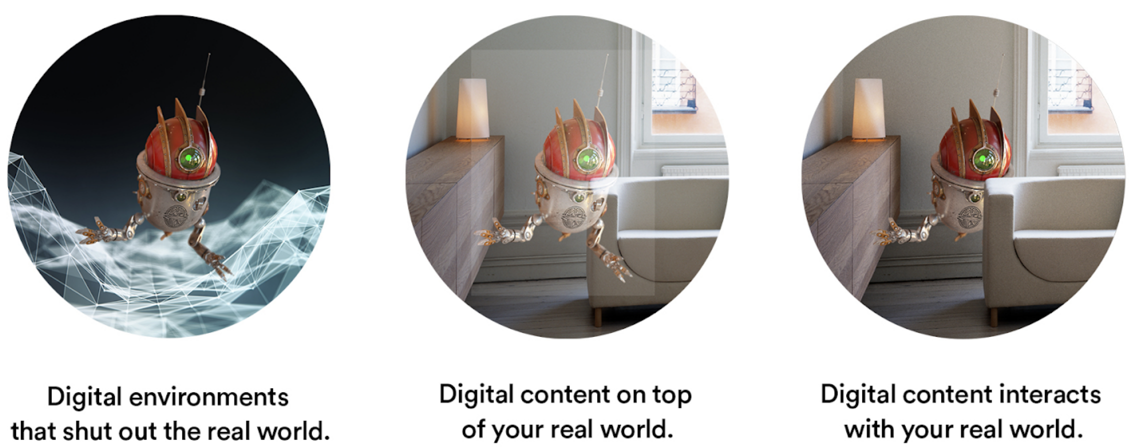

Figure 2.2: Magic leap's definition for VR (left), AR (middle), and MR (right). For our thesis, XR includes all three of these terminologies.[2]

from that of AR or VR. As such, we updated the terminology from Milgram et al. to define XR as technologies in which real world and virtual world objects are presented together within a single display. As such, XR encompasses all the previously mentioned categories.

2.2 User Experience Guidelines

Consistent with Nielsen et al., 1993 [72], design guidelines are well-known principles for user interface design, which should be followed in the development project, and that can also be used to evaluate the usability of a system. According to Endsley et al., 2017 [24], in user interface design, the term guideline is almost synonymous with heuristics and can be used by both designers and evaluators. Certainly, the most well-known design guidelines/heuristics are the ten usability heuristics from Nielsen et al., 1990 [75]. Like psychological heuristics, usability guidelines are often used as shortcuts when data from a formal user study is not available. Guidelines can be used across the stages of the design process, guiding small and large decisions and predicting success or failure of the usability in prototypes with varying levels of fidelity.

Several authors have stated that it is necessary to create new guidelines for evaluating specific applications. For example, Kuparinen et al. [49] conclude that the existing usability guidelines were too general to be applicable for evaluating the usability of mobile map applications. Thus, it is necessary to develop a new set that evaluates the specific features of that domain. To further understand how to design for specifically XR, we overview related work concerning HCI guidelines for XR applications in the next section.

[2] Picture from `http://mobileedar.weebly.com/what-is-ar.html`

2.3 Extended Reality Guidelines

The most recent and relevant study for our purposes is [24]. Endsley et al., 2017 [24] aimed at providing practitioners with a set of AR heuristics. They developed their heuristics by making use of affinity diagrams, expert evaluations, feedback from active AR designers, and statistical analyses. According to these authors, the literature review revealed few validated, generalized AR heuristics in use. The authors used a set of 11 heuristics, including related fields, such as: [5, 23, 27, 29, 31, 44, 46, 47, 73, 79]. Their affinity diagramming approach sought to leverage the existing heuristics in the AR space and generating themes for immersive AR interactions.

Dunser et al., 2007 [23] investigated how general HCI guidelines may relate to the domain of AR application design. To do so, they combined some known user-centered design guidelines with the demands of AR systems to identify issues that should be considered by AR interface researchers. According to the authors, this work was an initial attempt to fill the gap that existed in the area; however, they noted that the presented design guidelines were rather general and had to be further refined.

In her master's thesis, Kalalahati et al., 2015 [44] aimed at developing generic usability heuristics for AR applications. According to her, based on a literature review, a preliminary version of the heuristics was developed, which was evaluated by four experts. As a result, six evaluation criteria were formed that should be used in conjunction with Nielsen's [74] generic usability evaluation heuristics. She noted that the proposed heuristics still needed to be tested in practice.

Ko et al., 2013 [46] proposed the creation of usability guidelines for the development and evaluation of smartphone applications using AR technology. The authors developed these guidelines by analyzing existing research about heuristic evaluation methods, design guidelines for AR systems, guidelines for handheld mobile device interfaces, and usability guidelines for tangible user interfaces. They conducted a heuristic evaluation for three popularly used smartphone AR applications to identify usability problems. The authors suggested new design guidelines to solve the identified problems. Afterward, they developed an improved AR application prototype which later was evaluated by conducting user testing sessions to validate the effects of usability guidelines.

Kourouthanassis et al., 2015 [47] proposed a set of interaction design guidelines for the development of Mobile Augmented Reality (MAR) applications. According to the authors, the design recommendations adopt a user-centered perspective, and thus, they focus on the necessary actions to ensure high-quality MAR user experiences. To formulate their propositions, they relied on theoretical grounding and evaluation of eight MAR applications that provide published records of their design properties. The design guidelines have then been applied to guide the development of a MAR travel application. The authors then performed a field test to elicit whether their design choices effectively lead to enhanced satisfaction and overall user experience. Their results suggest that the proposed guidelines contribute to ensuring high usability and performance of the MAR application as well as evoking positive feelings during user and system interactions. According to the authors, their guidelines may be employed either as a guide during the initial stages of the design process or as a benchmark to assess the performance of MAR applications.

In his master's thesis, Bloksa et al., 2017 [7] analyzed user interfaces and guidelines for AR and reviewed existing interfaces for VR and other devices to determine the plausible application in AR with the addition of auctorial ideas and guidelines. His research extracted practical parts of the analysis to suggest the right application within the guidelines. The purpose of his work was the creation of a set of guidelines for the user interface design. Besides that, it describes potential applications of the guidelines for the AR technology in the industrial environment, especially for the instructions and assembly tasks.

In his thesis, Frojdman et al., 2016 [28] focused on what aspects should be considered when designing a head orientation input graphical user interface in virtual reality for quality user experience. The author carried out a heuristic evaluation, interviews, usability tests, and a survey. The author also developed a virtual reality prototype of a video on-demand service. In combination with previous recommendations, the result led to the development of seven guidelines. However, these guidelines are considered only to serve as a foundation for future research since they need to be validated.

The reviewed work presents interesting, novel and useful approaches for the purpose of this thesis, and our work ultimately builds on the ideas and information introduced by the literature. With that said, these works also highlight the limited academic research and the lack of real-world validation around this topic. Additionally, observations from other communities, such as XR device manufactures, news articles, and developer's blogs, has shown that there is a wealth of knowledge that was not being reflected in academic works. Even though not all of the information or ideas found were academically validated, they were concepts that developers were using to build and design XR applications. This suggest that non-academic sources provide additional insights and should be incorporated in the development of guidelines. Our eleven UX guidelines extend to include the wealth of insights from other communities in conjunction with academic work. As such, concepts that developers have used to build and design current XR applications are being reflected in our research that were not in prior works.

2.4 Methods

Throughout our research, we used various established methodologies as a guide for conducting our work. In this section, we describe the approaches that were used as the bases for creating our set of proposed guidelines. These were eventually adapted and applied to fit within the context of our situation and research goals, which is laid out in more detail in Chapter 3.

2.4.1 Developing Usability Guidelines

The main approach we employed was based on the work of Rusu et al. [85] and Quinones et al. [81]. Rusu et al. proposed a methodology for researchers to follow in order to facilitate the development of usability heuristics. The methodology includes the following six stages.

- *Exploratory stage*: to collect bibliography related to the main topics of the research
- *Descriptive stage*: to highlight the most important characteristics of the previously collected information
- *Correlational stage*: to identify the characteristics that the usability heuristics for specific applications should have, based on traditional heuristics and case studies analysis
- *Explicative stage*: to formally specify the set of the proposed heuristics, using a standard template
- *Validation stage*: to check new heuristics against traditional heuristics by experiments, through heuristic evaluations performed on selected case studies
- *Refinement stage*: based on the feedback from the validation stage.

In addition to outlining the different steps, Rusu showcased how the methodology was applied to develop usability heuristics for grid computing applications, interactive digital television, and virtual worlds. The paper by Quinones et al. aimed at building off and extended the work of Rusu et al. Quinones identified the lack of detail in Rusu stages as a potential weakness that could cause confusion for future researchers who want to implement the methodology. As such, he proposed new steps, definitions, and diagrams based on results from a systematic literature review and feedback from studies that involved both researchers and experts who have developed their own set of heuristics in different domains.

Both Rusu et al. and Quinones et al. work serves as the main methodology that inspired our approach. More specifically, our research implemented the six stages described above;

however, while the goals of each stage were kept intact, the actual steps that were taken were changed to fit within our situation. As such, we used additional methodologies to help guide our research. These are explained in the following subsections.

2.4.2 Systematic Mapping of Literature

A systematic mapping study provides a broad overview of the understanding of a given topic. Through sorting large amounts of literature, it can recognize topics with high-density areas to direct future systematic reviews on and identify areas for more studies to be conducted. In Petersen et al. Systematic Mapping Studies in Software Engineering [78], he details five major steps for completing a literature survey. (Fig. 2.3)

- *Definition of Research Questions (Research Scope)*: The first step is to define a research question that reflects the goals of the study.
- *Conduct Search for Primary Studies (All Papers)*: To find primary studies that are related to the research question, a search string is created to find relevant papers, articles, and publications.
- *Screening of Papers for Inclusion and Exclusion (Relevant Papers)*: To find which studies are significant to the research question and which to exclude from the study, an inclusion and exclusion criteria is created. All papers from the primary study are screened by the researchers using the criteria. References and citations of relevant papers should be searched to find new literature that is deemed relevant and to refine the search string to include the newly identified resources. This step is repeated until the researchers have an extensive list of papers.
- *Keywording of Abstracts (Classification Scheme)*: Keywords are identified from the abstracts of relevant papers and are then combined to develop a high-level overview. This is then used for categories to and sort the articles that were deemed relevant.

- *Data Extraction and Mapping of Studies (Systematic Map)*: After all articles are sorted in a scheme, the results are analyzed. The focus is on seeing the frequencies of publications for each category to determine clusters of research that were done in the past as well as areas that require further research.

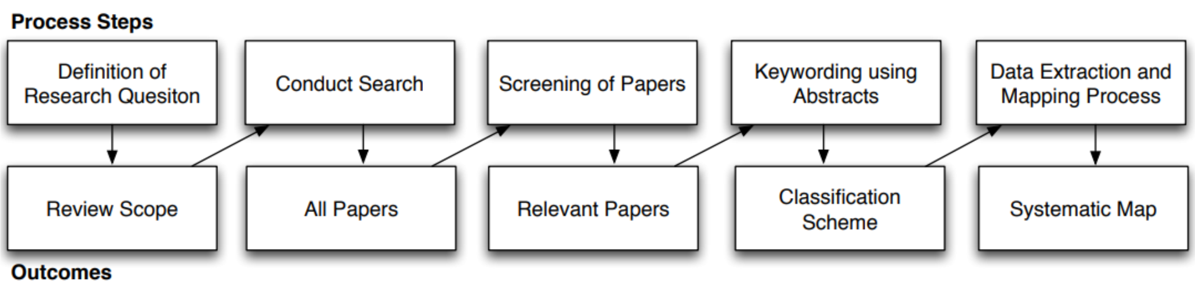

Figure 2.3: Overview of Petersen et al. methodology on conducting Systematic Literature Surveys. [78]

2.4.3 Self Design as a Method

Within the human computer interaction (HCI) research community, we have seen the rise of methodologies that focuses on using design, instead of traditional user studies, as an alternative way of evaluating a system. For example, in Zimmerman et al. [103], the authors proposed a model for interaction design research called Research Through Design (RtD). This approach uses the process of design practice and encourages researchers to engage with the problem itself with the intention of generating new knowledge. Through a continual process of ideating, revamping, and critiquing potential solutions, RtD allows researchers to integrate "*the true knowledge (the models and theories from the behavioural scientist) with the how knowledge (the technical opportunities demonstrated by engineers)*." Additionally, this process forces design researchers to continually reevaluate and reframe the initial research problem, thus creating in-depth knowledge about the problem itself and a collection of artifacts that showcase the researchers' journey.

In Neustaedter et al. [70] we can see the continuation of design research being further defined as an approach in HCI. The paper discusses the practice of Autobiographical design, which is "*design research drawing on extensive, genuine usage by those creating or building the system.*" The authors define "genuine usage" as focusing on fulfilling the needs of the researcher instead of pretending to have needs expected of targeted users. Through interviewing experts in HCI who have engaged in a similar design process, they found that while this approach is not viable in every scenario and does have its share of drawbacks, autobiographical design supports early innovation, detailed understanding, and recognition of important issues, among other benefits.

Autoethnography is a form of qualitative research that aims to use ethnographic methods and techniques on personal experiences [82]. The method has been employed across different research disciplines and focuses on using self-experience and self-reflection as a way to develop an understanding of certain behaviours or situations. The researcher acts as both the informant "insider" and the analyst "outsider" during this process. While not perfect, this approach allows the researcher to be immersed in the situation and is exposed to the nuances of the experience. Thus, the first-person perspective that is created may have additional details that could be harder to come by in other approaches.

For our research, we borrowed from both RtD, autobiographical design, and autoethnography methodologies to evaluate our Eleven UX guidelines. Our approach involved a project with AESO, where we were tasked to develop an XR prototype application. With this project, we had a genuine use case for our developed guidelines and were able to gain insight into their effectiveness by engaging with them in the development process, documenting the journey, and reflecting on our experience. More details about our approach can be seen in Chapter 3.5.

2.5 Summary

This chapter clarified definitions, overviewed related work around XR guidelines, and provided a recap on methodologies that were used to inspire our research. The goal was to provide the necessary background information needed to understand the research presented in the rest of this thesis. In the following chapter, we give a detailed look into how we used and adapted the methodologies described in this chapter by outlining the approach for developing our UX guidelines for HMD XR applications.

Chapter 3

The Process

In this chapter, we provide an in-depth look into our approach for creating our UX guidelines. As previously mentioned, we used the methodology defined by Rusu et al. [85] and Quinones et al. [81] as the bases for establishing our approach and adapted it to fit within the context of our situation and goals. Our research is split into the following six stages: Exploratory, Descriptive, Comparative, Specification, Evaluation, and Reflection.

3.1 Exploratory stage: Conducting Search for Resources

In the first stage, our goal was to understand what work has been done regarding design guidelines for XR applications and obtain existing literature from different source. To achieve this, we conducted a systematic mapping study to get an overview of published literature on this topic [78]. We started off by defining a search string following systematic literature reviews (SLR) recommendations [45], that was iteratively reworked to accurately reflect the scope of the research. The resulting search string was:

(heuristic OR principle OR guideline) AND ("virtual reality" OR "augmented reality" OR "mixed reality" OR immersive) AND (usability OR "user experience") AND (design).

The search string was then applied to search title, abstract, and keywords in Scopus, a database containing a variety of peer reviewed papers published in either conferences or journals, which resulted in 350 papers found. Each paper was screened by two researchers with a third providing feedback to exclude studies that are not relevant to our topic. The criteria we used was based on the abstract explicitly mentioning dealing with HCI guidelines, heuristics or guidelines for VR, AR or MR applications and, from the abstract, being able to deduce that the focus of the paper has relevance to the creation of HCI guidelines for HMD XR design and/or evaluation.

Through this process, we found a wide variety of different types of resources. When looking at the resources we excluded, most of these publications contained the keywords but were not relevant to the topic. However, we did find a few papers that were within the scope of our topic but focused on a very specific domain. For example, Wijdenes et al. [100] explores how augmented reality can be leveraged as a training tool for medical education and compiled usability heuristics specific to AR healthcare applications. While this publication, and papers that are similar in focus, could provide relevant information, we decided to exclude these types of publications because of their potential dependence on the specific context. In the end, only one paper (Endsley et al. [24]) fits in our inclusion criteria.

To broaden our resources, we expanded our approach by conducting a multivocal literature review (MLR). MLR is a form an SLR that promotes the use of "*Grey Literature*," such as scientific articles, thesis, previous experiments, books, and websites, in addition to peered review published literature [30]. By doing this, MLR focuses on understanding multiple viewpoints rather than constructing data from only the information reported in academic settings. For our purposes, since our initial search only yielded one paper, collecting resources that reflect the ideas and experiences of early practitioners serve as a valuable data source for our research. We started our search for grey literature by applying multiple variations of our initial search string on the Google search engine. This search resulted in a large number of related resources. After a quick overview, using backward snowballing as a complement to SLRs [102], we selected resources which focused on providing information regarding UX design for different XR technologies. The collection process continued until the researchers reached "*Theorical Saturation*", where the researchers found that the resources continually contained repeat ideas and that new concepts became difficult to come by [67]. We ended up with an additional 60 web resources, 3 non-peer reviewed academic sources, and 1 book which brought our total to 65. The list of resources is likely not exhaustive due to limitations of the search engine/process, however, it represents a large range of resources from a variety of different communities.

3.2 Descriptive Stage: Theme Extraction and Thematic Analysis

In order to extract themes from our collection of nonacademic resources, we choose to conduct a thematic analysis, in which we iteratively grouped, labelled, discussed and re-labelled categories and guidelines that described and explained the various guidelines and recommendations. This process involved several meetings among the researchers. According to Hawkins et al. [34], researchers conducting thematic analysis look for recognizable reoccurring topics, ideas, or patterns – themes – occurring within the data that provide insight. When a researcher uncovers common themes throughout the data, those themes may indicate areas that help explain phenomena or point out areas of needed improvement. Therefore, information that supports the theme is extracted directly from the data. As the analysis continues, the researcher revisits the data to ensure the understandings extracted within the data contribute to the research questions. A theme indicates a common line of understanding occurring within the data and may contribute explicit or implicit information. Themes may be overarching, providing a general idea under which subthemes exist and contribute to understanding [9]. It should be noted that we have used an Inductive – bottom-up – approach, in which, researchers choose to locate themes inductively, and build themes directly from the data under investigation. No prior theoretical frameworks specifically guided the research project. Therefore, any and all reoccurring themes within the data are under investigation as long as themes align with the goal of the project [34]. Thus, after the thematic analysis process, we identified eleven themes that turned into our initial set of UX guidelines for XR.

3.3 Comparative Stage: Comparing and Contrasting Existing Work

After the creation of our initial set of UX guidelines, we compared our findings with related work. In this step, our goals were to identify the existing heuristics and guidelines that were already addressed in our initial set of guidelines and discover new ideas that can be incorporated into our work [34]. There were two categories in which the resources we used fell under, academic research, found in both our initial search (peered review publication) and MLR (Thesis dissertation and non-peered reviewed papers), that proposed high level design guidelines surrounding XR applications, such as [7, 23, 28, 44, 24] and traditional UX heuristics and design guidelines such as [75, 90, 41]. The motivation behind using traditional design principles came from the belief that these resources still provide valid and useful information for designing XR applications despite the differences in medium. In order to find relevancy, two authors separately read each related resource and compared their high-level ideas to our initial set of guidelines. Each was marked as relevant or not relevant to indicate if the ideas were addressed in our, which was documented in multiple Google Spreadsheets (Fig. 3.1). Afterward, the results were combined. Discrepancies were resolved by looking at the paper together and coming up with a consensus through discussion. In the end, 39 of the existing guidelines were identified as not related by our guidelines. For each of them, we discussed whether to discard, to incorporate with our existing guidelines, or create a new guideline based on the idea. This decision was based on importance, similarities to other guidelines, and whether or not they fit within our scope. For example, through this

INDUSTRY	IN1. Provide feedback & consistency	IN2. Minimize abstractions	IN3. Use cues to help users throughout their experience	IN4. Use 3D space to your advantage	IN5. Let users shape their environments	IN6. Minimalist Design	IN7. Layout elements to minimize physical strain	IN8. Keep physiological, environmental, and social comforts in mind	IN9. Don't Force Actions without user's permission	IN10. Don't just create an application, create a compelling experience	IN11. Design for hardware capabilities in mind
NIELSEN											
N1. Visibility of system status	Y		Y					Y			
N2. Match between system and the real world		Y	Y	Y				Y		Y	
N3. User control and freedom: Support undo and redo.											
N4. Consistency and standards	Y		Y								
N5. Error prevention											
N6. Recognition rather than recall	Y	Y	Y	Y							
N7. Flexibility and efficiency of use: Accelerators — unseen by the novice user — may often speed up the interaction											
N8. Aesthetic and minimalist design						Y					
N9. Help users recognize, diagnose, and recover from errors											
N10. Help and documentation											
SHNEIDERMAN											
S1. Consistency	Y	Y	Y								
S2. Shortcuts											
S3. Informative feedback	Y		Y								
S4. Dialogue	Y		Y								
S5. Error handling											
S6. Permit reversal of actions											
S7. Support internal locus of control											
S8. Reduce short-term memory load	Y	Y	Y	Y		Y					
ISO 9241-110											
I1. Is the dialogue suitable for the user's task and skill level? (Suitability for the task)											
I2. Does the dialogue make it clear what the user should do next? (Self-descriptiveness)	Y		Y								
I3. Is the dialogue consistent? (Conformity with user expectations)	Y	Y									
I4. Does the dialogue support learning? (Suitability for learning)	Y		Y								
I5. Can the user control the pace and sequence of the interaction? (Controllability)											
I6. Is the dialogue forgiving? (Error tolerance)											
I7. Can the dialogue be costumised to suit the user? (Suitability for indivisualisation)					Y						
Jakub Blokša - Design Guidelines for User Interface for Augmented Reality											
Presentation											
A2.1. Immediate content should be shown only in natural viewing zones							Y				
A2.2. Spacing is important in content to environment ratio							Y				
A2.3. Use volumetric elements		Y									
A2.4. UI elements responsiveness is the key	Y										
A2.5. Use human body for simple UI elements placement											
A2.6. The color of UI elements can make the perception more natural and visible											
A2.7. Do not forget about the lighting											
Control											
A2.8. Enable change of control type in different situations											Y
A2.9. Avoid the misrepresentation of the commands: (Deals with input misrepresentations)											
A2.10. Combine various control types to achieve more control											
A2.11. The user should be notified by command response	Y		Y								
A2.12. Recognize significant commands	Y										
A2.13. Use creative approach for user text input design											
A2.14. Is standard login/unlock page design obsolete?											
Intructions											
A2.15. Offer multiple instruction showing variations											
A2.16. Allow hiding/showing the manual						Y					
A2.17. Vary the manual according to the user experience level											
A2.18. Give a feedback to the user	Y										
A2.19. Ensure the AR will be helpful											
A2.20. Emphasize parts of an object to be moved											
A2.21. Show the user work tools before needed											
A2.22. Tools inventory layout could be inspired by RPG games											
A2.23. Indicate the movement											
A2.24. Do not forget about extreme working conditions											
A2.25. Enable remote cooperation											
A2.26. Connect AR and VR usage for cooperation											
Navigation											
A2.27. Navigation interface should vary depending on the transport type											
A2.28. Navigation needs to be understandable			Y								
A2.29. Highlight real life objects when navigating to the POI			Y								
Notifications											
A2.30. Notifications should not be the primary communication channel											
A2.31. Let the user set the notification preferences					Y						
A2.32. Form of presentation needs to be responsive	Y										
A2.33. Create notification priority levels											
A2.34. Do not cover the center of user's FOV on the move						Y					
A2.35. Visual notifications should be used moderately											
A2.36. Use only relevant and necessary notifications						Y					
A2.37. Do not overload users' FOV with notifications						Y					
Andreas Dünser - Applying HCI principles to AR systems design											
A3.1. Affordance		Y									
A3.2. Reducing cognitive overhead	Y	Y	Y	Y							
A3.3. Low physical effort						Y					
A3.4. Learnability	Y	Y									
A3.5. User satisfaction										Y	
A3.6. Flexibility in use						Y					
A3.7. Responsiveness and feedback	Y										
A3.8. Error tolerance											
Sofia Frojdman - User Experience Guidelines for Design of Virtual Reality Graphical User Interface											
A4.1. Place the graphical user interface so it is comfortable to explore and interact with							Y				
A4.2. Place visual feedback to selections within the immediate interaction area	Y		Y				Y				
A4.3. Keep information dense areas interaction-free											
A4.4. Use dwell times of various lengths											
A4.5. Avoid using time-limited information											
A4.6. Never force users to interpret information in movement								Y			
A4.7. Use standards and affordances to minimize the cognitive load	Y	Y									
Joanna Kalalahti - Developing Usability Evaluation for Augmented Reality Applications											
A12.1. Interaction methods and controls		Y									
A12.2. Presentation of virtual objects						Y		Y			
A12.3. Relationship between virtual objects and real world		Y									
A12.4. Information related to virtual objects			Y								
A12.5. Suitability for the usage context											
A12.6. Physical comfort of the use							Y	Y			
Tristan C. Endsley - Augmented Reality Design Heuristics: Designing for Dynamic Interactions											
A13.1. Fit with user environment and task											
A13.2. Form communicates function		Y									
A13.3. Minimize distraction and overload						Y					
A13.4 Adaptation to user position and motion											
A13.5. Alignment of physical and virtual worlds											
A13.6. Fit with user's physical abilities							Y				
A13.7. Fit with user's perceptual abilities							Y				
A13.8. Accessibility of off screen objects			Y								
A13.9. Accounting for hardware capabilities											Y

Figure 3.1: The picture is of one of the google sheets used to document the comparative stage. The top row contains the main guidelines/categories that were created after the descriptive stage. The left columns represent the UX guidelines extracted from the related works. The letter "Y" was marked down when we identified that the UX guideline from literature (left column) was already addressed in our category (top row). UX Guidelines that were marked yellow were not addressed in our categories.

process, we identified ideas from [75, 90, 41, 23] around error tolerance and prevention that were not being reflected in our work. Eventually, a new guideline was created to incorporate these concepts due to their perceived value and lack of parallels with other guidelines. Through this process, we used three new resources to correlate to traditional UX heuristics and design guidelines which brought our total used resources to 68.

3.4 Specification Stage: Reframing UX Guidelines

In addition to integrating new ideas, the Comparative Stage identified aspects that needed to be improved. For example, we were able to find ambiguous parts through the different interpretations and discrepancies among the researchers. Based on the insights and new ideas until this point, we refined our initial set of guidelines. This process involved several meetings among the researchers around regrouping, merging, rewording, and restructuring different aspects of our work. Additionally, based on the structure provided by Quinones et al. [81], we organized our guidelines by providing a name, definition, and explanation with sub guidelines for each guideline. In the end, we had eleven guidelines. The guidelines created as a result from this stage are included in Chapter 4.

3.5 Evaluation Stage: Conducting a Case Study

For the Evaluation stage of our process, the goal was to obtain further insights that can be used to reflect on and refine the initial set of guidelines. While the HCI community has traditionally stressed the importance of user studies, many have also emphasized the importance of choosing an appropriate evaluation method to address the research questions that are under consideration [70, 33]. For our situation, the creation of our guidelines were the results of early exploratory research and our RQ3 focused on understanding how our work can aid in the creation of XR applications. As previously mentioned, one of the benefits of design approaches is that they support early innovation and allow the investigator to gain a detailed understanding of the situation through genuine usage of a system. Additionally, design research presents the opportunity to create a collection of artifacts that provide concrete embodiment of theory and showcases the researchers' journey [103]. As such, we decided to use this approach by conducting a case study where we used our guidelines throughout the development of an XR application and documented the entire process. More specifically, we worked in collaboration with the Alberta Electric System Operators (AESO) to create a prototype application that uses XR technologies to visualize and interact with data that exist within an AESO control center. Details of this stage are laid out in Chapter 5.

3.6 Reflection Stage: Retrospective on using and creating the UX Guidelines

For the final stage of our research, we focus on reflecting on our experience conducting the case study in the Evaluation stage and our overall experience creating the guidelines. The goal was to do a retrospective on the experience, identify in what ways our UX Guidelines can help XR developers and designers, and provide commentary on the state of UX design for HMD XR in both research and industry. Details of this stage are laid out in Chapter 6.

3.7 Summary

In this chapter, we documented the process of creating and evaluating our UX guidelines for XR applications. More specifically, we presented the six stages of our research, which were Exploratory, Descriptive, Comparative, Specification, Evaluation, and Reflection. In the next chapter, we present the work conducted in the Specification Stage by explaining each of our guidelines in detail.

Chapter 4

UX Guidelines for Extended Reality Applications on HMD

In this section, we present eleven UX guidelines for developing XR applications. They are ordered based on their specificity to the context of HMD XR applications.

4.1 Organize the Spatial Environment to Improve Efficiency

Definition. XR is inherently spatial. Use space as an organizational tool to create an environment that is comfortable to use and minimizes the amount of conscious thinking a user has to do to accomplish his or her goals [28, 57, 56, 76, 42, 54, 71, 95, 21, 69, 92, 77, 3, 4, 38, 6, 59, 65, 17, 64, 14, 55, 63, 51, 2, 43].

Explanation. XR can leverage how humans interpret spatial information to free up working memory and create dynamic environments. With that said, it is easy to create uncomfortable experiences depending on how the elements are placed around the user. It is important that the environment is carefully designed to take advantage of the extra space while limiting physical movement for accomplishing a task.

Additional Guidelines

Keep visual and physical restrictions in mind when arranging content. When positioning content, it is important to remember that users have physical limitations and a limited field of view. Place visual elements in areas where users' can comfortably view for long periods and interactive elements in areas where interaction is relaxed [28, 57, 56, 76, 42, 54, 95, 21, 69, 92, 77, 3, 4, 6, 59, 17, 64, 14, 51, 2].

Explore how space can be utilized. XR provides users with a larger area for placing and interacting with content. Depending on the context and type of application, designers should explore how the additional space can be used to avoid cluttering of objects and information. For example, the Windows Mixed Reality Home application in Fig. 4.1 lets users place apps and content in a virtual house similar to a 2D desktop. It showcases how a 3D environment can be used to spread out content to help with organization, multitasking, and visual appeal [57, 56, 94, 65, 55, 63].

Figure 4.1: The picture is of Windows Mixed reality home. The application lets users customize and place content throughout a 3D virtual house.

Group similar objects to make them easier to find. Placing similar objects together can use attention chaining behaviour to conceptually link application features together. This can help users find digital objects and information more efficiently and effectively. For example, in many kitchens' items meant for a specific task tend to be stored next to each other such that they are easier to find, like pots and pans, oils, utensils, etc. This concept can be extended to XR applications to help designer organize their virtual environments [57, 71, 38, 55]. (Fig. 4.2)

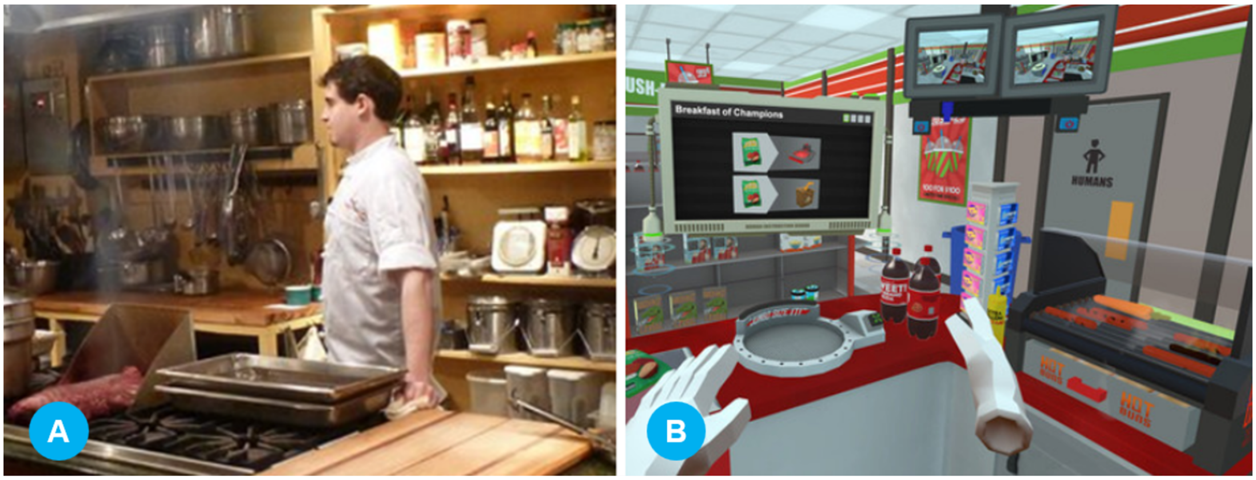

Figure 4.2: Picture showing environments where similar objects are grouped together. A: Show how kitchens are organized B: Show the VR game Job Simulator.[3]

4.2 Create Flexible Interactions and Environments

Definition. Provide users with the capability to customize the application to their personal preferences and comforts. Build in options that cater to a range of users that take into account different experience levels and physical considerations [56, 42, 66, 51, 75, 90, 41, 7].

Explanation. It is important to build in features that make the XR application accessible to a wide range of individuals. By giving users some control over the space around them and how they choose to carry out tasks, they will have opportunities to improve the overall satisfaction and ease of use for themselves. Moreover, designers and developers should consider how

[3]Picture adapted from `https://vrscout.com/games/job-simulator-oculus-rift/` and `https://www.tripadvisor.com/LocationPhotoDirectLink-g58313-d672387-i55763530-A_Chef_s_Kitchen-Williamsburg_Virginia.html`

factors, such as height and disability, may affect how people may use their application and build in options to accommodate different users' capabilities.

Additional Guidelines

Build in Interactions for Both Inexperienced and Experienced Users. The applications should have options that cater to users of varying level of experiences. Create cues for interactions for novice users and options to accelerate actions for more advanced users [75, 90, 41, 7].

Let Users Shape Their Environment to Optimize Their Workflow. Customization can be used to improve efficiency. Provide users with options to personalize the environment based on their preferences. For example, Google's Tilt Brush allows users to edit the layout of different elements on the menu based on their preference. [56, 66, 51]. (Fig. 4.3)

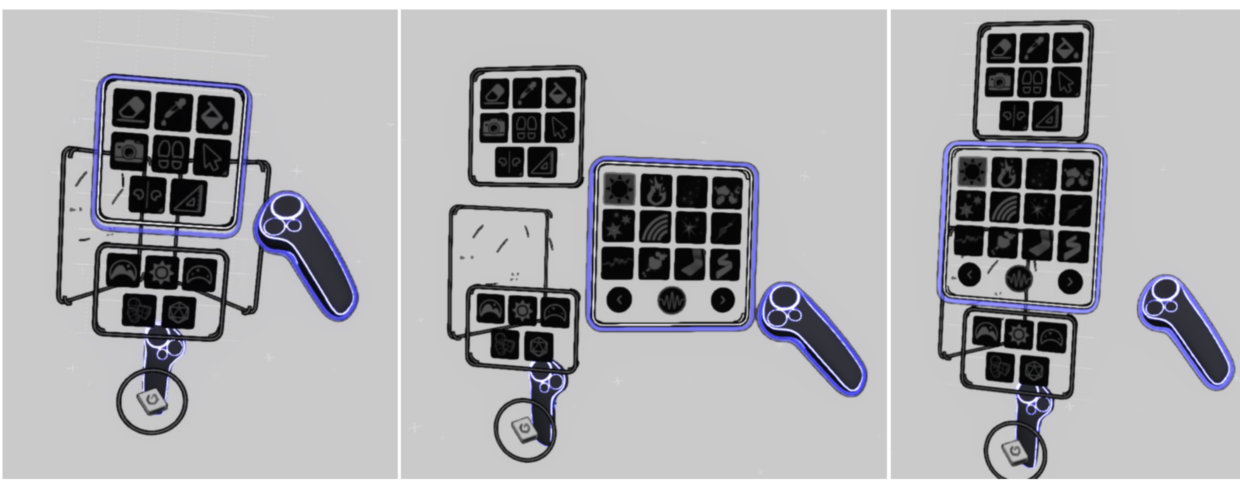

Figure 4.3: Picture from Google's Tilt Brush VR application. Shows how the menu can be altered based on user preference by allowing parts to be grabbed and placed in different areas of the menu.

Let Users Define What it Means to Be Comfortable. Factors that affect comfort like personal boundaries, physical limitations, social considerations, brightness, etc. should be flexible. The designer should identify potential aspects of their application that could negatively impact the user and build in options to adjust them in the settings [42].

4.3 Prioritize User's Comfort

Definition. The XR application should keep the user safe by taking extra precautions to maintain the physical, physiological, and environmental comforts for the user throughout the experience [57, 56, 76, 42, 20, 54, 95, 32, 36, 21, 39, 69, 92, 13, 86, 77, 40, 3, 8, 83, 4, 22, 50, 6, 61, 59, 17, 64, 14, 51, 2, 43].

Explanation. Being immersed in a 360-degree environment opens the user up to a lot of different factors that impact users' comfort. Avoid putting users in situations where potential distresses might arise and provide options for users to adjust settings related to comfort.

Additional Guidelines

Respect Users' Personal Space. People are both physically and mentally sensitive, especially around the head, to objects that are placed too close to them. Make sure objects are defaulted to a comfortable distance away from the user and allow them to dictate what happens within their personal space [57, 56, 76, 42, 54, 22, 61, 64, 51, 2].

Physiological Considerations. Due to the fact that XR provides users with an immersive experience, users might experience discomfort due to the disparity between what one feels and what one expects to feel. It is the designer's responsibility to take extra precautions to reduce the chances of users experiencing motion sickness. For example, avoid acceleration of the user inside of your application as the user will not feel the change in real life. Also, maintain a high framerate as delays and latency in rendering may make the user nauseous [57, 76, 42, 20, 32, 36, 21, 39, 92, 13, 86, 40, 3, 8, 50, 6, 61, 59, 43].

Environment Comfort. Certain users can experience various discomforts in certain situation like heights, small spaces, etc. Provide options for users to change or adjust the environment if they are uncomfortable [21, 40, 83, 51].

Be Mindful of Physically Draining Interactions. XR applications provide designers with the opportunity to create 3D interactions. Be cautious of the fact that 3D interactions can be physically exerting for users especially over long periods and repeated repetitions.

Additionally, where content is placed also dictates the type of physical interactions that are required. For example, content placed outside a user's field of view requires them to turn their body or head to view or interact with the object [57, 56, 42, 20, 21, 69, 92, 77, 40, 59, 64, 2, 43]. (Fig. 4.4)

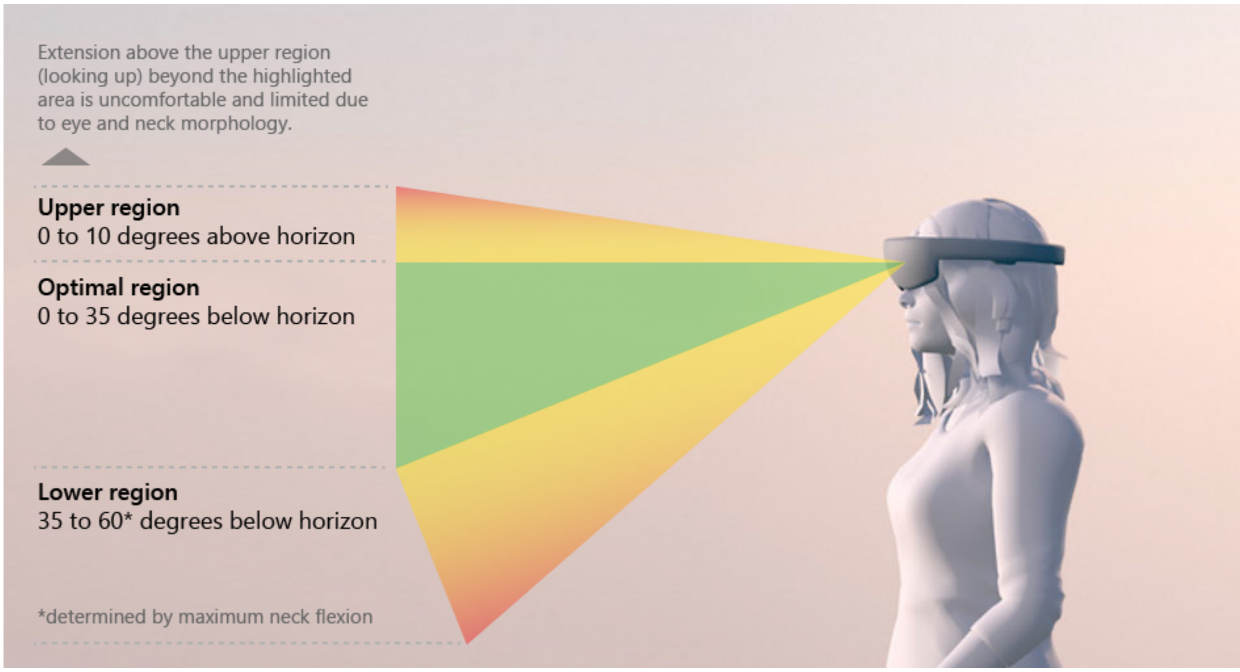

Figure 4.4: Microsoft proposed allowable field of view determined by the range of motion of the neck.[4]

4.4 Keep It Simple: Do Not Overwhelm the User

Definition. The more there is, the less the user remembers. Create simple and relevant elements in an environment that do not distract the user from what is important [57, 56, 76, 42, 92, 40, 25, 22, 38, 6, 61, 51, 7].

Explanation. There is a fine line between enhancing an experience through additional information and overwhelming the user. XR provides more virtual space but the user still has a limit to how much information she can consume. Designers should focus on minimalism

[4]Picture from https://docs.microsoft.com/en-us/windows/mixed-reality/comfort

as irrelevant information competes for user attention.

Additional Guidelines

Keep Tools and Information Ready, but not Distracting. Designers can provide a lot of information, but they should be implemented in a way that does not distract users when they do not require them. Provide users with the ability to hide, minimize, or turn off elements. Additionally, the element should be visually quiet while inactive as to not take the focus away from other tasks [57, 56, 42, 92, 25, 38, 51, 7]. (Fig 4.5)

Figure 4.5: Microsoft HoloLens can toggle between showing and hiding the main menu through a bloom gesture.

Don't Obscure the User's Vision with Virtual Elements. Minimize the density of information within a user's field of view and be wary of using persistent heads-up displays (HUD) that takes up a large portion of a user's view [57, 56, 76, 40, 22, 6, 61] (Fig. 4.6)

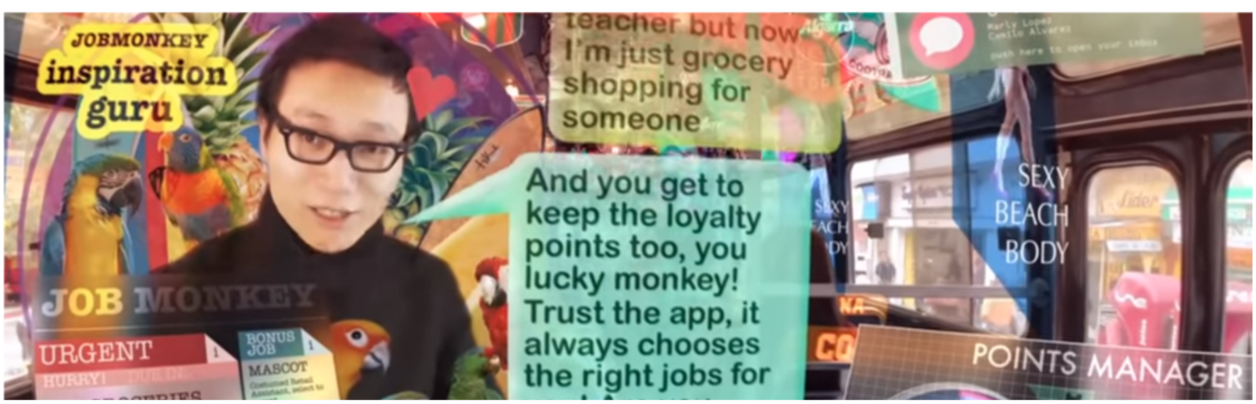

Figure 4.6: HYPER-REALITY rendition of an augmented reality future. The picture shows how a lot of visual elements can create an overwhelming experience.[5]

[5] Picture from `https://www.youtube.com/watch?v=YJg02ivYzSs`

4.5 Design Around Hardware Capabilities and Limitations

Definition. The way users interact and explore the environment will be greatly dependent on the system they are using. Always keep the capabilities of the hardware in mind when crafting XR experiences [20, 86, 51, 2]

Explanation. Currently, there is a lack of standardization across XR devices. VR, AR, and MR offer different experiences that require different design considerations. Additionally, there is a lot of variety within these categories regarding input type, tracking limitations, device features set, etc. As such, it is important that designers understand the medium and build an experience that suits its capabilities.

Additional Guidelines

Sensitive to the Capabilities of the Hardware. Applications should not include features that go beyond the limits of the hardware. The designer should be selective and choose features that comfortably stay within the capabilities of the system. For example, the Microsoft HoloLens has a field of view (FOV) of 35 degrees while HTC Vive has a FOV of 110 degrees. This difference affects how much content can be placed within a user's immediate line of sight. As such, the size and placement of visual elements should be adjusted based on the targeted system of the application [20, 86, 2]. (Fig. 4.7)

Use the Strengths of the Medium. It is important that designers focus on features that highlight the strength of the given hardware in their application. Showing off the advantages of the system will minimize the impact hardware limitations have on UX [51].

Figure 4.7: Picture showcase a range of different HMD XR product. From left to right: HP windows mixed reality headset with inside-out tracked controllers, Meta 2 with built-in hand tracking, Microsoft Hololens with gesture controls, HTV Vive with base station tracking. All these devices have differences that should be considered when designing for them.

4.6 Use Cues to Help Users Throughout Their Experience

Definition. Create signifying cues to help users to get started, provide additional information, guide user's attention, and simplify choice within the application [57, 56, 42, 20, 53, 71, 94, 101, 36, 19, 21, 92, 68, 99, 86, 77, 83, 6, 61, 11, 64, 63, 51, 43, 75, 7].

Explanation. The expanded capabilities of XR also comes with the greater potential of users being overwhelmed or lost. Designers should take extra measures to make sure that they provide enough guidance throughout the applications to keep frustrations to a minimum.

Additional Guidelines

Use Attention Directors to Help Users Discover What They Can Do and Where They Should Go. Provide the user with directional indicators to point them to important content in the application. This is especially vital for XR as the area in which content can be placed is much larger than traditional 2D application [57, 56, 53, 71, 36, 19, 21, 99, 86, 77, 83, 6, 61, 11, 51, 43].

Simplify Choice. Use cues to explicitly inform users what they can do next especially if the steps are not obvious. This can help reduce hard cognitive thinking and ease frustrations throughout the experience. For example, Fig. 4.8 illustrates how The Lab uses a yellow arrow to explicitly inform the user of a possible action that she could take. [56, 42, 20, 71, 94, 101, 68, 64, 63, 43].

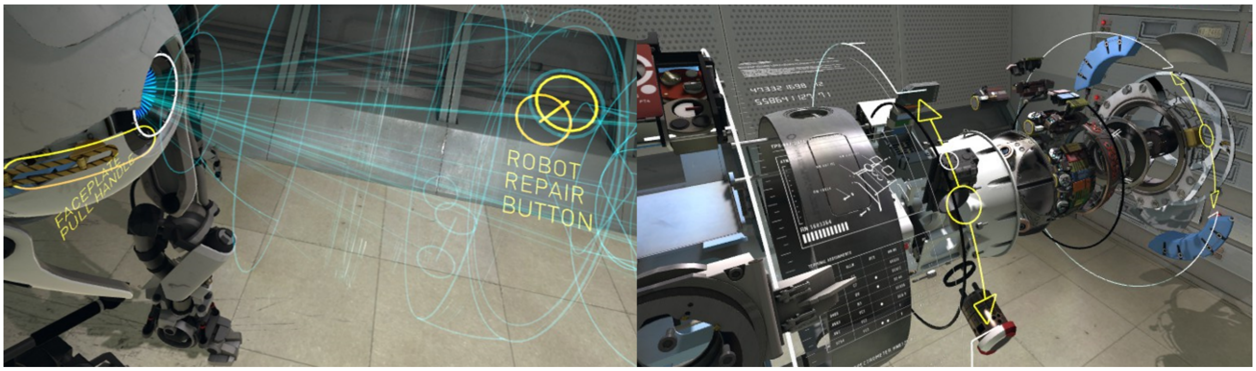

Figure 4.8: Picture from Valve's The Lab: Robot Repair. Yellow cues are placed throughout the experience to inform the user of the actions that need to take place in order to progress.

Do not Overload the User's Senses with Notifications. Be mindful of the fact that users can be easily overwhelmed by an excessive amount of information, especially in XR. When designing cues, not only think about delivering the information but also how it can be conveyed in an efficient and comfortable manner [56, 7]

Use Cues to Integrate Help and Tutorials in the Experience. It is important that users have access to help when they need it. Instead of just providing external documentation, think about how different cues can be used to integrate help into the XR application to create a seamless experience [75, 7]

Inform the Users of Actions That May Result in Errors. The best way to deal with an error is to prevent it from happening in the first place. Use cues to inform users of the potential dangers and consequences of an action before it is executed [75]

4.7 Create a Compelling XR Experience

Definition. XR allows users to be immersed in the virtual environment. Enhance their senses through comprehensive audio and visual elements that captivate them and enhance the sense of presence in the experience [57, 56, 76, 42, 20, 32, 36, 39, 69, 86, 77, 3, 25, 8, 83, 84, 80, 22, 6, 87, 62, 11, 66, 64, 63, 51, 43].

Explanation. Users senses are more exposed when immersed in XR applications. This presents additional challenges for designers, but it also offers an opportunity to elevate the experience. Explore how aesthetic elements can be used to captivate the user and provide them with an application that they want to use continually.

Additional Guidelines

Make the Experience Appealing. Add visual elements that make viewing and interacting with the application enjoyable [56, 20, 36, 87, 11, 63, 51, 43].

Use Audio to Enhance the Experience. In the real world, sound plays an important role in how people interact and understand the space around them. Use spatial sound to help users feel situated, suggest spatial relationships through feedback, and create ambiences to immerse users in the virtual environment [57, 56, 76, 42, 32, 36, 39, 69, 77, 3, 8, 83, 84, 22, 6, 15, 66, 64, 63, 51, 43].

Make a Complete Experience. The more comprehensive the environment, the more it resonates. XR provides the tools for immersion, but it is up to the designers to build in details to maintain the feeling of being in an environment the user know is not completely real [20, 36, 86, 3, 84, 22, 12, 62, 63, 51, 43]

4.8 Build upon Real World Knowledge

Definition. Help users to understand how to use the application by designing the interactions, objects, and environments around existing knowledge of the real world [56, 42, 94, 92, 68, 86, 83, 84, 22, 38, 26, 15, 87, 60, 65, 89, 88, 16, 64, 18, 51, 2, 43]

Explanation. People have prebuilt mental models on how objects should behave based on prior real-world knowledge and experiences. XR designers can capitalize on these familiarities by using aspects of the real world as inspirations for designing virtual environments. This can help lessen cognitive load and educate users without being explicit.

Additional Guidelines

Use Real-Life Inspiration to Create Affordances in Objects. Affordance refers to the properties of an object that informs the user how it should be interacted with and used. Build in virtual elements which reflect properties from real objects that hint at how users should use certain elements. For example, Fig. 4.9 shows how Weightless, a demo from Leap motion, used properties of a bowling ball to help inform users on the correct way to grasp certain objects in the application [56, 42, 94, 92, 83, 38, 26, 87, 60, 65, 89, 88, 64, 18, 51, 2, 43].

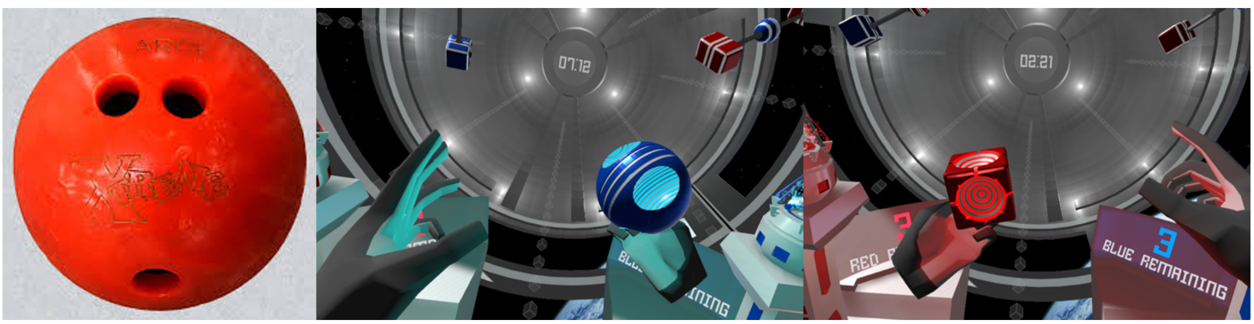

Figure 4.9: Picture is based on leap motions' blog Interaction Sprints at Leap Motion: Exploring the Hand-Object Boundary and Designing Physical Interactions for Objects That Don't Exist. It shows the process of building real life affordances into the design of a grabbable object in their demo Weightless.

Pair Actions with Outcomes That Users Expect. Keep in mind that certain visual characteristics may affect users' expectation of how certain elements should behave. Make sure that virtual elements act in accordance with their characteristics and associated affordances [56, 42, 94, 68, 84, 22, 15, 16].

Consider the Use of 3D (Volumetric) Representation. XR applications give designers the ability to create elements that can be explored and interacted with in 3D. This can be leveraged to better mimic and build upon real world objects [56, 94, 51].

Be Cautious of Simplified Interactions. Users' expectations for the detail of interactions may be higher in XR due to the increased associations with real experiences that comes with immersion. For example, a real screwdriver is a tool meant for screwing and unscrewing screws, but it has physical properties that allow it to do more than its original purpose. A virtual screwdriver may not have additional interactions outside its intended purpose. It is important that designer build protections to deal with or inform the user of the limitations of the application [86].

4.9 Provide Feedback and Consistency

Definition. Use feedback to generalize perception of events and interactions. Additionally, feedback should be consistent such that users can build an understanding of what they can and cannot do within the application [57, 56, 42, 20, 54, 94, 32, 69, 99, 3, 8, 83, 84, 6, 37, 48, 26, 87, 60, 64, 14, 51, 2, 43].

Explanation. The more consistent feedback that is provided to the user, the better off they will be to make informed decisions. Due to the immersive nature of XR applications, the importance of feedback is amplified as users may have expectations on how certain aspect of the application should behave based on real-life experiences. For example, real objects have properties, like weight, hardness, size, etc., that governs how they behave. Despite having similar visual appearance, digital elements do not have guarantees that their behaviour will match that of real-world objects with similar properties. As such, it is important that developers build in consistent feedback to inform the user on how to interact with the application.

Additional Guidelines

Use Feedback to Standardize Interactions States. Consider how elements in a digital environment should react to user interactions. All interactions should have distinct states that are conveyed through visual feedback. Furthermore, different states should have distinct properties that are consistent such that users can familiarize themselves and recognize them as they use the program [57, 56, 42, 20, 54, 32, 69, 99, 3, 8, 83, 84, 6, 37, 87, 60, 64, 14, 51, 2, 43]. (Fig. 4.10)

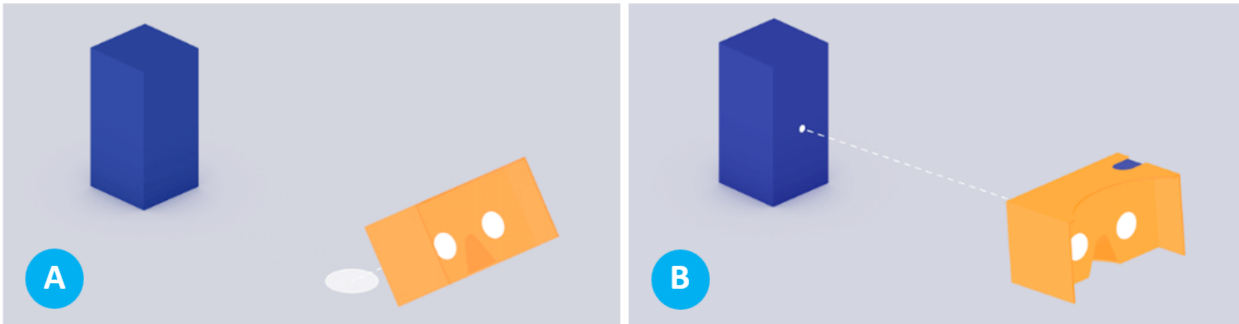

Figure 4.10: Example of dynamic feedback on Google Cardboard. A: Head reticle when looking at moveable areas B: Head reticle when looking at objects where no interaction is available. Picture from [83].

Use Feedback to Help Recognizes Errors and Unwanted States. Inform users of the results whenever an action is performed. For instance, the system should make it clear if an action is possible, whether an interaction was detected, if all requirements were met to perform a certain action, etc., such that users can alter their behaviour to learn from their interaction mistakes [14].

Design for Dynamic Exploration. Provide users with enough information to understand how to use the application by interacting with and exploring the environment. Digital elements should provide feedback that is consistent across the experience such that users can build a mental model of how the XR application works to recognize how to accomplish tasks quickly [56, 42, 94, 48, 26, 87, 60]. (Fig. 4.11)

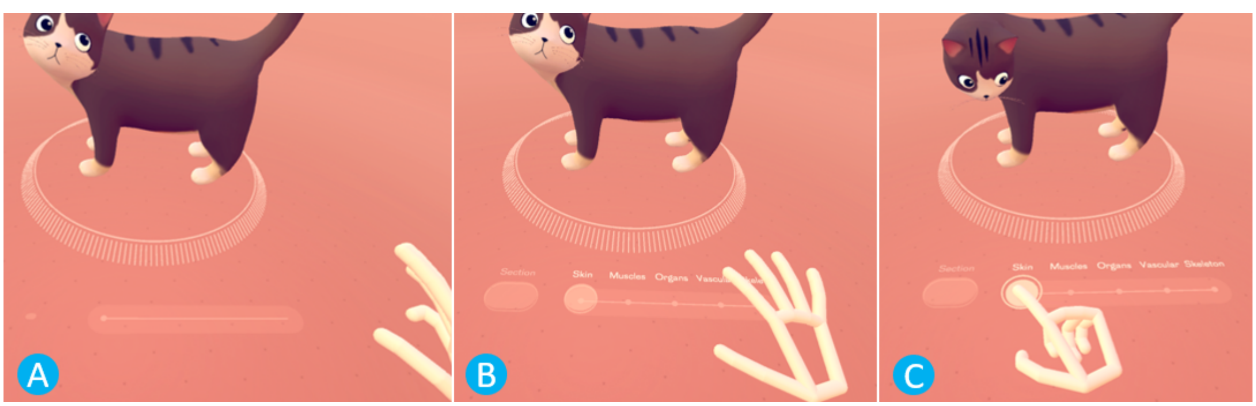

Figure 4.11: Example of dynamic feedback from leap motion's Cat Explorer. A: Menu does not appear when the user's hand is far away B: Menu appears when the user brings their hands' closer C: The button light up when it is pressed.

4.10 Allow Users to Feel in Control of the Experience

Definition. The application should act and respond in a way that gives users the sense that they are in charge. [57, 56, 42, 20, 54, 94, 99, 40, 6, 51, 75, 90, 41, 28].

Explanation. Users are vulnerable when they are using HMD XR devices. Traditional 2D screens display content at a distance from people, but with XR applications, users are immersed in virtual environments. It is important for the application to establish a feeling of trust with the user by making sure that they feel in control during the whole experience

Additional Guidelines

Don't Force Actions Without User's Permission. The application should never assume what a user wants to do. Allow users to get situated in their environment and move at their own pace. Additionally, it is a good idea to make sure that a user gives express permission before performing actions with consequences [42, 20, 54, 99].

Provide Exits for Users to Leave Unwanted States. Provide users with easy options to abandon certain actions or leave unwanted situations with minimal resistance and hassle from the application. For example, SteamVR, a platform for running VR games, has a dedicated button mapped to stopping the currently running app and entering a system menu. This concept can be integrated on a smaller scale within XR applications [75, 90, 41, 28].

The Application Should Be "Honest". Make sure the behaviour of the system matches the user's expectations. Breaks in consistent behaviour may cause unintended surprises and could discourage future exploration. Additionally, it could make the user feel like they are being deceived by the application [56, 94, 51].

Let Users Control Their Movements. For HMD XR applications, it is always important that the control of the virtual world camera stays with the user. This will help her or him feel in control and immersed in the experience [57, 40, 6, 28].

4.11 Allow for Trial and Error

Definition. As much as possible, allow actions to be reversible and set up protections around potential mistakes made by users. This will help relieve user's anxiety and promote exploration of the application [75, 90, 41, 23].

Explanation. XR designers have more opportunities to provide users with interactions that have a bigger impact on the experience. However, more control also equates to a larger possibility for mistakes. Furthermore, previous error tolerance techniques, such as dedicated back buttons or keyboard shortcuts, are not always meaningful in XR applications. It is important that designer builds in protections for when users' inevitably make errors.

Additional Guidelines

Permit Easy Reversal of Actions. Provide users with clear options to deal with actions that they may want to undo such that they can freely explore the application without worries. For example, Google's Tilt brush has an undo and redo button on the menu to manipulate actions done by the user [75, 90, 41, 23]. (Fig. 4.12)

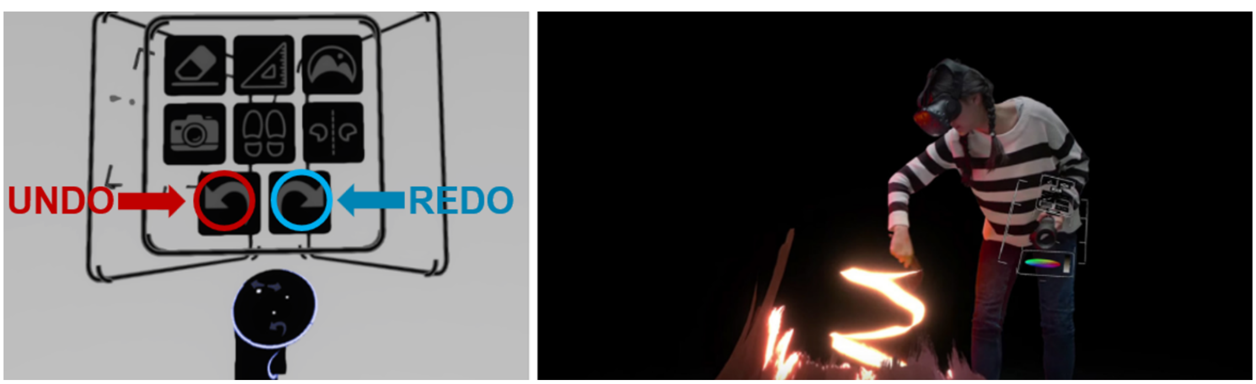

Figure 4.12: Picture of Google's Tilt Brush Undo and Redo buttons.[6]

[6]Picture from `https://www.youtube.com/watch?v=TckqNdrdbgk`

4.12 Summary

In this chapter, we outlined our set of eleven UX guidelines for XR applications. For each, we provided a name, definition, explanation, sub guidelines, and references to the original resources they were derived from. Additionally, we created Fig. 4.13 to provide a concise overview of our work. Also, a list of the specific references used in the creation of our guidelines can be found in Appendix B. In the next chapter, we describe the case study that was conducted as part of the Evaluation stage of the research that uses our guidelines in a development scenario.

User Experience Guidelines for HMD XR Applications

1. Organize the spatial environment to maximize efficiency
XR is inherently spatial. Use space as an organizational tool to create an environment that is comfortable to use and minimizes the amount of conscious thinking a user has to do to accomplish his or her goals.

2. Create flexible interactions and environments
Provide users with the capability to customize the application to their personal preferences and comforts. Build in options that cater to a range of users that take into account different experience levels and physical considerations.

3. Prioritize User's Comfort
The XR application should keep the user safe by taking extra precautions to maintain the physical, physiological, and environmental comforts for the user throughout the experience.

4. Keep It Simple: Do Not Overwhelm the User
The more there is, the less the user remembers. Create simple and relevant elements in an environment that do not distract the user from what is important

5. Design Around Hardware Capabilities and Limitations
The way users interact and explore the environment will be greatly dependent on the system they are using. Always keep the capabilities of the hardware in mind when crafting XR experiences.

6. Use Cues to Help Users Throughout Their Experience
Create signifying cues to help users to get started, provide additional information, guide user's attention, and simplify choice within the application

7. Create a Compelling XR Experience
XR allows users to be immersed in the virtual environment. Enhance their senses through comprehensive audio and visual elements that captivate them and enhance the sense of presence in the experience

8. Build upon Real World Knowledge
Help users to understand how to use the application by designing the interactions, objects, and environments around existing knowledge of the real world

9. Provide Feedback and Consistency
Use feedback to generalize perception of events and interactions. Additionally, feedback should be consistent such that users can build an understanding of what they can and cannot do within the application

10. Allow Users to Feel in Control of the Experience
The application should act and respond in a way that gives users the sense that they are in charge.

11. Allow for Trial and Error
As much as possible, allow actions to be reversible and set up protections around potential mistakes made by users. This will help relieve user's anxiety and promote exploration of the application

Figure 4.13: Overview of the Eleven UX Guidelines for HMD XR applications.

Chapter 5

AESO Immersive Control Room: A Case Study

In this chapter, we present the case study that was conducted during the Evaluation stage of our research. During this process, we used our guidelines throughout the creation of an XR application and documented the experience. The objective was to gain insight into the effectiveness of our work through genuine usage in a development scenario. This chapter is divided as followed: 5.1 introduces the project, 5.2 provides a detailed retelling of the case study, and 5.3 recaps the features of our final prototype. With this section, we aimed at addressing RQ3: *In what ways can HMD UX guidelines aid in the design and creation of future XR applications?*

5.1 Introduction to the AESO Immersive Control Room Project

5.1.1 Who is AESO

The Alberta Electric System Operators (AESO) is a not-for-profit organization that works with both industry partners and the government to ensure the safe, reliable, and economical operation of the Alberta electricity system [1]. Some of their responsibilities include monitoring and managing the electricity grid, operating the competitive market, planning the future of the system and its infrastructure, and connecting customers who either want to generate or consume power from the grid.

5.1.2 The Project

To ensure that millions of Albertans have access to power when they need it, AESO maintains a 24/7 control room and a backup facility where they monitor the electrical grid and balance the supply and demand of energy. The AESO control room houses a large number of screens, with an entire wall dedicated to displaying visualizations and each System Controller having multiple personal monitors (Fig. 5.1). This provides AESO's personnel with a lot of screen real estate to view all the information needed to accomplish their tasks. However, in situations where a system controller may want or need to carry out a task in a different location, it may be hard to fit and navigate through all their information with traditional hardware such as a laptop.

In recent years, we have seen the emergence of various Extended Reality (XR) technologies, such as Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR). More specifically, we have seen the rise of Head Mounted Displays (HMD) XR, such as the HoloLens, Oculus Quest, HTC VIVE, etc., that allow users to put on a headset and be immersed in a virtual environment. In contrast to 2D displays, by tracking and utilizing a 360-degree view, perceived depth, and movement tracking, HMD XR greatly expands the space by which users can view and interact with digital content. Additionally, these technologies provide these experiences with hardware that is relatively compact in size.

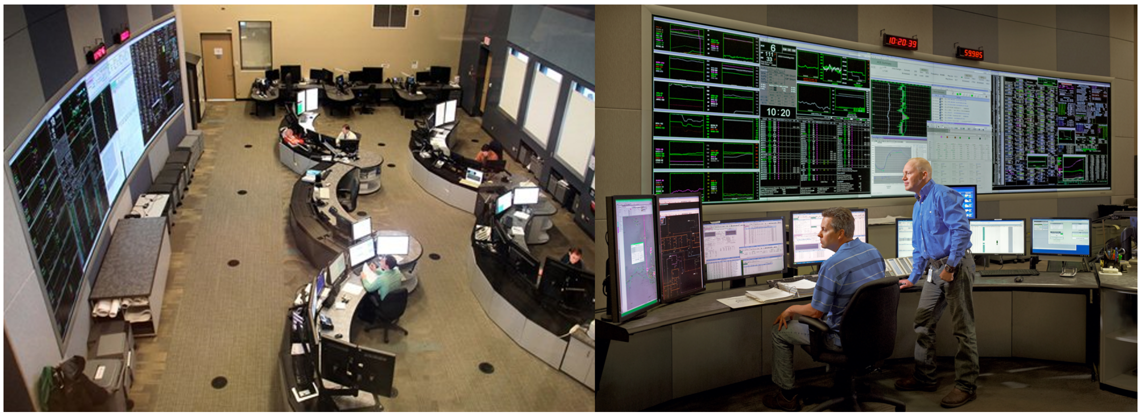

Figure 5.1: Pictures of the current control room in AESO Control Centre.[7]

In collaboration with AESO, we developed the Immersive Control Room, a prototype application that explores how the capabilities of XR can be utilized to create an accessible virtual environment for carrying out current control room tasks in different locations. The primary use case is to provide system controllers visibility to more information during an unplanned failure of the control room. For example, when controllers need to move to the backup site, they use laptops to view and navigate through their information, which is different than a video wall and multiple monitors. The goal of our prototype was to explore how we can design an HMD XR application that provides AESO's personnel with accessible visibility of their data.

5.1.3 Related Work

Previous work has explored using immersive technologies to create virtual environments for consuming and interacting with information for various use cases.

Wenn et al. [98] published a paper in 2001 that discusses the Control Room of the Future

[7]Pictures from `https://www.aeso.ca/aeso/media/`

(CRF) project, which researches technologies that could aid system operators in the future. Part of the project included working with the National Grid company PLC, which is responsible for the electricity transmission system in England and Wales, to develop an early prototype of a virtual control room based on Birmingham Dispatch Training Simulator on a CAVE Advanced Virtual Environment (CAVE) system. (Fig. 5.1A)

Broughton et al. [10] overviews the Virtual Planning Rooms (ViPr), a virtual environment for exploring course-of-action visualizations. Developed by the FOCAL lab at Australia's Defense Science and Technology Organization, the application places operators in a room where they can view and interact with relevant information. Additionally, the user can navigate to connecting rooms to view different data sets from different levels of abstraction. (Fig. 5.1B)

Lee et al. [52] developed a system called FIESTA, a prototype VR system for immersive collaborative analytics. The prototype allows users to author and create visualizations that can be repositioned, resized, and duplicated in the space around them. Moreover, the application supports collaboration such that groups can conduct team-based analysis.(Fig. 5.1C)

While these literature does present relevant examples, the goals and situation of our project are quite different than the reviewed work. For our project, we aim at creating an original design that is better suited for our situation.

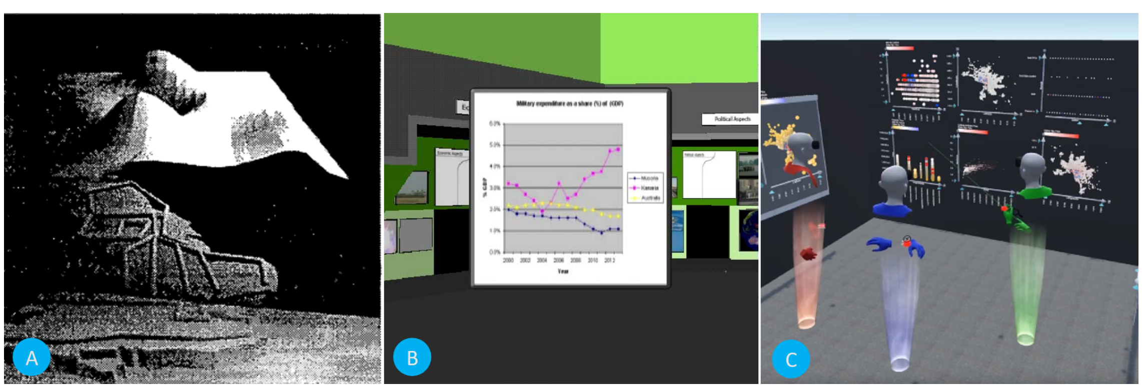

Figure 5.2: Pictures of previous Virtual Control Room Environments. A: CRF project [98] B: ViPr virtual environment [10] C: FIESTA Prototype [52].

5.2 Developing the AESO Immersive Control Room

In this section, we provide a detailed retelling of the development process and showcase how our HMD UX Guidelines were used throughout the project.

5.2.1 Starting the project

We initially came up with the idea of using XR technologies to create a virtual control room that can act as a backup alternative to real control rooms through our experience with previous work at the Agile Surface Engineering (ASE) Lab. However, at that time, this was nothing more than just a concept as we did not have enough extensive knowledge of real control room operations to warrant turning the idea into a full project. As we started to get more serious about building this system, we realized that we needed a partner that deals with control rooms to provide us with information, guidance, and data. We then turned to industry and contacted related companies to see if they were interested in partnering with us. After talking with a few businesses, we eventually met with AESO who agreed to work with us.

After all the paperwork and legal documents were finished, we started the project by first getting a general understanding of who is AESO and their responsibilities. Our contact at AESO gave us a presentation about their overall operations, the energy management system and software, and their role in maintaining the electrical grid in Alberta. Additionally, we were able to able to tour the Control Room and talk to some of the personnel working there. This was a very informative and essential first step for us. Before, we had an unrefined idea of the tasks that were carried out in a control room, but after seeing one in person, we had a lot more clarity on the subject and the project direction. A few things that stood out during this process:

- The system operators all work off traditional desktop PC hardware. We thought that there might be some specialized hardware that may be used in the control room (switch, control boards, etc.), but that was not the case for AESO.

- The AESO system operators mainly focused on consuming information rather than controlling different infrastructure.
- There were five main desks in the control room, with each assigned a different role.
- Each desk has 9 monitors for each system controller.
- Each system controller has their own preferred layout for the application on their desktop.
- One of the screens on the system controller desk was focused on displaying map data.
- The control room has a video front wall spanning the entire wall that displays information in real-time.
- Information on the front wall is meant for different system controllers to get a peek at general information about the grid.

In addition to providing us with guidance on this topic, we needed data such that we could use to simulate the visualizations being updated in our application. As such, AESO provided us with 24 hours of data for some of the visualizations on the front wall. This was enough for us to get started.

After we got a better sense of AESO operations, we started to come up with different ideas for our XR application. AESO provided us with resources and feedback but ultimately left the design of the project up to our discretion. To start, we were very open to the direction of the project but wanted the initial focus to be on exploring different ways we could view and interact with the visualizations. We started creating sketches and narrowed the ideas down to a select few (Additional sketches can be found in Appendix B). There were three main concepts that we considered as a starting point for our project.

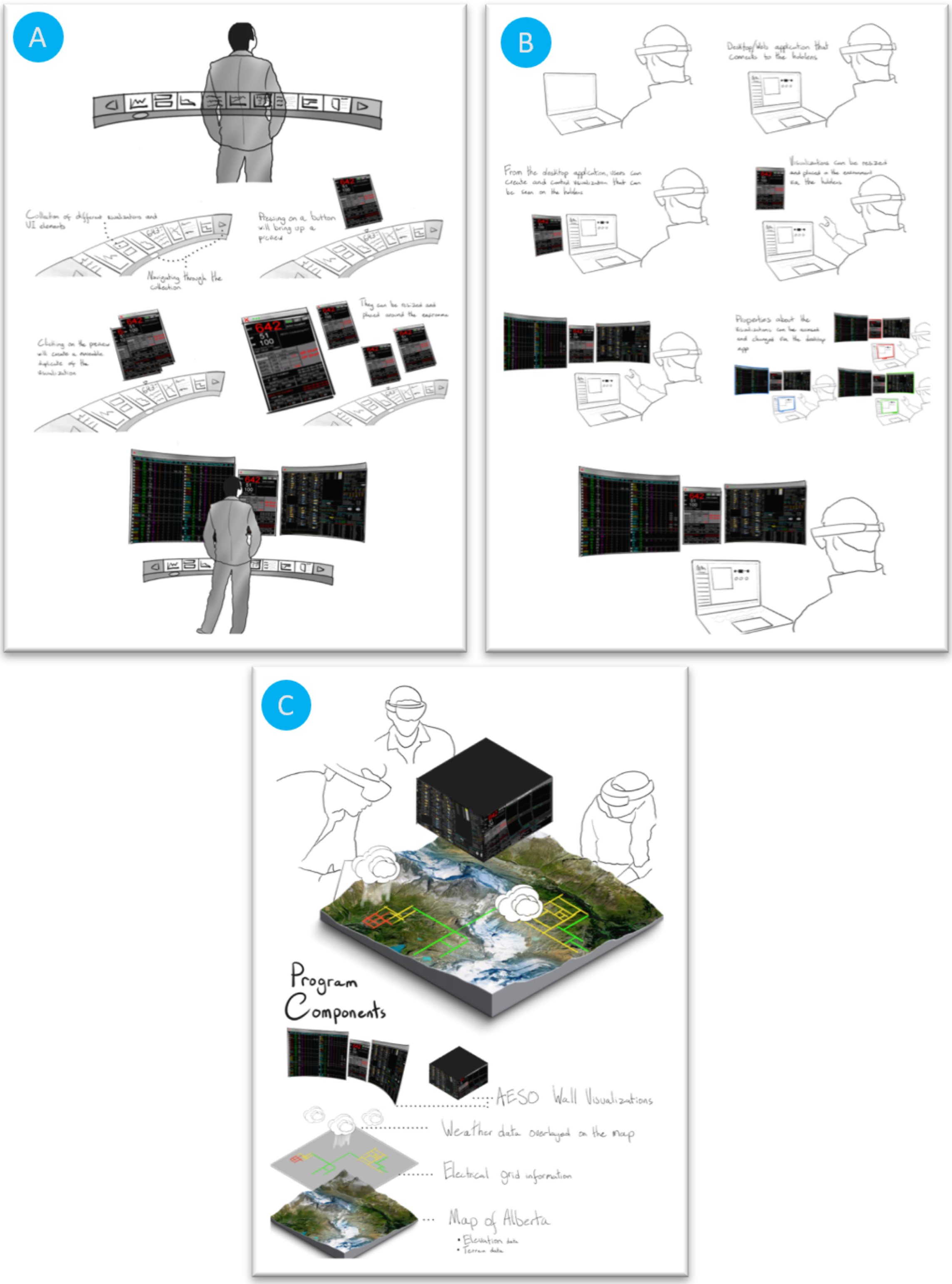

Figure 5.3: Shows three sketches that represent the main concepts that were considered for the starting point of the project.

- The first focused on building a virtual menu to view, spawn, and interact with the visualizations. We would use the menu as the main component to navigate to other features of the application as well. (Fig. 5.3A)
- The second concept was on extending traditional computers with an MR headset. In this idea, we would allow users to continue with their familiar workflow working on a laptop/desktop but also let them leverage MR to extend their screen real estate. We would build a 2D desktop application for common tasks, such as inputting information, that communicates with an MR application where the user can move and place visualizations around them. (Fig. 5.3B)
- The third concept was based on the idea of leveraging XR to create a 3D work environment with 3D visualizations. AESO had an application available on each system controller's desk that was dedicated to showing the Alberta map with electrical grid and weather data overlaid on top. This idea explores how we can design a 3D workspace with the Alberta map as the center focus. (Fig. 5.3C)

During this ideation/sketching phase, we started to use our UX guidelines in the design process. As previously mentioned, the direction of the project was fairly open, and we found ourselves using our work as general starting points to help spawn and generate different ideas.

- The second main concept was influence by G2 (*Create Flexible Interactions and Environments*), G3 (*Prioritize User Comfort*), and G5 (*Design Around Hardware Capabilities and Limitations*). Traditional input devices such as mouse and keyboard are very different than HMD XR devices input systems that often use controllers and hand gestures. This idea focused on expanding the hardware capabilities (G5) such that it is more familiar and comfortable for AESO's System Controllers (G3). Also, this design affords us the flexibility to explore different ways/inputs later as we have multiple ways of interacting with the system (G2).

- The third main concept spawns from G8 (*Build upon Real World Knowledge*), and the sub guidelines (*Consider the Use of 3D (Volumetric) Representation*) as the whole concept was meant to explore 3D environments and representation for our application.

We also used our work to help guide some of the finer details of our sketches.

- In the first main concept, G3 (*Prioritize User Comfort*) and the sub guideline (*Be Mindful of Physically Draining Interactions*) inspired the placement of the menu by trying to position it in a way that would minimize the strain of the neck and movement of the arms to interact with the menu.

- The third main concept used G8 (*Build upon Real World Knowledge*) to inspire the look of some of the elements in the sketch. We this being reflected in using clouds to indicate weather areas on top of our map and using sports arenas as a reference to place elements in our workspace. (Fig. 5.4)

Figure 5.4: Showcases how hockey arenas inspired our sketch following G8 (*Build upon Real World Knowledge*)[8]

[8]www.nhl.com/blackhawks/news/the-verdict-new-scoreboard-takes-game-experience-to-next-level/

Following a lot of discussion and feedback from both the teams and our AESO contact on the different ideas, we decided to go with the first main concept as the starting point for our project.

5.2.2 Starting development

After deciding on an initial concept, we assembled a team that would work on development for the project. This included me as the team lead, a full-time undergraduate student, a part-time graduate student, and Dr. Frank Maurer as the project supervisor. We set weekly team meetings where we would all discuss prior tasks, prioritize worklist, bring up any concerns, and brainstorm future features. The development started in May 2019 and was set to last until December of 2019.

After briefing the team on the project and providing them with a rundown of our HMD UX guidelines, we began development. We used Unity3D as the software platform for our application and the HTC VIVE as our main testing device. During the early phase of the project, a lot of time was dedicated to finding libraries to use, figuring out the data workflow, and mapping out the code architecture of our application. As such, when it came to the UI design, we started simply by creating a curved panel and placing 3D buttons along its

surface. When clicking the button, a line chart graph would spawn right above It was at this time when we started to explore incorporating feedback into the design based on G9 (*Provide Feedback and Consistency*) and the sub guideline (*Design for Dynamic Exploration*) by having a preview of a graph pop up when the controller ray cast cursor hovered over one the buttons. (Fig. 5.5)

The next goal was to recreate the visualizations that corresponded with the data that was provided to us by AESO. Using pictures and information given to us, we developed different visualizations in our application that replicated the aesthetic from the control room. We started with a dark opaque background for the visualizations, but as we continued to develop,

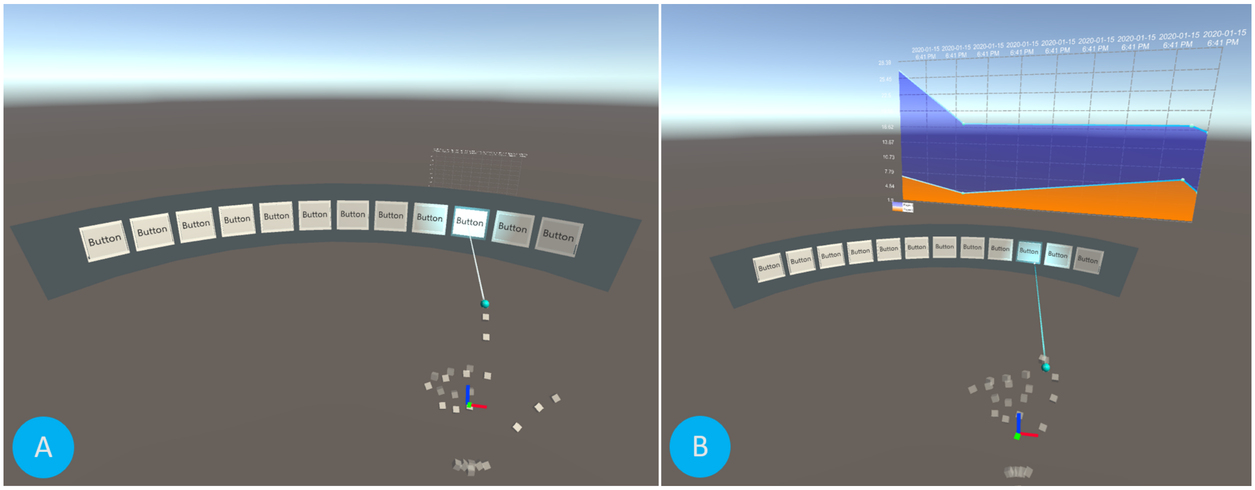

Figure 5.5: An early version of our main menu. A: shows a preview graph appearing when the hand/controller ray casts over a button. B: shows a line graph spawning when a button is clicked.

we transitioned to a semi-transparent background.

This change was inspired by G3 (*Prioritize User's Comfort*) specifically (*Environment Comfort*) as we felt that large opaque panels might cause a sense of claustrophobia and changing the background to be semi-transparent gave the user a better sense of their surroundings. Additionally, based on G7 (*Create a Compelling XR Experience*) and (*Make the Experience Appealing*) we thought this change looked more aesthetically pleasing. (Fig. 5.6)

At first, we had "building an environment" as a lower priority feature when compared to developing the menu and visualizations; however, we found ourselves prioritizing this task earlier than expected. This was due to us following G3 (*Prioritize User's Comfort*) more specifically (*Environment Comfort*) and (*Physiological Considerations*). The default unity scene we were using did not have a floor which made looking down while using the HTC VIVE unnerving for people who were sensitive to heights. Moreover, some of the people who tried the application mentioned that floating in an empty space caused them to feel nauseous. As such, we decided to address this issue early on by building a room to place the user in. While we could have constructed a simple environment, we used this opportunity to follow G7 (*Create a Compelling XR Experience*) and (*Make the Experience Appealing*) by taking

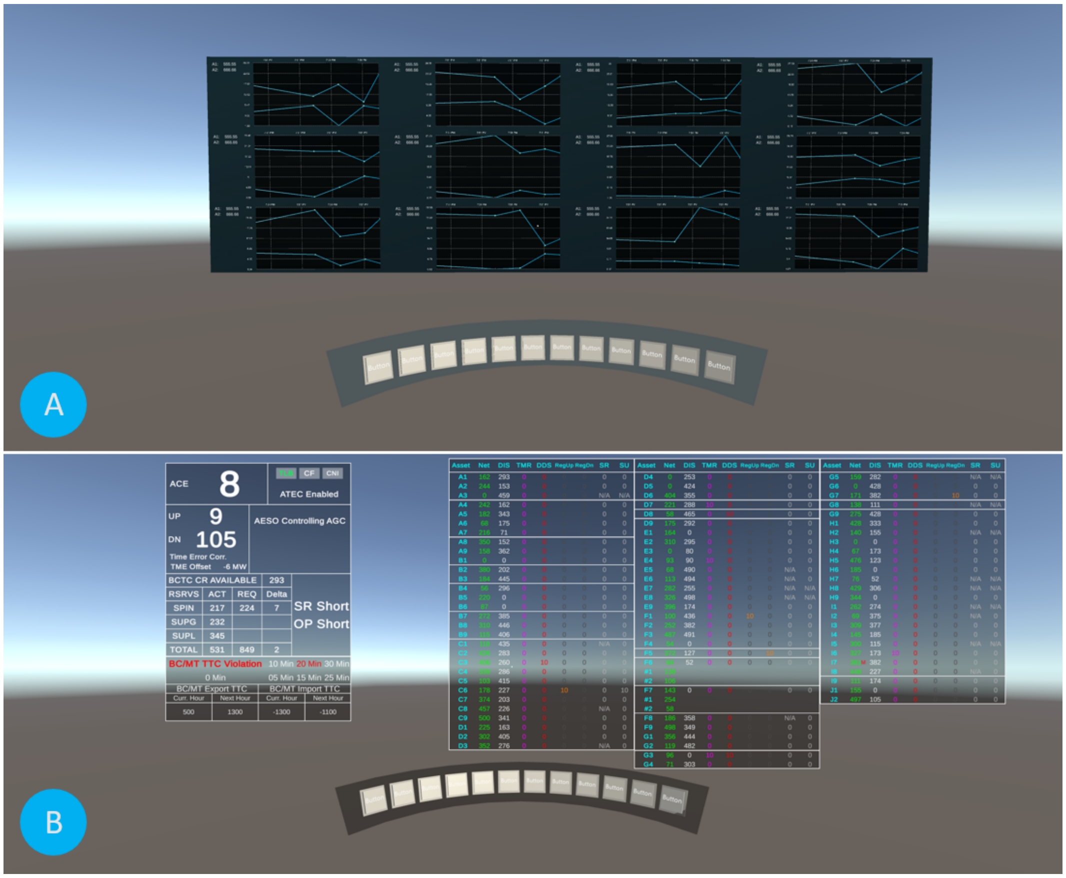

Figure 5.6: Shows 2D graphs and charts that are replicas of preexisting elements found in the control room. A: earlier version of one of the visualizations with an opaque background B: later version of the visualizations with a semitransparent background.

the time to create a detailed and aesthetically pleasing room. We decided on a toned-down sci-fi theme that would be used for room and throughout the application. Following G3 sub guideline (*Environment Comfort*), we made sure the room was large and spacious to reduce the chance of claustrophobia. Also, following G7 sub guideline (*Make a Complete Experience*), we decided to build out the corridors that were visible through the windows in the room. While these areas were not accessible, we wanted to maintain immersion for the user if they decide to look through the windows. (Fig. 5.7)

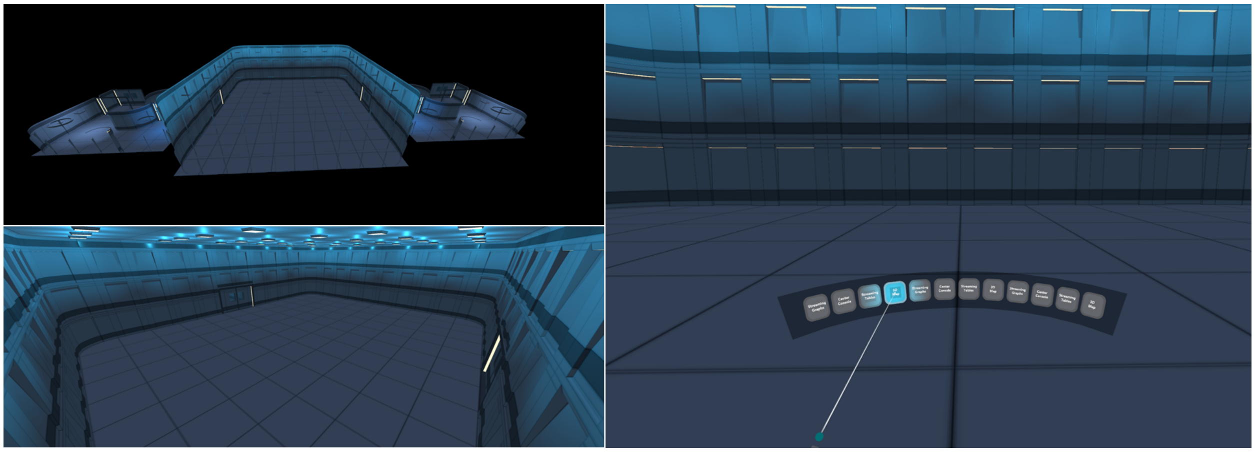

Figure 5.7: Shows the room that was constructed for our XR application.

5.2.3 Main Menu Redesign

After completing the environment and developing the graphs, we turned our focus to re-designing our menu. During this point in the development, the only capabilities of the menu were to spawn a graph when the corresponding button was pressed. As a group, we discussed expanding the types of interaction a user could perform with our visualizations (resize, show, hide, rotate) and adding additional features such as the ability to dynamically save and load the current configuration of the environment as a workspace. We realized that we needed to update our menu to accommodate these new elements and to make it easier to add future features on to the menu moving forward. As such, we came up with the following design seen in Fig. 5.8.

We used our guidelines to inspire parts of this design. As we were adding more options and content to the menu, we made sure to follow G4 (*Keep It Simple: Do Not Overwhelm the User*) and (*Keep Tools and Information Ready, but not Distracting*) by allowing the user to toggle between showing and hiding parts of the menu. Additionally, we gave the user the option to minimize the entire menu (Fig. 5.8B). Based on G2 (*Create Flexible Interactions and Environments*), we added a setting button on to the main menu. During this stage of the development process, we did not have any options to put in this menu; however, we wanted to make sure that we had a place to provide users with the ability to customize

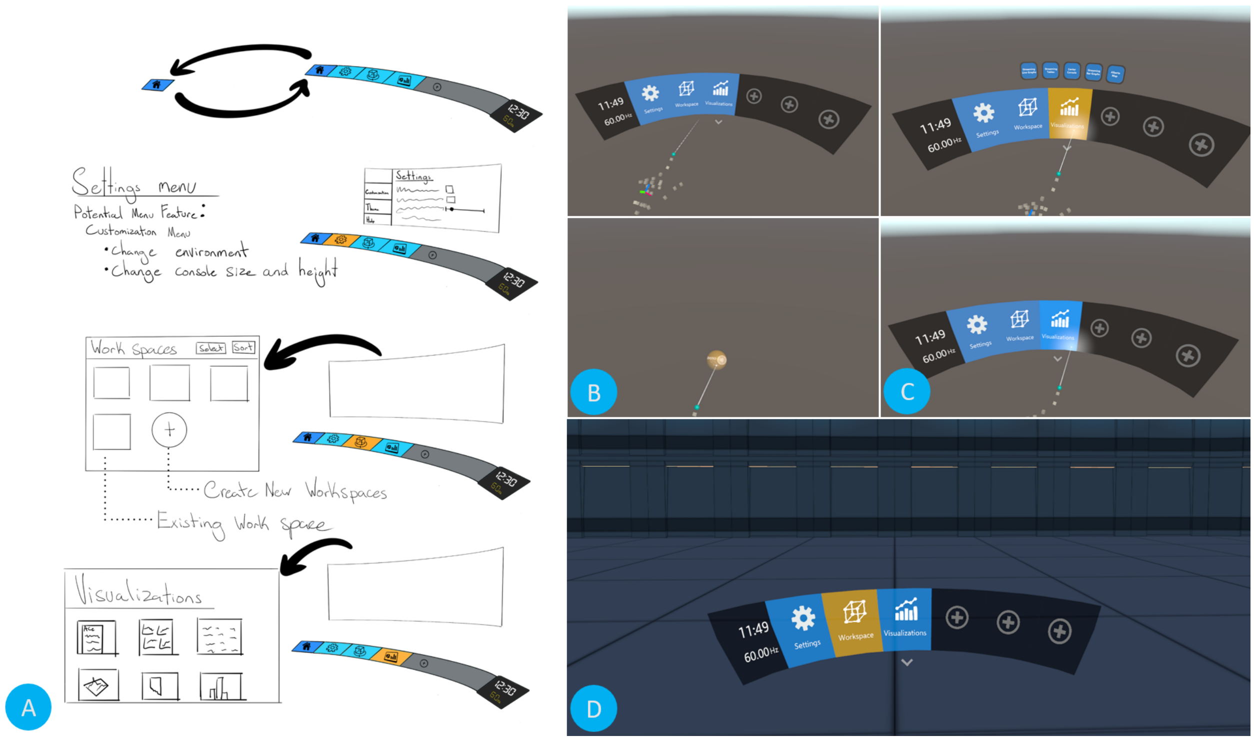

Figure 5.8: Shows the initial redesign of the new menu. A: Our sketch of the new menu design B: The main menu can be hidden by clicking the arrow under the menu and maximized by pressing on the AESO logo sphere C: The blue buttons on the main menu can be toggled to showcase a corresponding submenu. D: The new menu in the room environment.

their experience built into the menu in the future. It was also at this time where we started to use color to provide more feedback and consistency based on G9 (Provide Feedback and Consistency). We began to use orange as the color for active and blue as the color for non-active states. Also, as our menu was transparent, the button would become more opaque when the user would hover over it to indicate that it was interactable (*Design for Dynamic Exploration*).

After the initial version of our design was created, we did some internal testing of the new menu. One thing we noticed was the fact that positioning the secondary panels above the main menu could induce fatigue. Our initial plan was to place the menu in front of the user vision, but this would require them to lift their arm to almost vertical to interact with it. As such, we followed G3 (*Prioritize User's Comfort*) and sub guideline (*Be Mindful of Physically Draining Interactions*) by placing the secondary menu on the right side of the main menu where we had unused space and that was closer to the user's hands. Additionally, by doing this, we would follow G4 sub guideline (*Don't Obscure the User's Vision with Virtual Elements*). (Fig. 5.9)

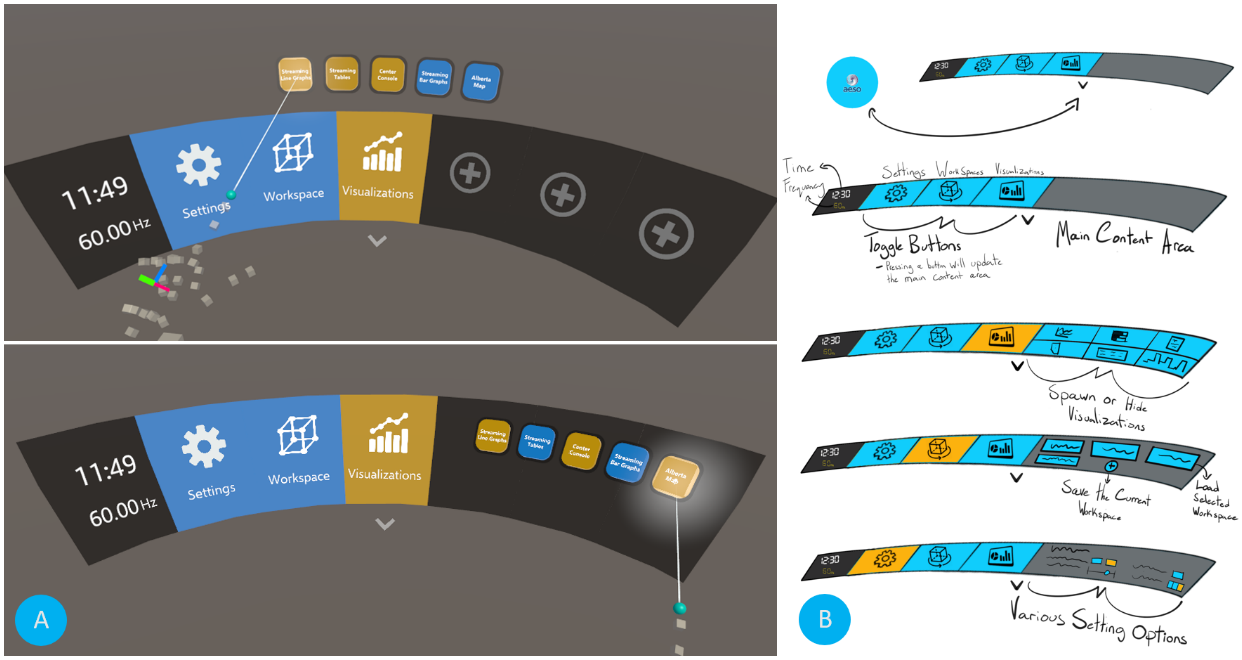

Figure 5.9: A: The image on the top shows the initial position of the sub menu. The bottom image shows the new position of the sub menu. B: Final updated sketch of the redesigned menu.

5.2.4 Defining Visualization Interactions

With the core of the new menu implemented, we continue development on workspaces, implementing real data provided by AESO, creating 3D maps visualizations similar to our other initial sketch (Fig. 5.3B), and tying in functionality onto our new menu. Additionally, we implemented additional options to interact with the visualizations directly. Pointing and grabbing with one controller allowed the user to move the visualizations with the hand. Pointing and grabbing with both controllers would allow users to scale the visualizations by placing their hands closer or farther apart and rotate them based on hand movements in relation to each. These types of movements were meant to mimic the motions of grabbing a real object with both hands, thus following G8 (*Build upon Real World Knowledge*) and (*Use Real-Life Inspiration to Create Affordances in Objects*). Additionally, we used G11 (*Allow for trial and error*) through restricting the rotation movement to just the horizontal orientation. Through some testing, we found that our rotation method lacked precision, which at times caused unwanted and unexpected results. By limiting the rotation to one axis, we were also limiting the potential for big mistakes and gave control back to the user which followed G10 (*Allow Users to Feel in Control of the Experience*). (Fig. 5.10)

Figure 5.10: Show the direct interaction with the visualizations A: Visualizations can be moved by grabbing with one hand B: Visualizations can be rotated and scaled when grabbing with both hands.

We found that restricting the rotation axis improved two-handed interactions; however, we wanted to provide the options for vertically tilting the visualizations as well. We decided to add in this interaction through following G2 (*Create Flexible Interactions and Environments*) and (*Build in Interactions for Both Inexperienced and Experienced Users*) by building in another way to scale and rotate objects. In the settings tab, we had a button called "*Bounding Box*" that could be toggled on to place a box surrounding all active visualizations in the room. These boxes had grabbable corners and spheres, similar to objects seen when interacting with images on many pc programs such as Microsoft Word and PowerPoint, that could be used to scale and rotate when interacted with one hand. Adding this gave the user the flexibility to choose when it came to interacting with the objects in the scene. (Fig. 5.11)

Figure 5.11: Shows the bounding box functionality. A: Map Visualizations with bounding box feature turned off. B: Bounding box feature turned on. C: Grabbing the circle allows the visualizations to be rotated on the corresponding axis D: Grabbing the corner allows for the visualizations to be scaled in the corresponding direction.

5.2.5 Designing with hardware in mind

One thing that became apparent as we continued to work with the HTC VIVE was that text was not a strength of HMD VR. We ran into issues in regard to text clarity, especially at smaller font sizes, because of multiple well-documented limitations of VR such as the screen door effect, limited pixel density, and anti-aliasing [35, 93]. Additionally, text input has also been a documented problem for HMD VR devices [97], and members of the team have had subpar experience with typing in other XR applications. In accordance with G5 (*Design around hardware capabilities and limitations*), we wanted to reduce the effect these drawbacks had on the overall experience. We updated our application by limiting the amount of small text on our menu by changing the text on the buttons to images where appropriate. (Fig. 5.12)

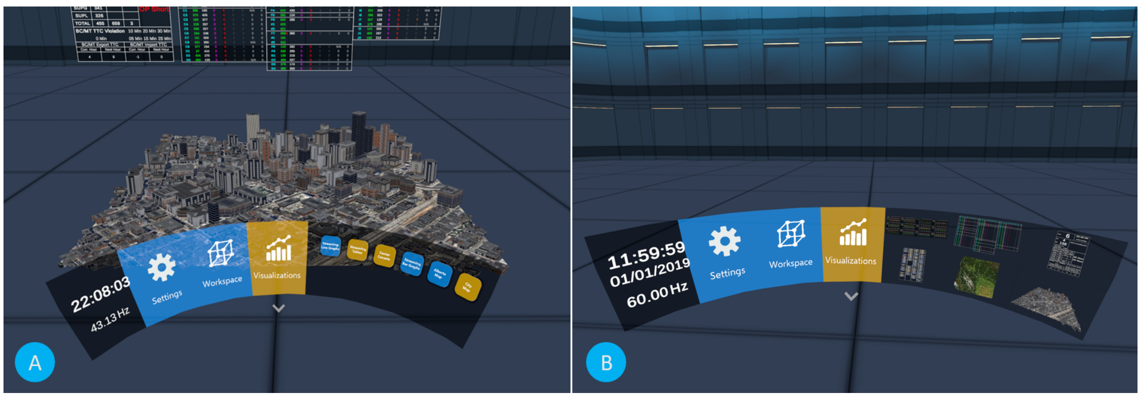

Figure 5.12: Shows how we updated the buttons on the visualization menu to be less reliant on text. A: Shows the old buttons that were texted based. B: Shows the new buttons that uses images.

For our workspace feature, we reconsidered our initial plan of forcing users to input a name for each workspace they saved. Instead, we developed a single click save slots, which was inspired by how many video games implement saving, that would take a screenshot of their visualization configuration and use the image as the identifier on the workspace menu. This way, we avoided using text input and reduce the amount of text that is needed to be displayed. (Fig. 5.13)

Another example where we followed G5 (*Design around hardware capabilities and limitations*) was during the process of porting our project to the Oculus Quest. During the early phases of development, we had been testing on the HTC VIVE, which is a tethered VR headset that runs off the hardware of a full computer or laptop. The Oculus Quest is an all-in-one tetherless device that allowed it to be mobile but at the cost of limited processing power.

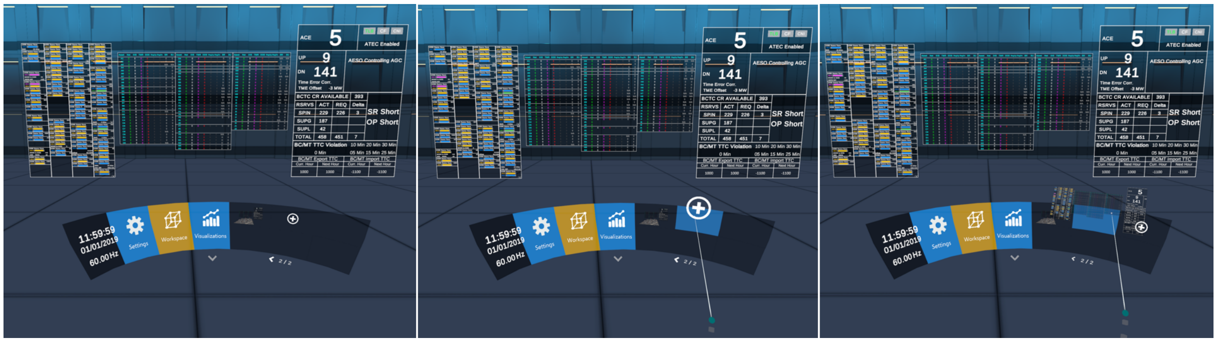

Figure 5.13: Shows the steps of saving the current workspace.

Our project was developed to be cross-platform from the start, but when we tested our application on the Oculus Quest, we ran into performance problems. The lower frame rates and stutter made the experience much less comfortable, and we quickly became concern about the chances of inducing motion sickness. We made an effort to follow both G5 and G3 (*Prioritize User's Comfort*) by creating different scenes that were optimized for each hardware platform. With the Quest, we used a simpler environment and lowered the detail on our Map-based visualizations, which drastically increased framerate performance. (Fig. 5.14)

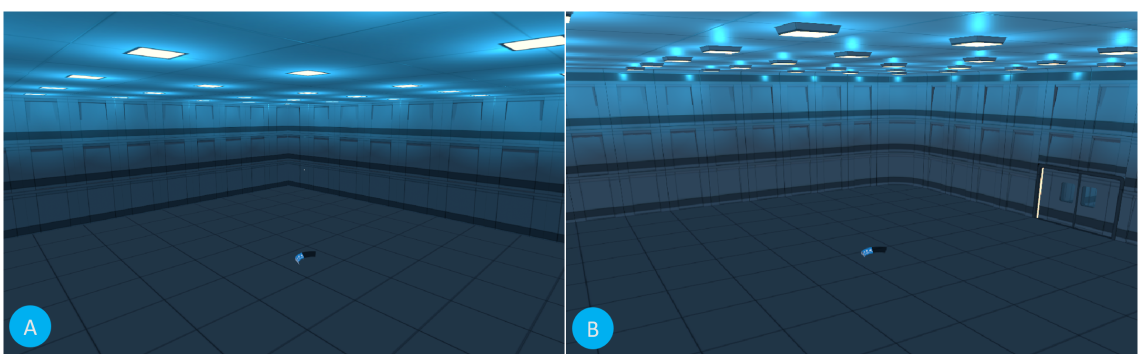

Figure 5.14: Comparison between the Oculus Quest scene (A) and the HTC VIVE scene (B).

5.2.6 Time Scrubbing Menu

The last major feature that we implemented was time scrubbing, which allowed users to navigate to different points in time within a 24 hours period. This would update the visualizations to display the corresponding data, and the application would continue from that point on. To access this feature, users would need to click on the clock where a slider would show up right above the menu. Inspired by the design of video players of streaming services like YouTube and Netflix, users could update the timeline by grabbing and moving the node. Additionally, we followed G2 (*Create Flexible Interactions and Environments*) by creating "micro scrubbers" which are sliders that can only directly affect a specific unit of time, such as days, hours, minutes, and seconds. This gave users finer control over the selection and provided an additional way of changing the time. Additionally, in accordance with G4 (*Keep It Simple: Do Not Overwhelm the User*) and (*Keep Tools and Information Ready, but not Distracting*), we made the menu and the micro scrubbers toggleable by pressing the corresponding buttons. (Fig. 5.15)

Figure 5.15: Show the initial implementation of the time scrubbing menu.

5.2.7 Finishing Development

As the development for the project started to near its end, our main focus was on finishing up features, updating visualizations, fixing bugs, and creating a polished demo. Additionally, we ported our application to the Microsoft HoloLens. It should be noted that this device was not our main focus, and due to time, we decided to put our main effort into polishing the Oculus Quest and HTC VIVE. During this time, we had a higher volume of people trying the project through internal stress testing from members of the ASE lab, showcasing our project to interested groups, and demoing to our contacts at AESO. One behaviour that stood out from observing different people use our application was how they discovered features in the application. We found that users responded well to feedback as an indicator that something was interactable, especially with the Blue Main Menu buttons and its content. However, we found ourselves giving more instruction on how to navigate and use the other features of our application. For example, the time scrubbing menu, which was accessed by clicking the clock on the left-hand side, was often missed by users unless we explicitly told them to use it. We believe the lack of consistency between the different elements in the scene did not encourage users to explore different aspects of our application. As such to follow G9 (*Provide Feedback and Consistency*) and sub guideline (*Use Feedback to Standardize Interactions States*) (*Design for Dynamic Exploration*) we doubled down on our usage of blue as a way to indicate that an element was interactable and our usage of orange to indicate an active state. This included making sure all the visualizations, workspace, and time scrubbing buttons were colored blue and making sure that interactable items had strong visual feedback when the user hovered over them. Additionally, to reinforce feedback, we added an audible click every time a successful action was executed, which also followed G7 (*Create a Compelling XR Experience*) and (*Use Audio to Enhance the Experience*). This was the last major design change to our application before the end of the project. (Fig. 5.16)

5.2.8 Reviewing Backlogged Tasks

There were multiple backlogged tasks that we never got the chance to implement due to time. A lot of these were created directly from trying to follow our guidelines, more specifically, G2 (*Create Flexible Interactions and Environments*), G3 (*Prioritize User's Comfort*). G5 (*Design Around Hardware Capabilities and Limitations*), G6 (*Use Cues to Help Users Throughout Their Experience*), G11 (*Allow for Trial and Error*). These tasks include:

Figure 5.16: Shows how we updated our application to use consistent colors to define different states. A: an older version of the menu. B: the final updated version of our menu.

- Providing multiple environments for the user to pick and choose from. (G2) (G3)
- Option to switch between right-handed and left-handed mode, which would switch the submenu area to be on the respective sides. (G2) (G3)
- Giving the user the ability to change the position of the menu. (G2) (G3)
- Options to let the Menu follow the user. (G2)
- Use other buttons of the VR Controller as shortcuts for functionality. (G2)
- Options to change the default spawn location and size of the visualizations. (G3)
- Reduce the transparency of the elements for the HoloLens version. (G5)
- Update the size of the default visualizations and menu to better fit within the HoloLens' limited field of view. (G5)

- Add directional cues when hovering over the visualization button that points to the location of the element if it is active in the scene. (G6)
- Implementing workspace "states" and allowing users to undo the last visualization movement. (G11)
- Adding an option to reset the placement of the visualization on the menu. (G11)

5.3 Final Prototype

In this section, we recap and showcase the features of the final prototype of the AESO Immersive Control Room.

Visualizations

Our app allows users to spawn, view, and interact with six visualizations that were created based on real data provided by AESO. Additionally, while the app is running, the visualizations are being consistently updated to accurately simulate what a system controller might see in the real control room. Out of the six visualizations, all four of the 2D graphs and charts are replicas of preexisting elements found on the front wall of the control room. With the remaining two map-based visualizations, we explored how we can use the third dimension provided by HMD XR technologies to create more compelling visuals. With these, we were able to show the locations of different substations and powerlines, the direction of power flow, elevation, and extreme weather location on a 3D map. One focused on displaying the whole of Alberta, and the other focused on showing just the city of Calgary. (Fig. 5.17)

Interactions

We provide users with the main menu to navigate to different features of our application. From here, users can toggle between the visualization, workspace, and setting tab, which shows more options on the right side of the menu based on the current selection. Additionally, clicking on the clock will spawn the interface for time scrubbing above the menu. The whole

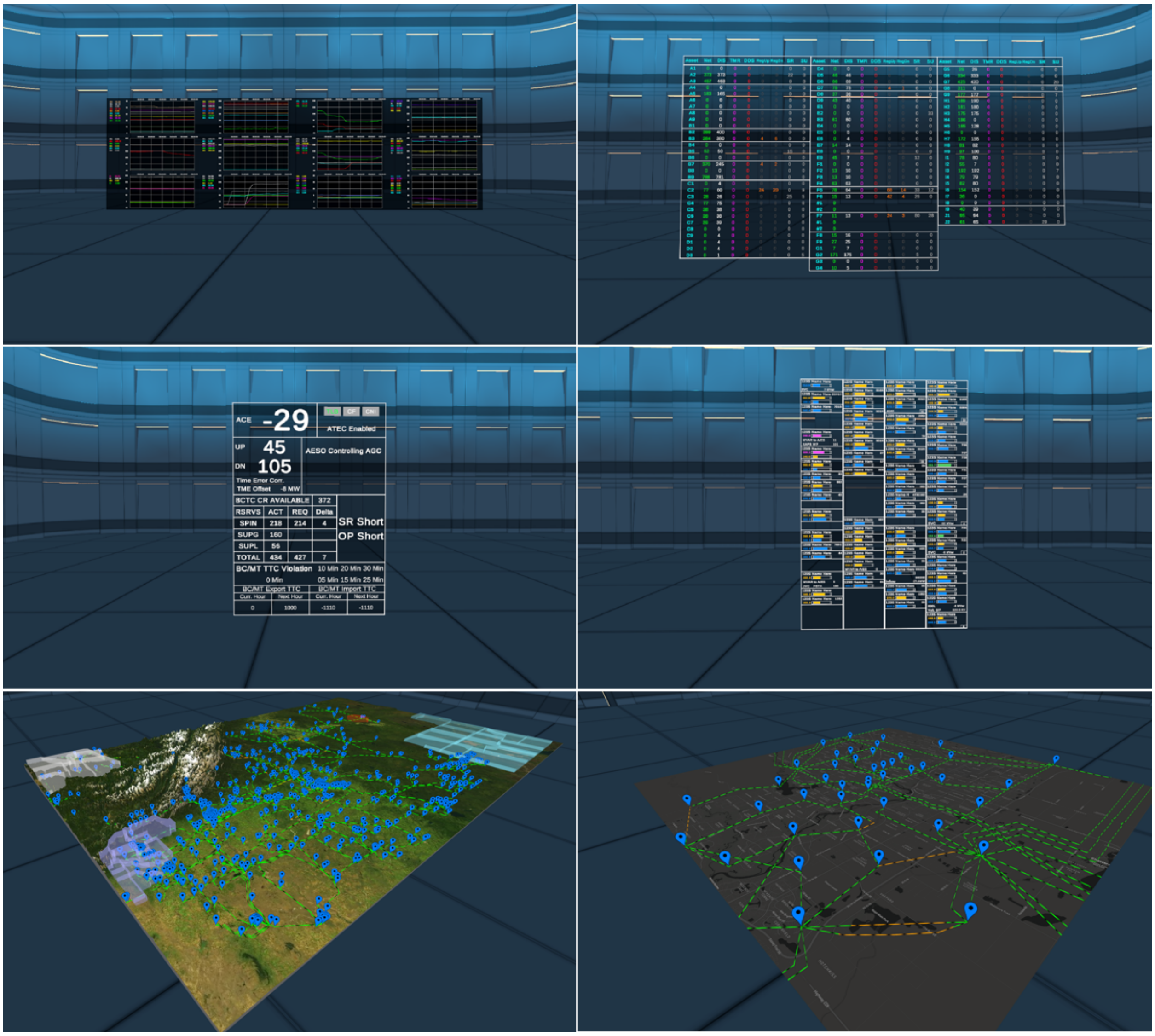

Figure 5.17: Showcase of all our visualizations.

menu can also be minimized by pressing the arrow located underneath the menu. Outside of the menu, users can move visualizations by grabbing with one hand, as well as scale and rotate by grabbing with two hands. We also provide a single hand "*Bounding box*" mode that can be toggled on in the setting menu that places a box with a grabbable corner for scaling and sphere for rotating in a specific axis. (Fig. 5.18)

Workspaces

Users can choose to save the current layout configuration of the visualizations by navigat-

Figure 5.18: Different menu options and visualization interactions of our application.

ing to the workspace menu and clicking the save icon. This will take a screenshot of the workspace, which is then placed as a tab on the menu. Clicking on any of the icons will update the current environment to match the corresponding workspace. It should be noted that the workspaces are saved directly to the device and will be available during subsequent sessions. Moreover, clicking and holding on the menu icon will provide the user with the option to delete workspaces as well. (Fig. 5.19)

Time Scrubbing

Our application allows users to navigate to different points in time within a 24 hours period. To do this, users can change a slider which will update both the time and the data of all the visualizations. Clicking on a specific unit of time, such as hours, minutes, or seconds will

Figure 5.19: Workspace feature of our application. A: Loading a workspace. B: Saving a workspace.

open a slider that affects only the value of the corresponding time unit. Also, we provide users with the capabilities to change the playback speed of the data. (Fig. 5.20)

Cross Platform

Our application can be deployed on desktop VR devices such as the HTC VIVE and Windows Mixed Reality Headsets, the Oculus Quest, which provides a tetherless VR experience, and the Microsoft HoloLens which is a Mixed Reality device. (Fig. 5.21)

5.4 Summary

This chapter overviews the Evaluation stage of our research. We outline the case study we conducted and described the development of the AESO Immersive Control Room Applica-

Figure 5.20: Time scrubbing functionality. A: Default time scrubbing menu. B: Changing the time through the main slider. C: Changing a specific time unit through a micro scrubber. D: Changing the playback speed.

tion. The goal of this stage was to gain further insight into the usage of our work in a genuine development scenario to better understand how our guidelines can aid in the creation of future XR applications. The next chapter reflects on our experience and discusses the lessons learned from the case study and the entire process of creating our UX guidelines.

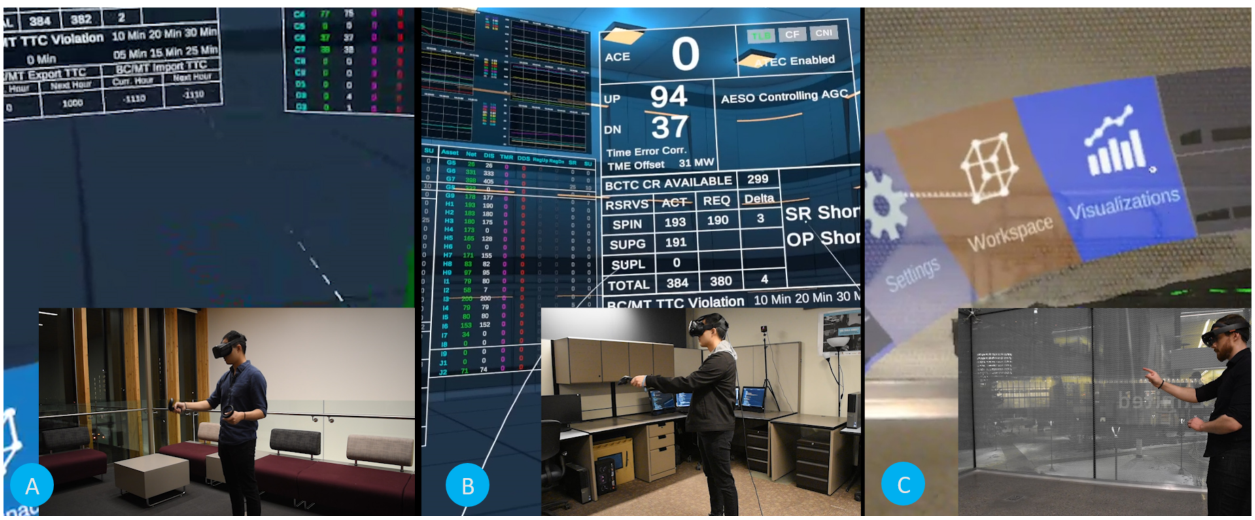

Figure 5.21: Show all the devices that we have tested our application on. A: Oculus Quest. B: HTC VIVE. C: Microsoft HoloLens.

Chapter 6

Reflection and Discussion

In this chapter, we reflect on our entire process of creating and using our eleven HMD XR guidelines. Section 6.1 discusses trends that were identified from the analysis of our 68 different resources, 6.2 uses the knowledge gained from our case study to obtain insight into the usage of our work in a development scenario, and 6.3 discusses the limitations of our research.

6.1 Discussion: Analysis of Related Work

Emphasis on VR Devices and Experiences.

During our analysis of the literature, it was noticed that most of the resources found were based around VR experiences. This may be due to the differences in accessibility among XR devices. VR headsets, such as the HTC VIVE, Oculus Rift, and the Window Mixed reality suite, are cheaper on average and provide a larger range of options when compared to AR and MR devices. At the time of collecting the resources, many AR or MR manufacturers, such as the Microsoft HoloLens and Magic Leap, only had developers/creators or business versions of their devices available to the public. As such, the community around VR is larger and has had more time to explore the technology, which was reflected in the content of our resources. This trend suggests that there is an opportunity for further research around UX design practices, specifically in the context of AR and MR.

Emphasis on Addressing Comfort.

Our guidelines show that ideas around comfort were a common theme in previous works. In addition to the high occurrence, these guidelines were often more defined and consistent throughout the various resources. For example, [57, 76, 95, 21, 4, 6, 2] all explicitly discussed zones of comfort for XR based on human ergonomics. All these sources shared similar concepts, and a few referenced each other. This pattern extends to the other sub guidelines under UX guideline 3 (*Prioritize user's comfort*). This trend was not as prominent in other guidelines which suggest that comfort has been a common problem that designers faced when building applications for HMD XR devices. Further exploring user comfort within XR application may be a valuable area for future research to be conducted.

Opportunity for Evaluation, Validation and Empirical research.

By opening up our search for resources to communities outside of academic sources, we drew upon ideas and concepts that were not academically validated. Additionally, as seen in Chapter 2, related academic literature showed limited work around validation and often expressed the need for further research in this area. This suggests that there are lots of opportunities for these concepts to be further explored to understand better if and how these ideas can help in the development of XR applications.

Few Developed XR Examples.

While exploring the resources, we found relatively few XR examples that were given to support the concepts being conveyed. Instead, the literature would often borrow from other domains to further explain a concept. For example, [94] discusses how space can be used to amplify mental capabilities for spatial applications. Instead of showing an example in XR, the author references how chefs, carpenters and other experts constantly rearrange items to easily track the state of different tasks or to better notice properties signaling what to do next. A lot of XR examples seen in our guidelines are from us connecting the concepts with XR applications that we were familiar with. From the lack of XR examples, it becomes apparent that there is a need for further work around applying these concepts in actual applications. With the case study that we conducted, we aimed at addressing this problem by documenting how these concepts were applied in a real scenario.

6.2 Discussion: AESO Immersive Control Room Case Study

Variation in how we used and applied our guidelines.

One of the major insights that were gained from our case study was around figuring out how to use our work in a development scenario. During the creation of our guidelines, our focus was on understanding the theoretical side through organizing the numerous concepts around XR design. With our case study, our aim was to take a practical perspective on our work by exploring how our guidelines can help practitioners develop HMD XR applications. Reflecting back on the experience, we can see drastically different ways in which we applied our work. More specifically, we identified three distinct categories that can be used to describe the usage of our guidelines. First, was to provide support on the details of our design. A good example of this can be seen with G3 (*Prioritize User's Comfort*), whereby the placement and shape of the main menu were specifically made to follow G3 and the sub guideline (*Be Mindful of Physically Draining Interactions*). The second was to use our guidelines as a way to provide general direction to either kickstart new ideas or facilitate larger changes in the design. This is illustrated in how we used G5 (*Design Around Hardware Capabilities and Limitations*). We realized that text input and reading text were not strong capabilities of VR headsets. As such, to follow this guideline, we redesigned how we were initially planning on implementing saving and loading workspaces, which involved a lot of text. While the specific of the final design of the workspace feature cannot be attributed to G5, we can say that it was the main reason for the change. Third, we found that our work can be used to inform designers and developers to help support decision making instead of directly influencing design. For example, G10 (*Allow Users to Feel in Control of the Experience*) and G11 (*Allow for Trial and Error*) were guidelines that were not obvious in their impact on the direction of the project. However, as we were playtesting throughout development, we made sure that we built in error tolerance into the application, and it did not behave in a way that would betray the user's expectations.

Importance of addressing comfort.

To build on the previous finding that comfort was a well-documented subject in related literature, when looking back at the usage of all of the guidelines in the case study, the one that we felt had the largest impact in the design process was Guideline 3 (*Prioritize User's Comfort*). We can see numerous illustrations where it was used to directly influence parts of the developments. Examples include inspiring the second main concept sketch, placement of our main menu and the submenu to minimize physical strain, changing the graph panel to be semi-transparent to avoid claustrophobia, prioritizing the creation of the environment to allow the user to feel situated, and optimizing framerate on the oculus quest to avoid nausea. Moreover, an important part of the usage was in how frequently it was brought up in discussion. Out of all the guidelines, this one was top of mind for the entire team from the very beginning of development and the influence that it had can be traced to the majority of the design features in our application.

Value of traditional design principles.

In Chapter 3.3, "*Comparative Stage: Comparing and Contrasting Existing Work*," we mention that the main motivation behind using traditional design principles in our work came from the belief that these resources still provide valid and useful information for designing XR applications despite the difference in medium. In our case study, we found that Guidelines such as G2 (*Create Flexible Interactions and Environments*), G8 (*Build upon Real World Knowledge*), G9 (*Provide Feedback and Consistency*), and G11 (*Allow for Trial and Error*) that build on or incorporated ideas from traditional resources to be extremely helpful throughout development. In fact, we found that these guidelines were more valuable in our situation when compared to building 2D applications because of the scarcity and lack of consistent XR examples that implement these concepts. As such, we had to put a lot of thought into how we went about following these guidelines. A good example of the value of non-XR specific concepts was when we followed G9 (*Provide Feedback and Consistency*) to create a consistent design language in order to inform users what they can interact with.

Leveraging 2D design in 3D development.

To build off the previous discussion point, one aspect that was overlooked in our guidelines was the importance of leveraging existing 2D design. Guidelines G1 (*Organize the Spatial Environment to Maximize Efficiency*) and G8 (*Build upon Real World Knowledge*), and the sources they were derived from, focus on encouraging designers to explore how real-life designs, such as real objects, architecture, industrial design, etc., can be used to inspire XR application. While we did explore this throughout development, we more often found ourselves using 2D applications as inspiration for our design. Similar too how affordance of real world objects can inform users on possible actions, we found ourselves leveraging the design language of existing 2D design to inform the user of the XR application's actions. For example, our main menu design was inspired by the main taskbar on the Windows operating system. Since we knew that Windows was used on the computers in the control room, our goal was to leverages users' familiarity with elements to help guide them through the experience. Additionally, instead of thinking exclusively between 2D or 3D, we found ourselves often aiming for a middle ground between the two. A lot of our designs were functionally 2D, but we also played with the use of depth or 3D elements to make it conducive to a 3D application. For example, the slider on our time scrubbing menu used a 3D object as the node such that it was easily visible for multiple angles and provided a larger target to grab.

Guidelines not Rules.

As previously mentioned, the intent behind our work was not to present absolute rules but rather to provide in a concise manner a reference for understanding what others have discovered in order to aid practitioners in creating XR applications. This idea was reinforced throughout development as there were instances where we actively made the decision not to follow our guidelines. For example, the grabbing interaction to move and scale the visualizations required users to perform physically active movements, thus going against G3 (*Prioritize User's Comfort*) and (*Be Mindful of Physically Draining Interactions*). However, as a prototype application that was mainly going to be used as a demo, we ended up valuing the simplicity over the drawback of the physically active nature of the interaction. Even in these times, we found that the guidelines were still beneficial as they helped us make educated decisions. Through this case study, we found that the main benefit of our work was to support XR design and innovation by providing designers and developers with additional knowledge to make informed decisions based on their situation.

6.3 Limitations

There are many documented challenges of using grey literature as part of the literature review process. One of our primary limits is quality assurance. As mentioned in the previous section, a majority of the resources used to develop our guidelines came from grey literature. Although we did aim to make sure all our resources were high quality, we recognize that the information gathered from these may not be as reliable as literature that has been through the rigors of the academic review process.

While our case study was meant to raise more questions rather than to conduct a rigorous evaluation of our work, it is important that we acknowledge the limitation of this approach. As with most case studies, the insights gained from our development are not generalizable because it relies on a single scenario. Additionally, while we did attempt to take a neutral position on our work since we both created the guidelines and carried out the case study, we should also recognize that our bias may have played a role in our findings. Moreover, since we were using a legitimate development project in order to explore "genuine" usage of our guidelines, we also opened ourselves up to practical aspects that affected the design decisions. For example, factors such as deadlines, development effort, using libraries with prebuilt functionality, coding personnel, clients want and needs, etc., all had influence on what features were ultimately implemented and thus affected our findings.

6.4 Summary

In this chapter, we outlined the Reflection Stage of our research, where we presented several points of discussion that were identified from the creation and evaluation of our guidelines. More specifically, we look at the lessons learned from both the analysis of the related work and from the AESO Immersive control room case study. Additionally, we discuss the limitations of our research. In the next and final chapter, we revisit the research questions and contributions, discuss potential opportunities for future research, and provide a conclusion to wrap up the research in this thesis.

Chapter 7

Conclusion and Future Work

Recent developments in XR has provided hardware that allows users to experience spatial environments and interactions. However, the increased potential for consuming and interacting with digital information also comes with a need to expand our current knowledge of UX design. In this thesis, our primary aim was to address the research problem,

How do we design usable HMD XR applications?

Since this is a very broad topic, we focused our effort on three more specific research questions whose objectives ultimately contributes to the overall understanding of this problem.

- *Research Questions 1 (RQ1)*: What is the current state of research regarding UX design for XR platforms?

To answer the question, an extensive review of existing work was conducted to understand the current state of UX guidelines for HMD XR technologies. A total of 68 different resources were identified from both peered review published literature and "grey literature," such as scientific articles, thesis, previous experiments, books, and websites.

- *Research Questions 2 (RQ2)*: What observations can be made from existing resources, to help the design and implementation of XR applications?

Using the resources collected as a result of RQ1, we conducted a thematic analysis of the related resources to find recognizable reoccurring topics or patterns occurring within the data. The results were then used to provide a useful set of guidelines to support developers and designers in the creation of XR applications.

- *Research Questions 3 (RQ3)*: In what ways can HMD UX guidelines aid in the design and creation of future XR applications?

With the guidelines created as a result of RQ2, we ran a case study that explored how our guidelines can be used in the development of an XR project and documented the entire process. More specifically, in collaboration with Alberta Electric System Operators (AESO), we developed the Immersive Control Room, a prototype application that explores how information from AESO control room can be replicated and reimagined in a virtual environment. We then reflected back on the experience to obtain insight into when, where, and how we went about applying our guidelines in the development process. By answering the previously mentioned questions, this thesis makes the following contributions:

- *Thesis Contribution 1 (TC1)*: Provide a guided overview of the existing literature on UX for XR applications in academic research and in industry.

- *Thesis Contribution 2 (TC2)*: Propose a set of guidelines that are encompassing the body of work in a concise and structured manner.

- *Thesis Contribution 3 (TC3)*: Detail a case study that explores how our guidelines are used in the development of an HMD XR application.

7.1 Future Work

One of our aims of our research was to provide a resource for recognizing what others have tried and discovered such that future research can challenge, build off, and extend the ideas presented in this thesis. While we believe that our work provides a useful starting point, we acknowledge that our research only scratches the surfaces for what is needed to comprehensively understand how to design XR applications. As such, we believe that there are numerous interesting opportunities to pursue in future work.

One interesting topic that arises from our case study was the structure of our guidelines. In Chapter 6.2, we discussed the various different ways our work was used to guide our design. This got us thinking more about the role the presentation of information has on helping designers and developers. It may be important to spend time exploring different ways to present the information in our guidelines, such as a structured framework, that are less abstract and more focused on a specific type of usage.

As previously mentioned, by opening up our search for resources to communities outside of academic sources, we drew upon ideas that were not academically validated. Additionally, our case study was geared toward generating more questions rather than rigorously validating our work. While we believe that the guidelines and the information in them still require further improvement before they are ready to be meticulously tested, getting more objective perspectives on the concepts behind our work would be very beneficial in refining the guidelines. As such, we believe that there is an opportunity for future work to conduct qualitative studies where experts provide commentary on the guidelines themselves and XR design in general.

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Appendix A

Comparative Stage Tables

A	B	C	D	E	F	G	H	I	J	K	L
INDUSTRY	IN1. Provide feedback & consistency	IN2. Minimize abstractions	IN3. Use cues to help users throughout their experience	IN4. Use 3D space to your advantage	IN5. Let users shape their environments	IN6. Minimalist Design	IN7. Layout elements to minimize physical strain	IN8. Keep physiological, environmental, and social comforts in mind	IN9. Don't Force Actions without user's permission	IN10. Don't just create an application, create a compelling experience	IN11. Design for hardware capabilities in mind
NIELSEN											
N1. Visibility of system status	Y		Y					M			
N2. Match between system and the real world		Y	M	Y				M		M	
N3. User control and freedom: Support undo and redo.											
N4. Consistency and standards	Y		Y								
N5. Error prevention											
N6. Recognition rather than recall	Y	Y	Y	Y							
N7. Flexibility and efficiency of use: Accelerators — unseen by the novice user — may often speed up the interaction											
N8. Aesthetic and minimalist design						Y					
N9. Help users recognize, diagnose, and recover from errors	X		X								
N10. Help and documentation											
SHNEIDERMAN											
S1. Consistency	Y	M	Y								
S2. Shortcuts											
S3. Informative feedback	Y		Y								
S4. Dialogue	Y		Y								
S5. Error handling											
S6. Permit reversal of actions											
S7. Support internal locus of control											
S8. Reduce short-term memory load	M	Y	Y	Y		Y					
ISO 9241-110											
I1. Is the dialogue suitable for the user's task and skill level? (Suitability for the task)					X						
I2. Does the dialogue make it clear what the user should do next? (Self-descriptiveness)	Y		Y								
I3. Is the dialogue consistent? (Conformity with user expectations)	Y	Y									
I4. Does the dialogue support learning? (Suitability for learning)	Y		Y								
I5. Can the user control the pace and sequence of the interaction? (Controllability)											
I6. Is the dialogue forgiving? (Error tolerance)											
I7. Can the dialogue be costumised to suit the user? (Suitability for indivisualisation)					Y						
ACADEMIC 2											
Presentation											
A2.1. Immediate content should be shown only in natural viewing zones							Y				
A2.2. Spacing is important in content to environment ratio							Y				
A2.3. Use volumetric elements		Y									
A2.4. UI elements responsiveness is the key	Y										
A2.5. Use human body for simple UI elements placement											
A2.6. The color of UI elements can make the perception more natural and visible											
A2.7. Do not forget about the lighting											
Control											
A2.8. Enable change of control type in different situations											Y
A2.9. Avoid the misrepresentation of the commands: (Deals with input misrepresentations)											
A2.10. Combine various control types to achieve more control											
A2.11. The user should be notified by command response	Y		M								
A2.12. Recognize significant commands	Y										
A2.13. Use creative approach for user text input design											
A2.14. Is standard login/unlock page design obsolete?											
Intructions											
A2.15. Offer multiple instruction showing variations											
A2.16. Allow hiding/showing the manual						Y					
A2.17. Vary the manual according to the user experience level											
A2.18. Give a feedback to the user	Y										
A2.19. Ensure the AR will be helpful											
A2.20. Emphasize parts of an object to be moved											
A2.21. Show the user work tools before needed											
A2.22. Tools inventory layout could be inspired by RPG games											
A2.23. Indicate the movement											
A2.24. Do not forget about extreme working conditions											
A2.25. Enable remote cooperation											
A2.26. Connect AR and VR usage for cooperation											
Navigation											
A2.27. Navigation interface should vary depending on the transport type											
A2.28. Navigation needs to be understandable			Y								
A2.29. Highlight real life objects when navigating to the POI			Y								
Notifications											
A2.30. Notifications should not be the primary communication channel											
A2.31. Let the user set the notification preferences					Y						
A2.32. Form of presentation needs to be responsive	Y										
A2.33. Create notification priority levels											
A2.34. Do not cover the center of user's FOV on the move						Y					
A2.35. Visual notifications should be used moderately											
A2.36. Use only relevant and necessary notifications						Y					
A2.37. Do not overload users' FOV with notifications						Y					

ACADEMIC 3											
A3.1. Affordance		Y									
A3.2. Reducing cognitive overhead	Y	Y	Y	Y							
A3.3. Low physical effort						Y					
A3.4. Learnability	Y	Y									
A3.5. User satisfaction										Y	
A3.6. Flexibility in use						Y					
A3.7. Responsiveness and feedback	Y										
A3.8. Error tolerance											
ACADEMIC 4											
A4.1. Place the graphical user interface so it is comfortable to explore and interact with							Y				
A4.2. Place visual feedback to selections within the immediate interaction area	Y		Y				Y				
A4.3. Keep information dense areas interaction-free											
A4.4. Use dwell times of various lengths											
A4.5. Avoid using time-limited information											
A4.6. Never force users to interpret information in movement								Y			
A4.7. Use standards and affordances to minimize the cognitive load	Y	Y									
ACADEMIC 4 Initial set of guidelines (from ohters)											
A4a.1. Allow users to be lazy							Y				
A4a.2. Allow 'magic'											
A4a.3. Keep the DOFs the user is required to control to a minimum											
A4a.4. Help the user by using affordances		Y									
A4a.5. Design for the hadrware											Y
A4a.6. Do not use floating, interpenatrating, or invisible objects											
A4a.7. Place the VRUI at a reasonable and comfortable distance							Y	Y			
A4a.8. Use a gaze cursor when gaze is used as the input modality											
A4a.9. A video screen in VR should cover less than 70 of the horizontal FOV							Y				
A4a.10 Avoid rapid movements, to not drop frames or lose head tracking								Y			
ACADEMIC 12											
A12.1. Interaction methods and controls		Y									
A12.2. Presentation of virtual objects						Y		Y			
A12.3. Relationship between virtual objects and real world		Y									
A12.4. Information related to virtual objects			Y								
A12.5. Suitability for the usage context											
A12.6. Physical comfort of the use							Y	Y			
ACADEMIC 13											
A13.1. Fit with user environment and task											
A13.2. Form communicates function		Y									
A13.3. Minimize distraction and overload						Y					
A13.4 Adaptation to user position and motion											
A13.5. Alignment of physical and virtual worlds											
A13.6. Fit with user's physical abilities							Y				
A13.7. Fit with user's perceptual abilities							Y				
A13.8. Accessibility of off screen objects			Y								
A13.9. Accounting for hardware capabilities											Y

INDUSTRY	IN1. Provide feedback & consistency	IN2. Minimize abstractions	IN3. Use cues to help users throughout their experience	IN4. Use 3D space to your advantage	IN5. Let users shape their environments	IN6. Minimalist Design	IN7. Layout elements to minimize physical strain	IN8. Keep physiological, environmental, and social comforts in mind	IN9. Don't Force Actions without user's permission	IN10. Don't just create an application, create a compelling experience	IN11. Design for hardware capabilities in mind
NIELSEN											
N1. Visibility of system status	Y		Y					Y			
N2. Match between system and the real world		Y	Y	Y				Y		Y	
N3. User control and freedom: Support undo and redo.											
N4. Consistency and standards	Y		Y								
N5. Error prevention											
N6. Recognition rather than recall	Y	Y	Y	Y							
N7. Flexibility and efficiency of use: Accelerators — unseen by the novice user — may often speed up the interaction											
N8. Aesthetic and minimalist design						Y					
N9. Help users recognize, diagnose, and recover from errors											
N10. Help and documentation											
SHNEIDERMAN											
S1. Consistency	Y	Y	Y								
S2. Shortcuts											
S3. Informative feedback	Y		Y								
S4. Dialogue	Y		Y								
S5. Error handling											
S6. Permit reversal of actions											
S7. Support internal locus of control											
S8. Reduce short-term memory load	Y	Y	Y	Y		Y					
ISO 9241-110											
I1. Is the dialogue suitable for the user's task and skill level? (Suitability for the task)											
I2. Does the dialogue make it clear what the user should do next? (Self-descriptiveness)	Y		Y								
I3. Is the dialogue consistent? (Conformity with user expectations)	Y	Y									
I4. Does the dialogue support learning? (Suitability for learning)	Y		Y								
I5. Can the user control the pace and sequence of the interaction? (Controllability)											
I6. Is the dialogue forgiving? (Error tolerance)											
I7. Can the dialogue be costumised to suit the user? (Suitability for indivisualisation)					Y						
Jakub Blokša - Design Guidelines for User Interface for Augmented Reality											
Presentation											
A2.1. Immediate content should be shown only in natural viewing zones							Y				
A2.2. Spacing is important in content to environment ratio							Y				
A2.3. Use volumetric elements		Y									
A2.4. UI elements responsiveness is the key	Y										
A2.5. Use human body for simple UI elements placement											
A2.6. The color of UI elements can make the perception more natural and visible											
A2.7. Do not forget about the lighting											
Control											
A2.8. Enable change of control type in different situations											Y
A2.9. Avoid the misrepresentation of the commands: (Deals with input misrepresentations)											
A2.10. Combine various control types to achieve more control											
A2.11. The user should be notified by command response	Y		Y								
A2.12. Recognize significant commands	Y										
A2.13. Use creative approach for user text input design											
A2.14. Is standard login/unlock page design obsolete?											
Intructions											
A2.15. Offer multiple instruction showing variations											
A2.16. Allow hiding/showing the manual						Y					
A2.17. Vary the manual according to the user experience level											
A2.18. Give a feedback to the user	Y										
A2.19. Ensure the AR will be helpful											
A2.20. Emphasize parts of an object to be moved											
A2.21. Show the user work tools before needed											
A2.22. Tools inventory layout could be inspired by RPG games											
A2.23. Indicate the movement											
A2.24. Do not forget about extreme working conditions											
A2.25. Enable remote cooperation											
A2.26. Connect AR and VR usage for cooperation											
Navigation											
A2.27. Navigation interface should vary depending on the transport type											
A2.28. Navigation needs to be understandable			Y								
A2.29. Highlight real life objects when navigating to the POI			Y								
Notifications											
A2.30. Notifications should not be the primary communication channel											
A2.31. Let the user set the notification preferences					Y						
A2.32. Form of presentation needs to be responsive	Y										
A2.33. Create notification priority levels											
A2.34. Do not cover the center of user's FOV on the move						Y					
A2.35. Visual notifications should be used moderately											
A2.36. Use only relevant and necessary notifications						Y					
A2.37. Do not overload users' FOV with notifications						Y					
Andreas Dünser - Applying HCI principles to AR systems design											
A3.1. Affordance		Y									

ACADEMIC 3											
A3.1. Affordance		Y									
A3.2. Reducing cognitive overhead	Y	Y	Y	Y							
A3.3. Low physical effort						Y					
A3.4. Learnability	Y	Y									
A3.5. User satisfaction										Y	
A3.6. Flexibility in use						Y					
A3.7. Responsiveness and feedback	Y										
A3.8. Error tolerance											
ACADEMIC 4											
A4.1. Place the graphical user interface so it is comfortable to explore and interact with							Y				
A4.2. Place visual feedback to selections within the immediate interaction area	Y		Y				Y				
A4.3. Keep information dense areas interaction-free											
A4.4. Use dwell times of various lengths											
A4.5. Avoid using time-limited information											
A4.6. Never force users to interpret information in movement								Y			
A4.7. Use standards and affordances to minimize the cognitive load	Y	Y									
ACADEMIC 4 Initial set of guidelines (from ohters)											
A4a.1. Allow users to be lazy							Y				
A4a.2. Allow 'magic'											
A4a.3. Keep the DOFs the user is required to control to a minimum											
A4a.4. Help the user by using affordances		Y									
A4a.5. Design for the hadrware											Y
A4a.6. Do not use floating, interpenatrating, or invisible objects											
A4a.7. Place the VRUI at a reasonable and comfortable distance							Y	Y			
A4a.8. Use a gaze cursor when gaze is used as the input modality											
A4a.9. A video screen in VR should cover less than 70 of the horizontal FOV							Y				
A4a.10 Avoid rapid movements, to not drop frames or lose head tracking								Y			
ACADEMIC 12											
A12.1. Interaction methods and controls		Y									
A12.2. Presentation of virtual objects						Y		Y			
A12.3. Relationship between virtual objects and real world		Y									
A12.4. Information related to virtual objects			Y								
A12.5. Suitability for the usage context											
A12.6. Physical comfort of the use							Y	Y			
ACADEMIC 13											
A13.1. Fit with user environment and task											
A13.2. Form communicates function		Y									
A13.3. Minimize distraction and overload						Y					
A13.4 Adaptation to user position and motion											
A13.5. Alignment of physical and virtual worlds											
A13.6. Fit with user's physical abilities							Y				
A13.7. Fit with user's perceptual abilities							Y				
A13.8. Accessibility of off screen objects			Y								
A13.9. Accounting for hardware capabilities											Y

INDUSTRY	IN1. Provide feedback & consistency	IN2. Minimize abstractions	IN3. Use cues to help users throughout their experience	IN4. Use 3D space to your advantage	IN5. Let users shape their environments	IN6. Minimalist Design	IN7. Layout elements to minimize physical strain	IN8. Keep physiological, environmental, and social comforts in mind	IN9. Don't Force Actions without user's permission	IN10. Don't just create an application, create a compelling experience	IN11. Design for hardware capabilities in mind
NIELSEN											
N1. Visibility of system status	Y		Y					Y			
N2. Match between system and the real world		Y	Y	Y				Y		Y	
N3. User control and freedom: Support undo and redo.					X				X		
N4. Consistency and standards	Y		Y								
N5. Error prevention			X								
N6. Recognition rather than recall	Y	Y	Y	Y							
N7. Flexibility and efficiency of use: Accelerators — unseen by the novice user — may often speed up the interaction					X						
N8. Aesthetic and minimalist design						Y					
N9. Help users recognize, diagnose, and recover from errors	X		X								
N10. Help and documentation											
SHNEIDERMAN											
S1. Consistency	Y	Y	Y								
S2. Shortcuts					X						
S3. Informative feedback	Y		Y								
S4. Dialogue	Y		Y								
S5. Error handling	X		X								
S6. Permit reversal of actions					X						
S7. Support internal locus of control								X	X		
S8. Reduce short-term memory load	Y	Y	Y	Y		Y					
ISO 9241-110											
I1. Is the dialogue suitable for the user's task and skill level? (Suitability for the task)					X						
I2. Does the dialogue make it clear what the user should do next? (Self-descriptiveness)	Y		Y								
I3. Is the dialogue consistent? (Conformity with user expectations)	Y	Y									
I4. Does the dialogue support learning? (Suitability for learning)	Y		Y								
I5. Can the user control the pace and sequence of the interaction? (Controllability)					X						
I6. Is the dialogue forgiving? (Error tolerance)	X		X								
I7. Can the dialogue be costumised to suit the user? (Suitability for indivisualisation)					Y						
ACADEMIC 2											
Presentation											
A2.1. Immediate content should be shown only in natural viewing zones							Y				
A2.2. Spacing is important in content to environment ratio							Y				
A2.3. Use volumetric elements		Y									
A2.4. UI elements responsiveness is the key	Y										
A2.5. Use human body for simple UI elements placement											
A2.6. The color of UI elements can make the perception more natural and visible											
A2.7. Do not forget about the lighting										X	
Control											
A2.8. Enable change of control type in different situations					X						Y
A2.9. Avoid the misrepresentation of the commands. (Deals with input misrepresentations)											
A2.10. Combine various control types to achieve more control											
A2.11. The user should be notified by command response	Y		Y								
A2.12. Recognize significant commands	Y		X								
A2.13. Use creative approach for user text input design											
A2.14. Is standard login/unlock page design obsolete?											
Intructions											
A2.15. Offer multiple instruction showing variations											
A2.16. Allow hiding/showing the manual						Y					
A2.17. Vary the manual according to the user experience level					X						
A2.18. Give a feedback to the user	Y										
A2.19. Ensure the AR will be helpful											
A2.20. Emphasize parts of an object to be moved											
A2.21. Show the user work tools before needed											
A2.22. Tools inventory layout could be inspired by RPG games											
A2.23. Indicate the movement											
A2.24. Do not forget about extreme working conditions											
A2.25. Enable remote cooperation											
A2.26. Connect AR and VR usage for cooperation											
Navigation											
A2.27. Navigation interface should vary depending on the transport type											
A2.28. Navigation needs to be understandable			Y								
A2.29. Highlight real life objects when navigating to the POI			Y								
Notifications											
A2.30. Notifications should not be the primary communication channel			X			X					
A2.31. Let the user set the notification preferences					Y						
A2.32. Form of presentation needs to be responsive	Y										
A2.33. Create notification priority levels					X				X		
A2.34. Do not cover the center of user's FOV on the move						Y					
A2.35. Visual notifications should be used moderately			X			X					
A2.36. Use only relevant and necessary notifications						Y					
A2.37. Do not overload users' FOV with notifications						Y					

ACADEMIC 3											
A3.1. Affordance		Y									
A3.2. Reducing cognitive overhead	Y	Y	Y	Y							
A3.3. Low physical effort						Y					
A3.4. Learnability	Y	Y									
A3.5. User satisfaction										Y	
A3.6. Flexibility in use						Y					
A3.7. Responsiveness and feedback	Y										
A3.8. Error tolerance	X		X								
ACADEMIC 4											
A4.1. Place the graphical user interface so it is comfortable to explore and interact with							Y				
A4.2. Place visual feedback to selections within the immediate interaction area	Y		Y				Y				
A4.3. Keep information dense areas interaction-free											
A4.4. Use dwell times of various lengths									X		
A4.5. Avoid using time-limited information									X		
A4.6. Never force users to interpret information in movement								Y			
A4.7. Use standards and affordances to minimize the cognitive load	Y	Y									
ACADEMIC 4 Initial set of guidelines (from ohters)											
A4a.1. Allow users to be lazy							Y				
A4a.2. Allow 'magic'		X									
A4a.3. Keep the DOFs the user is required to control to a minimum							X		X		
A4a.4. Help the user by using affordances		Y									
A4a.5. Design for the hadrware											Y
A4a.6. Do not use floating, interpenetrating, or invisible objects		X									
A4a.7. Place the VRUI at a reasonable and comfortable distance							Y	Y			
A4a.8. Use a gaze cursor when gaze is used as the input modality											
A4a.9. A video screen in VR should cover less than 70 of the horizontal FOV							Y				
A4a.10 Avoid rapid movements, to not drop frames or lose head tracking								Y			
ACADEMIC 12											
A12.1. Interaction methods and controls		Y									
A12.2. Presentation of virtual objects						Y		Y			
A12.3. Relationship between virtual objects and real world		Y									
A12.4. Information related to virtual objects			Y								
A12.5. Suitability for the usage context											
A12.6. Physical comfort of the use							Y	Y			
ACADEMIC 13											
A13.1. Fit with user environment and task											
A13.2. Form communicates function		Y									
A13.3. Minimize distraction and overload						Y					
A13.4 Adaptation to user position and motion											
A13.5. Alignment of physical and virtual worlds											
A13.6. Fit with user's physical abilities							Y				
A13.7. Fit with user's perceptual abilities							Y				
A13.8. Accessibility of off screen objects			Y								
A13.9. Accounting for hardware capabilities											Y

Appendix B

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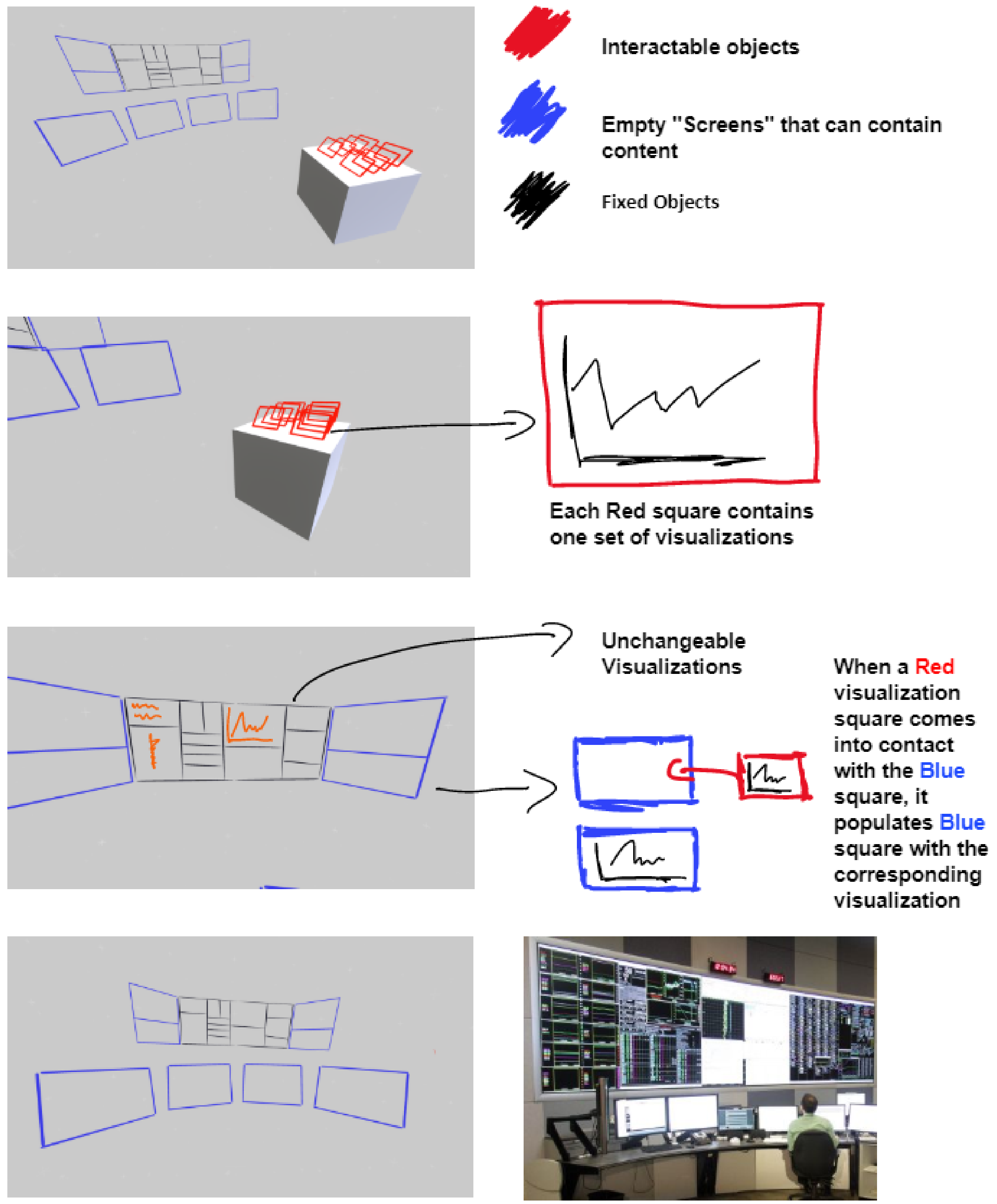
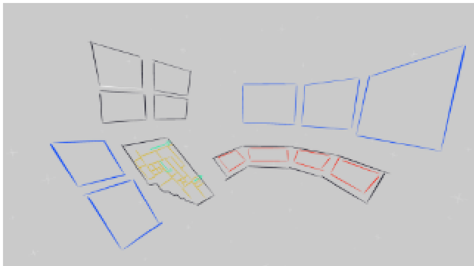
Appendix C

Additional Sketches



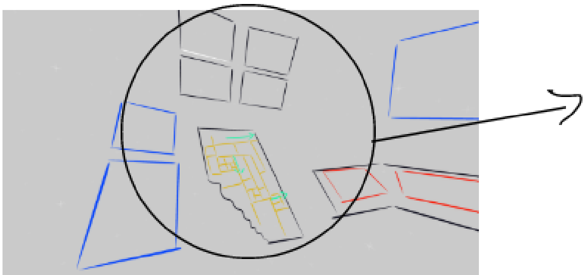
Layout will be similar to that of AESO's actual control room



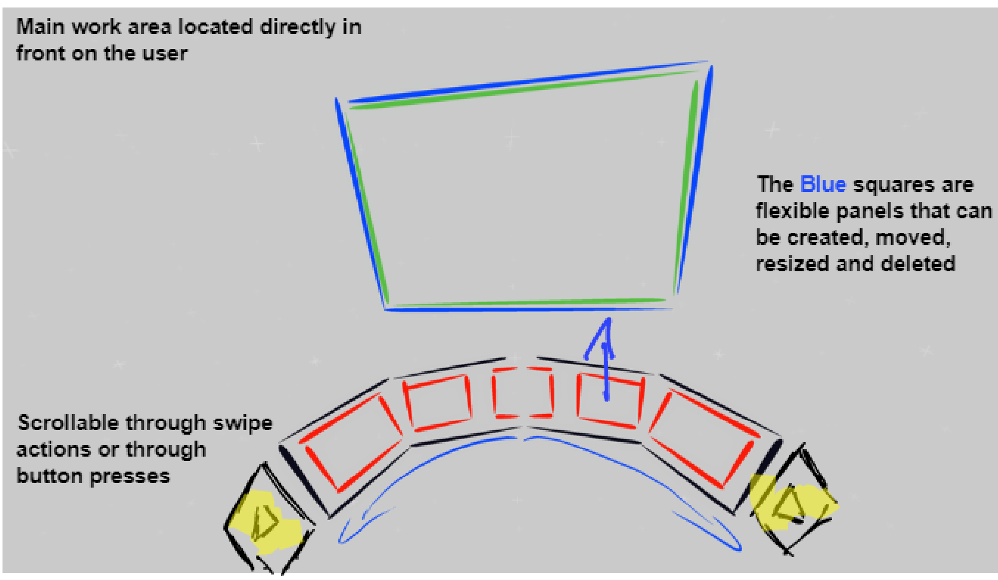
Interactable objects

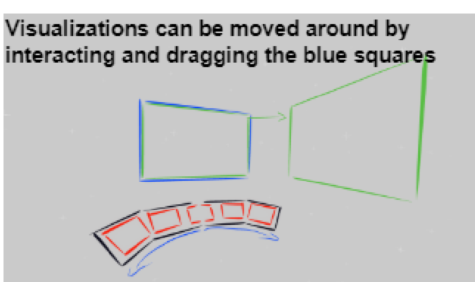
Empty "Screens" that can contain content

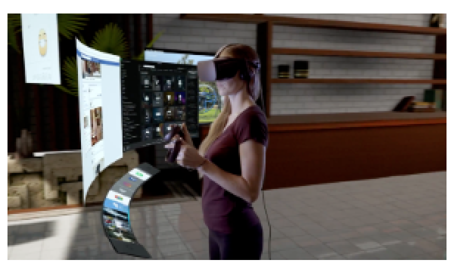
Fixed Objects



Control Room Video wall visualizations are located to the left of the user







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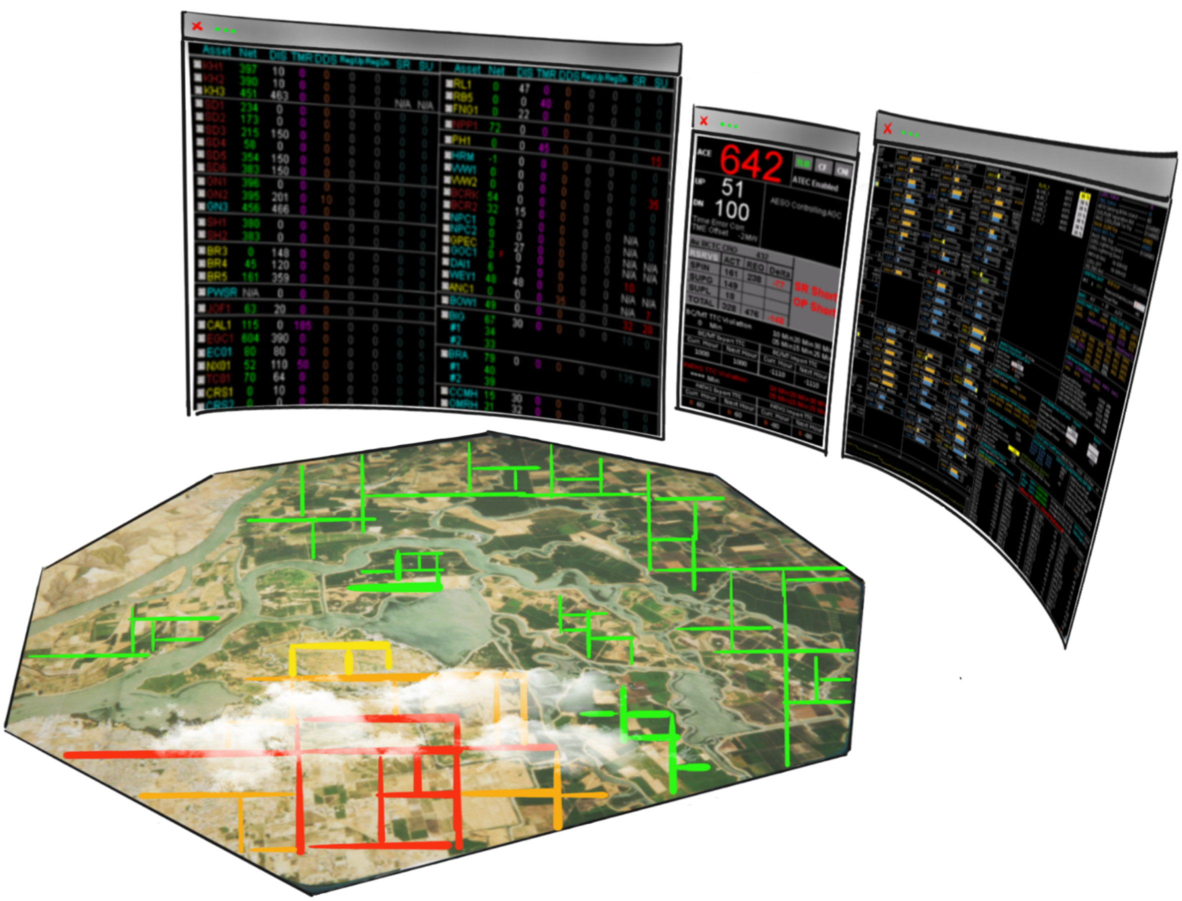
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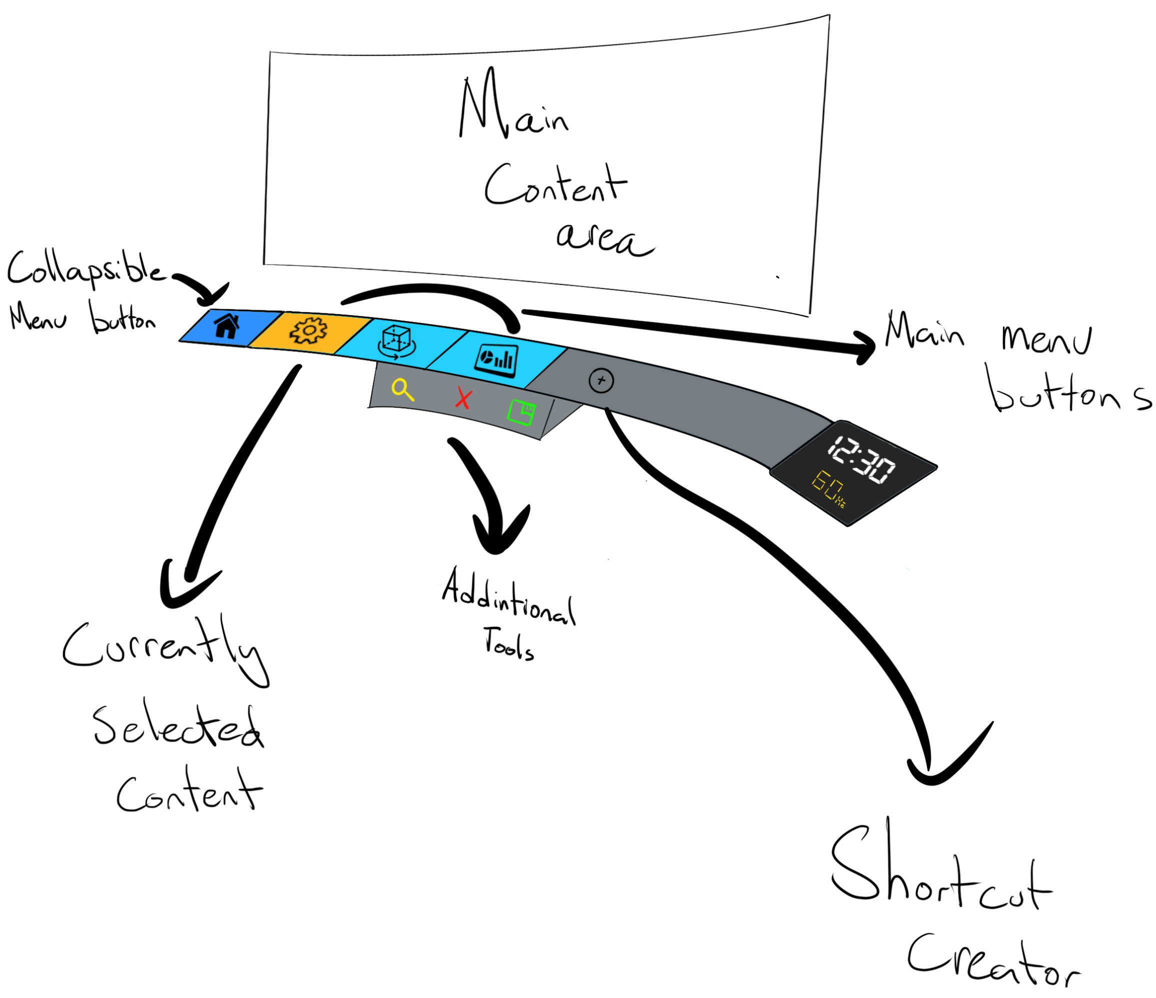
Main Content area
Collapsible Menu button
Main menu buttons
12:30
60
Currently Selected Content
Addintional Tools
Shortcut Creator

Appendix D

Co-Author Permission

UNIVERSITY OF CALGARY

12 March 2020

University of Calgary
2500 University Dr NW
Calgary, AB T2N 1N4
Canada

I, Frank Maurer, give Steven Vi permission to use co-authored work from our publication, "User Experience Guidelines for Designing HMD Extended Reality Applications" for his Msc thesis.

Sincerely,

Frank Maurer

UNIVERSITY OF
CALGARY

12 March 2020

University of Calgary
2500 University Dr NW
Calgary, AB T2N 1N4
Canada

I, Tiago Silva Da Silva, give Steven Vi permission to use co-authored work from our publication, "User Experience Guidelines for Designing HMD Extended Reality Applications" for his Msc thesis.

Sincerely,

Tiago Silva Da Silva