EVALUATING XR TECHNIQUES IN AIR TRAVEL DESIGN FOR THE EARLY STAGES OF THE TECHNOLOGY READINESS LEVEL

by

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Abstract

Extended Reality (XR) is an emerging technology and potential tool to create early design concept sketches for remote collaborative design, review and evaluation. In the field of air travel design, researchers, designers and engineers have been studying the use of XR (e.g., Virtual Reality and Augmented Reality) to support design workflows and comparing this new technique to traditional industrial design methods. This research explores how designers can implement XR techniques in developing early concepts for air cabin design within the Technology Readiness Level framework. The research consists of 2 phases: (1) comparing virtual reality sketching to traditional sketching methods from the researcher's first-hand experience; and (2) the distribution of traditional 2D versus 3D VR developed sketches for designers and the public to review the designs and evaluate their experience with these 2 mediums. The finding from the exploration identifies the advantages of using XR techniques for design and the limitation of learning and of sharing 3D sketches for publishing and sharing with the public.

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List of Acronyms

AR: Augmented Reality

CAD: Computer-Aided Design

CMF: Colour, Material, and Finish

COVID-19: Coronavirus Disease 2019

DLR: Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)

HCI: Human-Computer Interaction

HMD: Head Mounted Display

MR: Mixed Reality

NRC: National Research Council

PEU: Perceived Ease of Use

PU: Perceive Usability

SUS: System Usability Scale

TAM: Technology Acceptance Model

TRL: Technology Readiness Levels

UX: User Experience

UI: User Interface

VEs: Virtual Environments

VR: Virtual Reality

XR: Extended Reality

Chapter 1 Introduction

Extended reality applications have become more accessible as a tool for design and development in innovation sectors. Extended reality (XR) is an umbrella term encompassing virtual, augmented, and mixed reality technologies [1, 2, 3, 4]. In the field of industrial design, the use of virtual reality (VR) and augmented reality (AR) as tools to aid in the development phases of design workflows has become a popular trend [2, 4, 5, 6]. A keyword search in the Engineering Village database for “Virtual Reality and Industrial Design” between 1993 and 2011 yielded 1,289 journal articles. In contrast, a search for “Augmented Reality and Industrial Design” during the same time period resulted in 119 articles. A more recent search conducted between the years 2012 to 2021 for the same keywords resulted in 4,981 articles for VR and 592 for AR articles, an approximately fivefold increase in activity. Additionally, a search that included “Virtual Simulation Testing and Industrial Design” resulted in 1,150 from 1993 to 2011, whereas from 2012 to 2021, keyword results doubled to 2,427 articles. XR technologies are being more widely explored to aid in design processes—including simulating experiences for prototyping, testing, and training—possibly because the digital means can allow the project to be more cost-effective compared to traditional analog methods [2, 4, 7, 8, 9].

Design and engineering for air travel can be a particularly lengthy and expensive process, which can interfere with rapid innovation [4, 8, 10, 11]. Early steps in aerospace design, such as research and brainstorming, have largely employed traditional methods, including sketching concepts, prototyping, and eliciting user feedback on early development work [4, 8]. In recent years, XR tools have been adopted to augment the design process and help drive innovative solutions such as using VR for simulated architecture design [3, 9]. However, XR development has primarily focused on simulating experiences, and comparatively fewer resources are available to support the implementation of XR in the early phases of the design workflow [4, 10].

In response, this study investigated the application of XR techniques to support the early stages of air travel design workflows with a focus on the industrial design contribution to the process. Specifically, the study evaluated the use of XR techniques to support the early stages of design within the Government of Canada's Technology Readiness Levels (TRL) framework. This workflow is well established in Canadian air travel design, with comparative frameworks in other nations [12]. The study used VR sketching as the tool for experimentation and VR/AR hardware and software to engage users in evaluating 3D design sketches generated using VR.

1.1 Air travel workflow

The workflow in air travel design can be a long and costly process [4, 8, 10, 13]. The concept development and user testing phases involved in designing a new product for an aircraft cabin can take several months or years [8, 13]. The aircraft design process in Canada follows the Government of Canada Technology Readiness Levels (TRL) model of design development [12]. In the TRL model (Figure 1), 40% to 60% of the design development time is spent on brainstorming concepts, sketching, 3D modelling (with software), and prototype testing before entering an onsite simulation testing phase [4, 8].

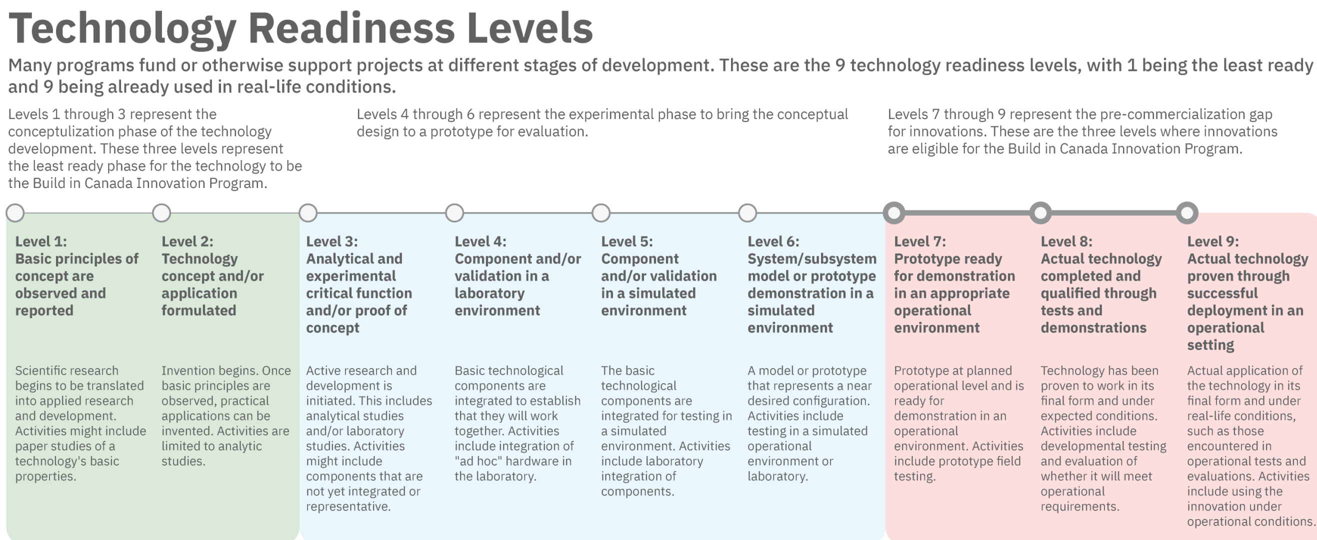

FIGURE 1 THE TECHNOLOGY READINESS LEVELS (TRL) WITH DESCRIPTION OF THE DESIGN TASK

This process can be time-consuming and expensive—even before concepts are evaluated in real physical simulated environments. Some of the limitations of these methods include: the difficulties of collaborating remotely with team members to develop preliminary concepts, the prohibitive cost to conduct early evaluations or usability testing with participants, and the inability to conduct remote participatory design sessions [2, 5, 8]. These process limitations were accepted as the 'norm' until the COVID-19 pandemic presented conditions that accelerated interest in new processes to support remote design across interdisciplinary teams and participation of end-users.

Extended reality is a promising emerging technology to help address some of the current issues in air travel design. Given recent improvements in computer-aided design (CAD) for VR, sketching software now has the potential to make the early development phase of air travel design sketching and three-dimensional (3D) modelling significantly more cohesive and efficient [6]. For instance, 3D concepts can be realized early in the design process, and users can ‘enter’ into these concepts. As opposed to passively viewing static 2D drawn concepts or rendered animations, 3D images can be manipulated by the people viewing it [6, 14, 15, 16]. The immersive aspect of virtual environments (VEs) can likewise enhance the sketching experience for the designer. Using VR, designers can import existing 3D models that meet the context for which the objects are designed—e.g., importing a classroom environment in which the chair being developed will most likely be placed [2].

Another advantage of XR is that it can support more significant participation/user testing by providing a more active conceptual model earlier in the design process. As part of getting user feedback on a design, designers traditionally develop a prototype to present the idea to the participant to help them visualize, touch, interact with, and think through the concepts in the design [6, 14, 15]. Prototypes can facilitate and streamline conversation between the designer and participants, but they can also take significant time to create, depending on the spectrum of the fidelity required. A higher-fidelity prototype might give a more polished idea for the user to visualize, but it comes with the trade-off of a higher time and cost investment to produce it. With XR, designers can reduce both the time it takes to develop a concept as well as the development cost since a digitally developed prototype is more efficient with time and cost compared to producing a physical version [1, 2, 4, 8, 17].

Apart from the above benefits, physical distancing measures due to the COVID-19 pandemic essentially halted in-person collaboration and user testing/evaluation studies, which made XR even more attractive. Among other things, XR can support virtual collaboration, remote product reviews, and remote usability and participatory design studies. As XR technology evolves and becomes more mainstream, accessibility to remote XR 3D simulations can benefit design teams and perhaps help them reach or diversify user participation to provide insight into the early stages of design development.

1.2 Research objectives

This study explores the advantages and disadvantages of using XR techniques in the early development phase of air travel design. The results may help inform the development of new XR techniques that can be implemented in the Human-Computer Interaction (HCI) field of research, Industrial Design (focus on Aerospace and Air Travel Design), and Human Factors research, and may help advance design methods through the adoption and use of XR technology in everyday workflows. The study's methodology was designed with the following research questions in mind:

1. *What is the experience of design sketching in VR compared to traditional methods?*
2. *What advantages and disadvantages does XR (VR/AR) offer in the early stages of design and TLR workflows?*
3. *Considering the limitations of physical distancing measures during the COVID-19 pandemic, what are the potential benefits and barriers of using XR (VR/AR) for remote design?*

The organizational stakeholders in this study include the National Research Council (NRC) and the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt - DLR). Their contributions to the project included sharing their existing design workflows and participating in this study.

1.3 Contributions

As mentioned, this research is in collaboration with the NRC and DLR in joint exploration of implementing XR technology into the air travel design process. This research is the start of an ongoing project, the Aerospace Future Initiative, conducted by the NRC focused on applying XR techniques into human factors research for airline design. Portions of this research have been published in the AIAA AVIATION 2021 FORUM as a full-paper publication [18], and in the 2022 International Conference on Applied Human Factors and Ergonomics [19].

Cooper, N., Kelsey, S., Emond, B., Lapointe, J. F., Astles, S., & Trudel, C. (2021). Evaluating VR practices to support the collaborative cabin design process using a human factor approach. In *AIAA AVIATION 2021 FORUM* (p. 2774).

Astles, S., Trudel, C. & Kelsey, S. (2022) " Evaluating XR Techniques in Air Travel Design for Early Technology Readiness Level." International Conference on Applied Human Factors and Ergonomics. Springer, Cham, 2022.

The goal of this collaborative project is to identify the opportunities XR offers for design to reduce resource requirements in developing aircraft cabin concepts. The study also evaluates XR's promise for remotely reviewing concepts by designers and the general public.

1.4 Thesis outline

This chapter introduced the research study which explored how XR methods can support early concept development and remote review/participation in air travel design. Chapter 2 explains the current design workflow for airline design and the methods used in the development process. Chapter 2 also explores recent literature about the implementation of VR techniques in the design field. Chapter 3 describes the study's methodology, which includes an analysis of traditional design sketching techniques (2D) compared to VR sketching (3D) and a survey of viewers' user experience with XR. Chapter 4 shares the results, supported by the researcher's self-assessment of using XR techniques versus traditional 2D sketching. This chapter also reports the results from the two user groups that participated in this study, designers and non-designers, specifically, their ratings of the usability of the XR medium, followed by the designers' perceived acceptance of XR technology to support design workflows. Chapter 5 present a discussion of the results relative to the literature and the advantages/disadvantages of using XR for the airline design workflow. The conclusion follows in Chapter 6, wrapping up the research study and implications for future research in XR to support airline design.

Chapter 2 Background and literature review

This chapter presents background research and a literature review on air cabin design, design workflow, and current literature on the use of XR techniques in design. Also explored are the ideas and theory of applying XR techniques, such as VR sketching and VR or AR assessment of design ideas, and how these can benefit existing airline design workflows.

2.1 Early stages of design and workflow

The early stages of design and traditional design workflows, for almost all fields of design, follow various models that share common stages in the process. For this research we focus on the Technology Readiness Level framework and the Double Diamond Model which are two systems relevant to industrial design and airline design workflows.

2.1.1 Airline design workflow and the TRL framework

In Canada, the airline design process follows the Government of Canada's Technology Readiness Levels (TRL) as a guideline for the development process [12]. The TRL is a linear representation of the stages of development for design and engineering projects, where Level 1 is the least ready and Level 9 is ready to be used in real-life conditions. More specifically, Levels 1 and 2 (green section in Figure 1) indicate the preliminary phases of development, including design research and concept pitching. Levels 3 to 6 (blue section in Figure 1) refer to when the design brief is more defined, and concepts are put into sketches or prototypes for analysis. The final phases, Levels 7 to 9 (red section in Figure 1), describe the final steps when a concept has been developed to a near-final product and is almost ready for actual real-world use.

In discussions with the NRC and DLR about the airline design process and the TRL workflow, most of the design time is spent in the early stages of development. From discussions with researchers and designers at the NRC and DLR, Figure 2 is a user journey map presented in a comic vignette of the airline design workflow depicting the ups and downs of the TRL levels. The vignette demonstrates that the early stage of a project's design entails developing ideas and iterating concepts using various design techniques. In the TRL model, this process falls within Levels 2 to 4 (Figure 1). This phase of the design workflow consists of brainstorming designs by creating many ideas through sketching and computer-aided design (CAD) and building low fidelity prototypes. These techniques allow designers to iterate multiple ideas while keeping the project as low-cost as possible since design budgets tend to be primarily distributed towards manufacturing the final design concept (Levels 7-9). The emphasis on the early stage of design allows the designers to safely explore and define the problem using an iterative process which leads to many concepts to determine the best solutions for end-users and related stakeholders. The existing process of using traditional techniques can be time-consuming, incurring a high cost before evaluating concepts in real physical simulation environments. Some of the limitations of these methods include difficulties of collaborating remotely with team members and the inability to conduct remote evaluations or usability testing with participants [5, 8, 20].

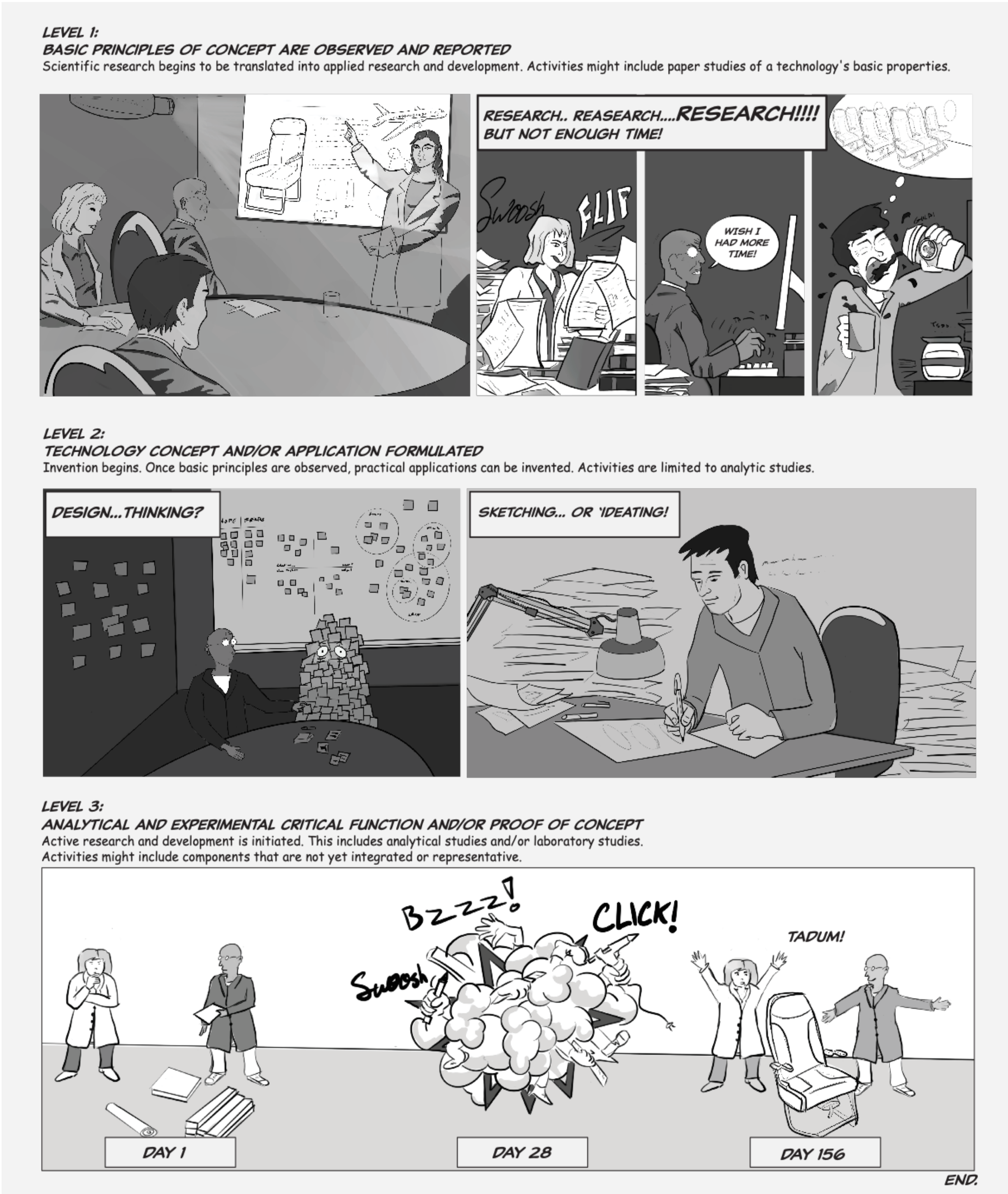

FIGURE 2 AIRLINE DESIGN WORKFLOW REFLECTING TRL LEVELS 1-3

2.1.2 Industrial design workflow: Double Diamond model

The TRL model is a visual representation of the development stages for a project and is an overview of the process for multiple disciplines with specific tasks involved in each stage. For the field of industrial design, the project stages do reflect the TRL but may follow different trajectories depending on the project goals and resources. The workflow for industrial design is not always linear; rather, it is often defined as a complex process that incorporates creativity, business strategies, and engineering to innovate [21, 22]. There are countless frameworks for different types of design processes; however, the focus for this research will be on the Double Diamond design process since the model is widely used in the interdisciplinary field of design. Stages of the workflow generally follow a linear fashion while revisiting some stages as needed to find the best approach before moving on [22].

The Double Diamond model, developed by the UK Design Council in 2005, is a graphic diagram of two diamonds that together reflect the process or workflow of design, which consists of ideas being narrowed or broadened depending on the phase of the project [21]. As shown in **Error! Reference source not found.**, the diamonds are divided into four p hases: discover, define, develop, and deliver. The figure expresses the divergent and convergent stages of the design process. In 2016, the UX Collective revisited the model and developed a more elaborate version featuring more design tasks throughout the stages [22]. Each diamond represents the two main goals of design: *designing the right thing* and *designing things right*. The first goal, *designing the right thing*, is represented in the first phase of the workflow, where the focus is more on design research. Designers use techniques such as reviewing literature, clustering topics and insights, and identifying themes to help define the *How might we* (HMW) statement of a design solution. A “How might we” is a design method where a statement is created to reframe known challenges and narrow down a design to a problem or design brief into a simpler design goal [21]. The second goal, *designing things right*, corresponds to the second phase of the workflow, which works based on the HMW but focuses on the development side, where the designer creates ideas with sketches and prototypes that will later be evaluated or tested with users. This second phase is repeated until the design is ready to be tested in the real world by end-users.

The Double Diamond model shares similarities with the TRL model but more accurately depicts the iterative nature of the design workflow since designers will repeat and revisit phases until the product achieves the design goal before moving on to the next step. The early stages of the workflow applies the practice of design thinking with prototyping where its “purpose is commonly to facilitate the development and transform novel ideas into preliminary models that can be evaluated” (p.20) [23] which identifies the readiness of the design before moving to the next phase of the workflow [24]. This practice is to avoid poor design outcomes and manage the cost of the project. In Figure 3 colour is used to show where the TRL stages overlap with the Double Diamond diagram. The first diamond (painted green) is similar to the TRL model levels 1-2 (Figure 1), where the project stage mostly consists of design research which is narrowed down eventually to define a design solution. The second diamond (painted in mostly blue) represents TRL levels 3-6 and demonstrates the iterative design stages where the concept is explored with countless concept development cycles (depending on the project) and testing and/or evaluation. The last part of the diamond also features a small section in red, which aligns with TRL levels 7-9. At this stage, the concept meets the design brief and is ready to be tested in a simulated environment with the desire to see whether the design is ready for the public.

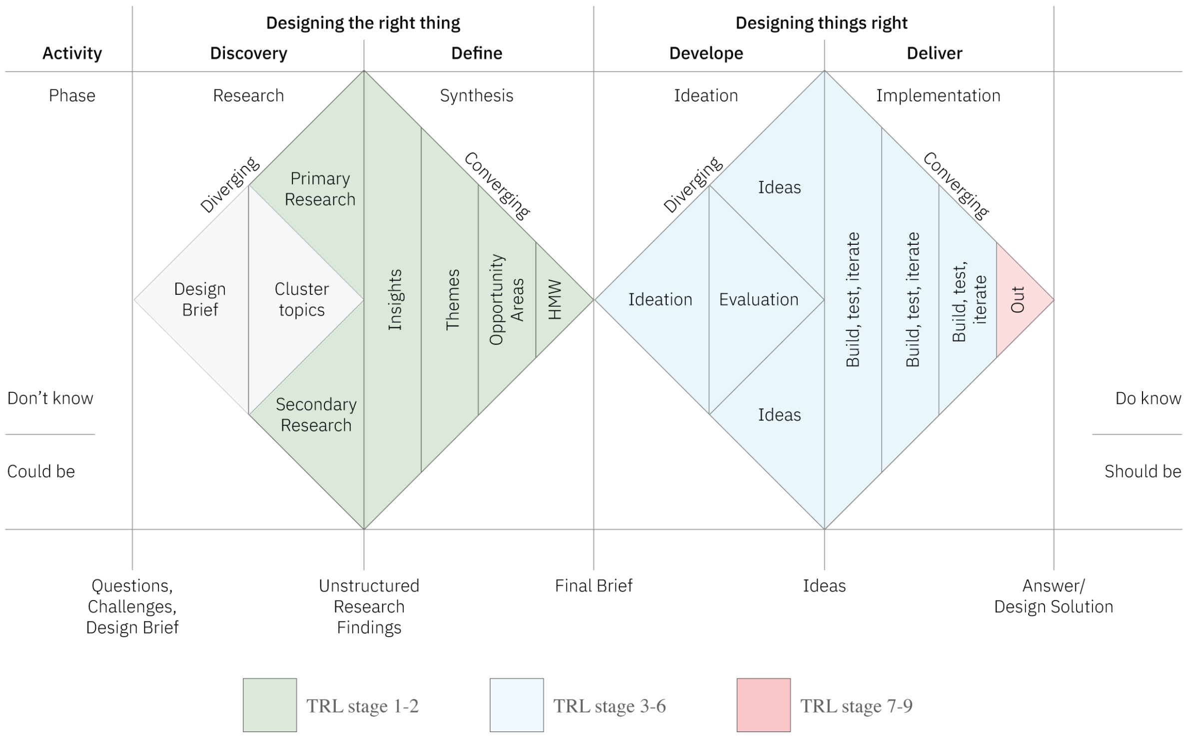

FIGURE 3 DOUBLE DIAMOND MODEL COMPARED TO STAGES OF THE TRL MODEL

2.1.3 Design prototyping: benefits and limitations

Prototyping for design is a task where concepts are explored by multiple iterations either through sketches or physical models in different levels of fidelity [4, 25]. Prototyping is defined as “the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)” (p. 25) [26]. The task and goals of prototyping helps avoid poor design decisions and negative user experience outcomes [27, 26]. Design research for product development relies heavily on creative and scientific resources to find insights and solutions regarding the user's interaction with the product. Research allows for endless exploration of the design through qualitative and quantitative prototyping techniques. Design research helps predict interaction errors in the early design stage to reduce the chances of developing an inferior design [25]. Though research and prototyping in design help eliminate the risk of bad designs, not every project has the funding or access to necessary tools to conduct research. Also, research may have a negative association to being high cost, and many projects are constrained by budgets or time making it difficult to complete research correctly or conduct user testing or evaluation with prototypes [21].

In software and user interface (UI) design, there is some leeway for bad interface design. If there is an error or flaw in the application of the UI or it does not satisfy the user interactions, the developer can go into the code to adjust or update the system and change the software for the next update [21, 28]. An example of this is the smartphone, such as the iPhone, a successful product partly due to the flexibility of adjusting its UI. Since the product's design is driven through the interface, when an update is available for its application system, the user can simply download the update for the new version [28].

In hardware design, physical products do not have the same opportunity for restoration or redevelopment. Once the product is out and available to the public, it is nearly impossible to change the physical design unless it is recalled and replaced completely [29, 24]. Finding interaction flaws during the early development stages of hardware design can help eliminate issues and errors that may be harmful to or undesirable for individuals when the product becomes available in the real world [30].

Exploring many ideas in this early phase can provide better control over the design itself before the product gets into the hands of the consumer. Using XR for design development has the potential to marry the benefits of digital prototyping and with hardware design in the early stages of design. As pointed out by Elverum *et al.,* applying available technology to create mixed prototyping techniques such as digital and physical can "make it is possible to create highly flexible prototypes that enable short learning cycles at an affordable cost" (p. 117) [24]. Using digital and physical techniques for earlier phases has the great potential for developing and evaluating the usability of product interfaces and uncovering how users will interact with the product before creating a higher fidelity prototype. The following section will explore how XR can be a digital tool and technique for prototyping.

2.2 Sketching with VR

Virtual reality has become more accessible in recent years with the product becoming more affordable for the public to obtain (e.g., Facebook sells their Oculus headset for approximately the same price as most video game consoles) [31]. Virtual reality is widely known in gaming but the application development software for VR, such has Unity 3D, has also become more available and friendly and fueled an emergence of independent developers creating VR software for engineering and design (e.g., Gravity Sketch, Mind Desk, Vector Suite, and more) [32, 33]. Though many software applications continue to be updated and developed to improve VR sketching, there are still many unknowns about the physical experience of developing in VR and creating meaningful content while sketching in VR.

2.2.1 Hardware ergonomics and affordances for VR sketching

Using VR for sketching has many ergonomic considerations, such as fatigue and strain on the eyes [3], hands/wrists [34], and neck [14], and a lack of feedback while drawing [3, 6, 33, 34]. Currently, sketching in VR relies heavily on the use of a connecting controller, which works with wireless joysticks and buttons (typical hardware design for commercial video games consoles), and a VR head mounted display (HMD). As mentioned, VR sets are becoming more accessible for users to attain, with additional accessories that can be paired via Bluetooth™ with an HMD as substitute input devices depending on the task. Pham and Stuerzlinger (2017) comment that new pairing devices and continuous innovation in VR/AR "not only deliver a comfortable experience but also pave the way for professional applications" (p.1) [34].

Developing 3D drawings in a VE allows the user to sketch in free space compared to 2D sketching where the user relies on a stylus for digital sketching to draw on a surface (e.g., paper, tablet, etc.). Though it may seem appealing to sketch with 6 degrees of freedom (6-DOF) where your canvas is the space around you, the biggest concern is that the sketching experience may be too far away from the natural experience [14]. Designers are trained to draw following traditional methods (e.g., pen and paper digitally on tablets) but in VR drawing these techniques are not as readily available or relevant [6]. In VE, surfaces may not be available to give illustrators feedback to assist in their drawing and most input devices are designed to hold with a power grip instead of a pen grip [34]. VR software and hardware are designed to have natural affordances so that the user will feel immersed in the simulation, with the controllers used for pointing and grabbing [6]. This means that the hardware is designed for the interaction with the simulated content designed to enable and create immersive output (i.e., grab an object in VR). For sketching, the exact opposite is happening where you are using the hardware to create input (e.g., the 3D line, surface, and solid parts) to create an immersive drawing.

To make drawing a more immersive experience, Logitech developed the VR Ink Pen, an input accessory, that is designed like a pen for users to sketch in VR. However, it is also advertised as a technology that benefits creative professionals for 3D sculpting, prototyping CAD models, and many more creative pursuits [35]. The VR Ink Pen (Figure 4) is a relatively new device for VR sketching where most of the existing applications, such as Gravity Sketch and Google Tilt, are interface interactions designed to work with the HMD controllers of the VR set [32]. Currently, there is little information available on the ergonomic benefits of using this device for drawing in VR.

FIGURE 4 THE LOGITECH VR INK PEN STYLUS

Most input devices have been examined with a mind to which designs have the best pointing capabilities or are the most immersive in terms of interaction. Pham and Stuerzlinger (2017) examined various VR apparatus to identify their capabilities in performing a pointing task in AR and VR but also explored the ergonomic benefits of using either design (i.e., controller versus mouse versus stylus) [34]. The pointing task was evaluated with 12 participants to complete a Fit's Law test with participants providing heuristic feedback of their experience. Fit's Law entails examining the input device capabilities in pointing selection tasks by evaluating its time for movement, cursor speed, error rate, and throughput speed. Throughput is defined by effective measures that take the task that the users performed into account (p2) [34]. Overall, the Fits Law test concluded that the stylus succeeded in a quicker movement and cursor speed. As well, the stylus had less error and throughput values compared to the controller and mouse. Participants commented that their performance was better with the pen-like apparatus since it was more comfortable as a control for pointing tasks since using the device "was similar to using your finger to point at the target" (p8) [34]. Based off this evidence from Pham and Stuerzlinger a pen-like input device, such has the Logitech VR Ink, may be the solution to make interaction in VR more usable and provide a more natural drawing experience compared to current VR hardware.

2.2.2 VR sketching for accuracy

In their consideration of VR as a design sketching medium, Arora *et al*. identified some issues [33]; most notably, a virtual space does provide more spatial freedom compared to traditional methods of 2D sketching, but the way that lines connect in 3D space can be confusing. The study found that the lack of a physical drawing surface in VR was a significant cause of inaccuracies due to loss of precision compared to sketching on a 2D surface.

Likewise, the possibility of inaccuracies was found to increase in VR due to the confusion of in-depth perception and the larger scale of the drawings. Ban and Hyun (2020) designed a framework for developing and prototyping CAD models in VR with the aim of determining whether creating a car drawing in VR would be as accurate as drawing a 3D model using CAD software [6]. The study discovered that car sketch designers had the habit of sketching organic form in perspective; as a result, drawings of the wheels of the car in the final image were skewed, which affected the condition of the vehicle. In VR, the drawing condition should be done by orthographic projection (i.e., flat drawing) since the outcome of the sketch will be in 3D. To draw a wheel in VR means drawing a circle extruded into a cylinder. Ban and Hyun (2020) resolved the issue of skewing by including a Wacom sketching table (2D drawing method) to draw the forms that require more accuracy to refine the details [6].

As Ban and Hyun found, sketching in a 3D space eliminates the need for designers to sketch with consideration of a vanishing point [32]. A vanishing point is the point on the horizon line where the angular perspective lines of an object visually continue past its edges and eventually converge. These angular lines help artists draw forms in perspective to make it appear true to scale [6, 36]. With VR, the user can develop a 3D form from orthographic drawings produced on planes that can be sculpted into a volume form. Ban and Hyun resolved their perspective drawing issue by sketching the form using both isometric and perspective drawing techniques in 2D on a Wacom table, then inputting the sketch into their 3D drawing.

Barrera Machuca *et al.* (2019) explored this perspective sketching issue further with the aid of multiple planes projected in VR to help the drawer freeform sketch more accurately [16]. The planes acted as a 2D surface off which the user could project their sketch – similar to using a Wacom tablet sketch surface or a paper artboard to sketch on. With multiple planes, users could draw on a flat surface, which provided guides to sketch more accurately using orthographic drawing principles. In a continuing study, when assessing errors in 2D drawing, Barrera Machuca *et al*.(2019) noted that most errors were from delusion (i.e., errors in the conception of the image) rather than an illusion (i.e., errors in perception) and that these were mainly due to individual differences in visual attention, as in the ability to read and understand images [15]. By adding another dimension, drawing in 3D required higher manual effort and higher cognitive and sensorimotor (e.g., the ability take in information about the perceived environment through our senses) demands compared to 2D drawing. However, since errors due to individual visual attention abilities also exist in 2D drawing, it is possible that the problem of depth perception and drawing inaccuracies in 3D virtual spaces could be partly resolved with practice over time.

2.2.3 Potential roles of VR sketching for design

An emerging tool in the design industry is computer-assisted drawing (CAD) using VR techniques. Sketching in VR allows designers to create CAD models that provide a more immersive experience since VR offers the opportunity to create 3D drawings that can be perceived in a 3D environment [32, 37, 38]. A significant benefit of sketching in VR includes allowing the user to explore ideas in scales that exceed the barriers of paper or a desktop monitor; VR sketching software, such as Gravity Sketch, allows users to create free-form 3D graphics in a 3D environment. In a virtual creative studio, designers can create initial ideas as well as evaluate prototypes. Ideating in VR is similar to developing a physical prototype but eliminates the process of fabricating the model, thus potentially saving time and money.

Several studies have noted that one of the most significant advantages of sketching in a virtual environment lies in the sketching process itself. Since the object in view will be 3D and can be drawn to scale, it could also reduce the cognitive load of people experiencing the environment compared to 2D sketching since it is more closely depicting its actual form and size [14]. This reduced cognitive load could lead to more attention being paid to creatively developing the form instead of translating it from a 3D visualization to a 2D representation of the 3D form. As a result, an immersive 3D system could potentially help foster better spatial thinking [6, 14, 38].

2.2.4 Experience of designing in VR

Though it is a promising medium, drawing in a virtual space can be challenging. The lower quality depth perception in VR compared to physical reality can cause misjudgment of where lines will connect in space, which might lower the accuracy of drawings [6]. As well, experienced designers who have been sketching and making models in a certain way may find it frustrating to adopt a new technique that changes their methods and workflow [6, 14, 37].

To take full advantage of the benefits of VR as a design sketching medium, the ways that drawing can be made more effective need to be assessed, including what specific changes in sketching techniques can improve certain design ideation cases. It is important to note that both 2D and 3D sketching approaches have distinct advantages for different stages of the design process [14]. For instance, when comparing sketching and traditional CAD modelling, Shih *et al.* argued that CAD modelling can be better suited for complex problem-solving [**20**]. Since the model is accurate, it may help designers refine their design thinking. In contrast, physical sketching was found to be helpful for brainstorming and quickly manifesting a design idea. Shih *et al.* (2015) noted that, ultimately, designers switch back and forth between media, alternating at will [37].

Rahimian and Ibrahim (2011) provided an essential critique of CAD modelling and physical sketching in the design process [36]. Their study analysed the collective cognitive and design protocols of three pairs of novice architectural designers in both 3D and traditional 2D manual sketching sessions. They argued that CAD tools can be arduous and unintuitive, hindering the design process in the early concept stage. Physical sketching, meanwhile, is limited when the artefact becomes complicated.

Rahimian and Ibrahim (2011) also found that 3D sketching in VR improved designers' visuospatial perception, which refers to the visual perception of the spatial relationships of object, features and relationships compared to manual drawing and traditional desktop CAD approaches [36]. This is because the designer is able to sketch to scale and with their own bodies in mind while designing. Traditional methods of sketching lose these benefits since designers are confined to the dimension of the medium (i.e., the paper dimension) and need to draw the concepts with exaggerated dimensions and scales to make sense of the perceived drawing. Using VR for sketching removes these additional tasks in the sketching process; which may help designers focus on being creative and making discoveries while designing.

Israel *et al.* (2009) supports the research of Rahimian and Ibrahim (2011) on several points about the potential for VR to visualize complex 3D environments in design. Being able to move around can potentially change the way space is utilised and thought of, which could help solve design problems in the early development and evaluation stages. Israel *et al.* (2009) noted that the most significant advantage of 3D sketching is what the process enables [14]. In their qualitative study, the study's participants emphasized the 3D system's ability to foster inspiration and improve the recognition of spatiality and spatial thinking. Participants believed in the potential of 3D sketching to provide a new means for sketching in terms of one-to-one proportions, spatiality, and formability.

All in all, the studies mentioned above reinforce how VR for design is in its infancy, yet a promising technology for design and visualization and the experience of creating ideas. Rahimian and Ibrahim (2011) and Israel *et al.* (2009) describe the benefits of sketching while moving around in the VE which could promote more creativity in the drawing task. The actual process of sketching in VR can also contribute to the design process by solving problems while drawings acting as an emerging 3D prototype, since traditional 2D sketches tend to display only the final render of the design for review.

2.3 XR for prototyping

As mentioned in section 2.1.3, prototyping is a vital process in the development of a product design since it allows the designer(s) and/or user(s) to examine a concept at various stages of the development. Traditional methods of developing physical prototype models incurs high costs since it is primarily done using rapid techniques, such as 3D printing, and most of these techniques produce a low fidelity version of the design. Another disadvantage of traditional methods is that some rapid techniques are limited to the scale capabilities of 3D printing and the printer bed size.

XR is becoming an alternative option for prototyping since the technology can mimic the design process digitally. The benefit of XR as a tool in product design is similar to the benefits of user interface design (see section 2.1.3) since it is a digital environment where it is safe to test the concept and to fine tune errors in the design. A design can be conceptualized, tested or evaluated, further developed and explored using VR techniques, perhaps facilitating more product exploration and interaction that can easily be changed or updated by the design team. The following sections discuss previous work on the benefits of relying on XR during the prototyping phase within the design process.

2.3.1 Tools for remote evaluation

The early stages of design involve exploring a product design concept by communicating and evaluating the idea through images and prototyping techniques. VR has become a popular tool in the exploration phase of product design to create simulated environments that could easily be shared either through an application or online. As well, both VR and AR share the potential to easily import multiple 3D models into the digital environment. This allows the opportunity to explore concepts remotely through a simulated immersive experience and allows the viewer to have an experience with the concepts, albeit artificial. These technologies also allow the user to enter a VE that matches the context of the product being tested [2, 6, 8].

In 2010, Haocheng *et al.* evaluated the use of VR as a tool for testing simulated airports [8]. They developed a VR environment to conduct simulation of the ground handling area, specifically where loading luggage into the aircraft is conducted. The purpose of this simulation was to create a software to help investigate human factors considerations in airport workers' handling of passengers' luggage from baggage vehicle into the plane (e.g., task timing, luggage weight handling, and lifting luggage into various aircraft designs). The study explored whether VR implementation was sufficient to replace accurate onsite scenario testing. This would be of benefit since the act of testing in the actual ground handling requires time, a high rental cost to use the space, and testing disrupts the airport workflow. The simulation did succeed in conducting more efficient methods to collect the desired data but lacks evidence in comparing the simulation time results to real-life results. The authors did however share that the running time to set up the VR simulation tests can be completed in a day while the set up for in-person testing can take up to week or months to coordinate [8].

The need to test remotely is very desirable for design research. Remote testing or evaluation makes the process more accessible with the ability to gather data and feedback from more participants since traditional in-person methods require participants to be able to attend the location in person. In addition, scheduling a time and date that is suitable for the participants may not align with the project timeline. Further to this, physical distancing measures during the COVID-19 pandemic have put in-person user testing on hold, which while this study was being conducted (Fall 2020 - 2021) was still in full effect. Using XR techniques may have the potential to create a more accessible method to conducted remote user testing session with users safely while physical distancing.

A system designed by Milovanovic *et al.* (2017) explored the benefits and constraints of collaborative design reviews using AR and VR. Architecture students were asked to collaboratively review a digital prototype of an architecture design [9]. The goal of this experiment was to create a 3D medium of the interior space that could be viewed either in AR or VR allowing the student to learn from the simulation. The benefits of AR were that more students were able to participate remotely since all of them had a smart phone to run the simulation software. A downside from the AR simulation was that they were only able to view a low fidelity version of the simulation while the VR version was a more immersive and interactive experience. The limitation of the VR was that the student had to use the school's VR HMD set up since the simulation design could only work with this hardware and not all the students owned an HMD. Therefore, a limiting factor of VR was access to hardware, as high-quality equipment is better to conduct simulations.

Clergeaud *et al.* (2017) tested the differences between high- and low-quality VR apparatuses by conducting an asynchronous VR simulated test. The study compared user response to using VIVE Pro HMD VR set up in a lab (high-quality) to a VR cardboard HMD set up conducted remotely (low-quality) to complete a series of tasks [5]. In this study the participants tested both equipment set-ups while completing a series of tasks in VR which asked the user to rate their awareness in the simulation, ability to remotely interact and manipulate elements, as well the capability to navigate between locations. The research lacks quantitative value since each test was completed with only three engineers (who were partners on the project), and the study was conducted with the participants completing the tasks then verbally expressing their perceived experience. Despite the lack of quantitative data, the in-lab equipment performed better than the cardboard HMD for tasks where selection was involved. However, for the visual simulation experience the cardboard HMD was perceived to have the same immersion experience and was preferred since the participant was still able to feel where they were in the real-world room while conducting the task in the virtual environment.

Prototyping allows developers to explore their concept in various iterations of the design and explore the user's experience of the product. As mentioned, once a tangible hardware is designed - whether it's a near finished sample or prototype - it is difficult to go back and make changes. Additionally, to produce multiple prototypes to test various interactions, the product design can incur high resource and monetary costs [2].

To reduce the resources associated with physical prototyping, Kim *et al.* (2018) conducted a study of vehicle interior interface designs for car sharing vehicles, using VR to help gather feedback on participants' user experience with alterations to the design [4]. The goal of the study was to design a new interface that would work safely, making it easier to learn the car's features so drivers would not get distracted on the road while trying to learn the new interface. Kim *et al*. (2018) collected the insight from their participants' interactions with their own vehicle compared to the car sharing vehicle. The study's participants included 7 males and 5 females, asking them to drive their own car compared to a shared car and collect data on their interaction with the interface. The data collected included the time it took to complete a simple interaction task with the interface (i.e., turn up the music volume with the dial). The researchers hypothesized that users would know their car interface better and be able to perform the task quicker. The data was used to identify the features that made interactions seamless and safe for users to learn to assist the researchers in designing prototypes with these findings.

For the study, Kim *et al.* (2018) could not swap out the interior interface of the shared car thus they created a VR simulation of the new design in a simulated car ride. The methodology of this study design consisted of mixed reality (MR) of a 3D printed interior car interface to full scale with a VR simulation of a 5-minute car ride. The same participants completed the second study where they repeated the same task while being timed and provided feedback of their experience using this method.

Overall, the time to complete each task in the MR car interior design was roughly half compared to the shared car experience (average of 4.27 second per task for the MR car compared to 9.42 second per task for the shared vehicle). Comments on the use of VR for the study proved that participants were able to adopt the prototype version to complete the task, but participants also made further qualitative comments on the design appearance compared to the shared car. For example, most participants made comments on the shared car dial interaction (i.e., turn left or right for the HVAC control), however for the 3D printed version they commented more on the look and feel of the material and thickness of the dial.

The phase with the highest production cost with regards to time and value is exploring the product's appearance and feel regarding colour, material, and finish (CMF). The biggest drawback in CMF exploration is that it can include researching multiple combinations of the design (i.e., the same form design but in a multitude of colour and material combinations). VR has proven to be helpful in projecting the final render CAD model of the interior design, however it is unclear whether virtual testing results are similar or acceptable compared to existing evaluation methods conducted in person [2, 4].

Felip *et al.* (2020) compared users' perceptions of a product presented in real life and in a digital environment [2]. The study recreated a testing environment that was identical in real life and VR. The room, modelled in CAD for the VR evaluation, was rendered to animate the same colours, material, texture, lighting, and furniture featured in the real-life testing space. The product to be evaluated was a chair since the user could touch and sit on it when exploring the product in both test settings. The chair was also modelled in CAD for the VR evaluation. Participants explored the chair in both settings and rated the chair's design through sight and touch. At the end of their review of the chairs, the participants filled out an evaluation survey about the adjectives they would use to describe the chair (on a Likert scale; light to heavy, casual to professional, etc.). Lastly, they answered the question "How much do you like the armchair" using a Likert scale (from 1 to 5: 1 = "I do not like it at all", 5 = "I like it very much"). Overall, the results did not show any differences between VR evaluations of the chair. The Likert scores were separated by an average of only 0.24 for the question "How much do you like the armchair?". The armchair obtained a mean score of 3.87 points when viewed in VR ($\sigma = 0.61$), and a mean score of 3.79 in the real room when VR was not used ($\sigma = 0.80$). In both cases, a score of 4 points was the most frequently chosen. The researchers acknowledged that the VR may have scored higher since participants expressed excitement, and therefore were biased by feelings of novelty. Thus, the authors claimed that VR technology can be utilized as a tool for product exploration in design [2]. The testing capabilities of VR shown in both Felip *et al. (2020)* [2] and Kim *et al.*'s (2018) [7] case studies show that it is possible to use VR to explore tangible aspects of a design in a VE and gain insightful qualitative data about the user experience.

2.4 Study rationale

In summary, the literature has identified that VR has been implemented into the design process as a technique for prototyping for CMF evaluation [2], user testing through VR simulation rather than developing a physical product [7], and as a method to work off site [8, 9] and asynchronously [5] which may allow designers and the general public to participate in design reviews more efficiently. Additionally, developing 3D sketches has the potential to support designers in solving problems within the sketch process [15] and be more creative while sketching [14] compared to traditional methods of 2D sketching.

As mentioned, the organizational stakeholders interested in this study include the National Research Council (NRC) and the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR). Their contributions to the project include sharing their existing design workflow so that an XR method can be developed and evaluated for integration into air travel design. Currently, the DLR has researched the application of XR in the early stages of the design process, including collaborative brainstorming and design research [10]. Following the Double Diamond design model (Figure 5), the contribution of this research will continue from where the DLR left off in their research to examine other aspects of implementing XR in the design process [9].

The task set out in the methodology of this study is to evaluate if VR is a feasible technology for initial concept development via sketching and by having participants evaluate ideas using AR and VR techniques. The motive behind this experimental study is to evaluate if XR can be used for the next step in the Double Diamond model, highlighted in Figure 5, where XR can be used to sketch and brainstorm early design concepts, and be used and accessible for people to view and provide feedback in comparison to traditional 2D sketching techniques.

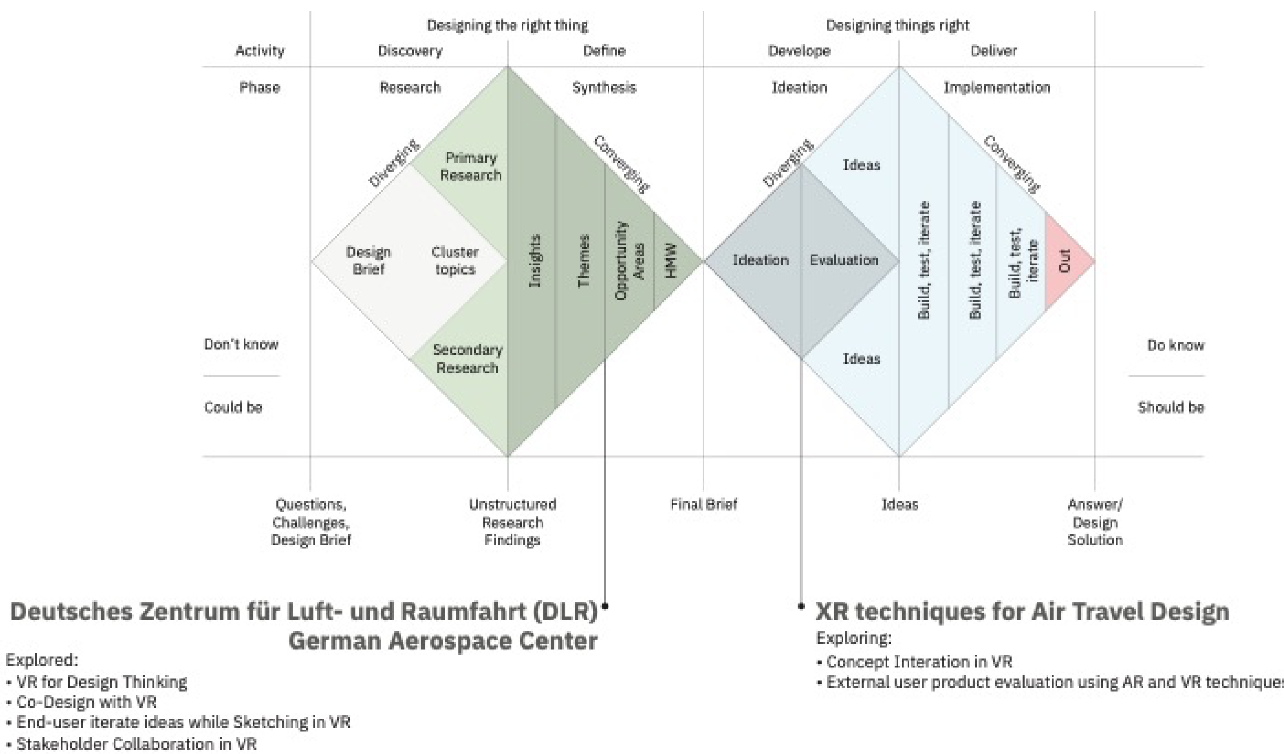

FIGURE 5 DOUBLE DIAMOND WORKFLOW RELATIVE TO PREVIOUS WORK BY DLR AND THIS STUDY

Chapter 3 Methodology

Evidence garnered from the above literature review suggests that XR techniques demonstrate the ability to allow design workflows to be more efficient and practical such as: using XR to develop sketches [32] to create a more immersive 3D drawing for product evaluation [2]; the designer being able to problem solve while sketching in a VE [36]; and the ability to share 3D sketched prototypes for review by users [5]. The following study examines the potential of XR to support the design process in air travel design. This is reviewed through: 1) first-person journaling of the researcher/designer perspective of the sketching experience using traditional 2D sketching techniques and 3D sketching using VR technology; 2) remotely sharing these 3D design sketches through VR and AR techniques compared to more traditional 2D concepts with the general public and designers to assess the technology's potential to be used for review or evaluation purposes; and 3) how this analysis applies to the current airline design development stages that follow the TRL workflow.

The study is divided into two phases, where each phase evaluates specific aspects of XR in design work. In the first phase, the lead researcher assessed the experience of using VR as a tool for design sketching. In the second phase, the XR survey was designed to allow users to remotely assess early design concepts in a review session. The study received ethics clearance from the Carleton University Research Ethics Board B (Appendix E, p.141).

3.1 Study design and overview

The two phases of the study were designed to mimic a typical design workflow of a designer working independently (i.e., not in a team-based environment) using traditional design practices and XR technology. Each phase of the study was mapped to stages of the TRL model (see sections 1.1 and 2.1.1). The infographic in Figure 6 demonstrates how each phase's methods reflect a specific level in the TRL and the associated design activity in the design workflow. The data collected from phase one included the researcher's journaling of their first-hand account of VR sketching experience versus using a traditional 2D sketching technique.

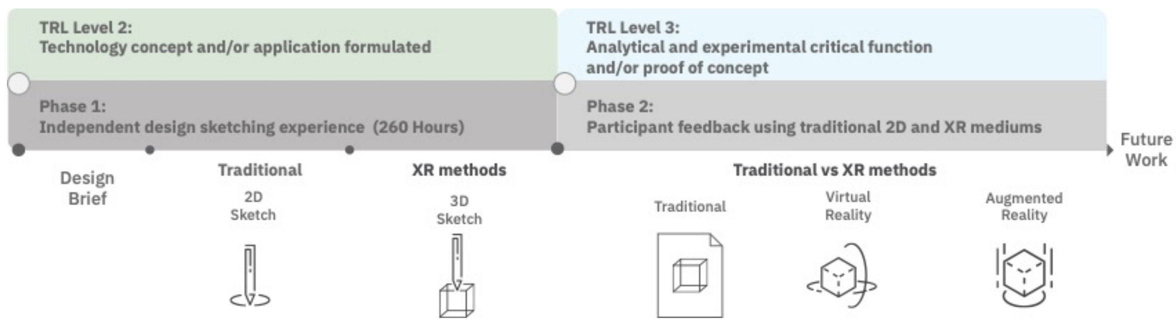

FIGURE 6 STUDY PHASE RELATED TO THE TRL MODEL FOR AIRLINE DESIGN

The design sketching brief was to generate aircraft cabin concepts focused on a timely event, namely, creating partitions between seats to separate passengers during the COVID-19 pandemic. In phase two, the 3D and 2D sketches developed were shared in an online survey with two user target groups: designers and non-designers - where the non-designer represents the general public. These groups reviewed the sketches independently and remotely online using Qualtrics an online survey software. After viewing the sketches, both groups completed a System Usability Scale to evaluate the system (traditional 2D illustrations versus VR/AR simulation) to view the sketches. The designer group completed an additional questionnaire based on the Technology Acceptance Model (TAM) to gauge their views on the ease and usability of using XR techniques in their design workflow. The following sections describe the procedure for each phase of the study and how the data was assessed.

3.2 Phase one: independent design sketching experience

In the initial phase of the study, the researcher developed and recorded their experience of sketching concepts in two mediums: traditional 2D drawing and 3D VR sketching. The researcher identified traditional sketching techniques and tools used to develop 2D medium drawings and new VR techniques for developing 3D medium drawings. The sketching task was assigned a 130-hour time restriction for each medium (total of 260 hours). The NRC suggested the specific 130-hour timeframe to mimic a previous study where a designer was assigned 130 hours to conceptualize a seat design for an aircraft.

The findings from this method reflect the qualitative value of designing with VR to produce early design concepts, identifying the advantages and disadvantages of the techniques. The data collected is the journaling of the first-hand account of the researcher's experience of the sketching session (described more in section 3.2.4), as well video recordings of the VR simulation and the researcher sketching.

3.2.1 Apparatus

The following section identifies the tools and hardware used to develop the two mediums and how the self-recorded data of the sketching experience was collected.

Traditional 2D sketching

Traditional 2D sketching was conducted using an iPad Pro (Model A1876, ver. 2019) with an Apple Pencil (ver. 2019). The sketches were drawn using the application ProCreate (ver. 5X five build 9c9698bade). Touch-ups and renderings of sketches were completed in Adobe Photoshop (ver.2021).

3D VR sketching

The VR sketching was conducted using a 3.9 GHz Intel Core i7 PC laptop running Windows 10 with a memory of 16GB RAM (model: ASUS ROG Strix Scar II GL504GW-DS74). The graphics card used for the system rendering was an NVIDIA GeForce RTX 2070 GPU. The VR head-mounted display (HMD) was an HTC Cosmos headset with 1440 x 1700 pixels per eye (2880 x 1700 pixels combined), a 90Hz refresh rate, and a 110- degree field of view (developed by HP Inc. model number 99HART000-00). The controller was a single Valve Index Pro, used as an eraser tool (or undo/redo actions) and acted as a secondary pointing device for navigating the user interface throughout the study. Sketches were drawn using a working prototype of a Logitech VR Ink Pen stylus (PN 814-000044) with the same features as the product intended for the final release (date TBA). Four Lighthouse 2.0 base stations tracked the HMD, controller, and VR Ink. The software used to simulate a sketching environment ran on SteamVR Beta (1.17.1), and the Logitech SDK Demo software (version 1.16 released in 2020), and the sketching software was Gravity Sketch (ver. 2021).

The sketching techniques used in the Gravity sketch software consisted of using the following CAD tools: ink, stroke, revolve, surface, volume, and insert primitive shapes or pre-fabricated models (tools UI showed in Figure 7).

FIGURE 7 GRAVITY SKETCH TOOLS UI

Distribution of the sketches for the survey

For phase two of the study the sketches and survey were distributed using online survey software Qualtrics (vers. 2021). The 2D sketches were displayed in a gallery viewer installed on Qualtrics. The 3D medium sketches were made available using an online simulator Vectary (vers. 2021.1.4).

3.2.2 Publishing and distributing AR simulations

The task of publishing 3D sketches for AR took roughly three hours per sketch, or a total of four hours including the rendering time in KeyShot. Publishing the rendered 3D sketch for

AR was set up in Unity 3D using the AR scene platform. Once exported into a filmbox (FBX) format, the simulation was uploaded to an online emulator, provided by Unity 3D, with a QR code that users could scan with a smart phone to view the 3D model (Appendix F, p.143).

A disadvantage of publishing an AR model in this way is that most smartphones can only download an AR model that has less then 100,000 polygons. From the researcher's experience, a polygon count is rarely considered while creating 3D models for design. In this study, the issue with the VR sketches was that most of them had an average polygon count of 500,000. To resolve this, the rendered models were manipulated in Blender, an animation rendering software, to reduce the polygon count of the model with the Decimate Modifier tool. The disadvantage of removing polygons from a model is that some of the features were removed in the VR simulation. For example, Figure 8 shows that the AR model is missing some detail on the edge of the chair design. Another limitation of this approach was with sketches that featured prefabricated models, which were almost impossible to reduce from a polygon count of roughly 2 million to the desired 100,000 count. The researcher used their discretion and opted not to attempt to share these sketches since the quality of the 3D models would not have been at the same standard as the 2D sketches.

3.2.3 Publishing and distributing for VR simulation

Publishing the 3D sketches for VR was the most time-consuming task to complete, taking the researcher roughly eight hours per sketch. Exporting to VR using the Unity software would require development of multiple versions of the VR simulation to be compatible with the variety of VR HMD hardware the participants might have (e.g., HTC Vive, Oculus, VR

Cardboard). To avoid this, the researcher created a Stereoscopics video for viewing the VR models; thus, all HMD hardware would be able to provide participants with the ability to view the simulation in VR.

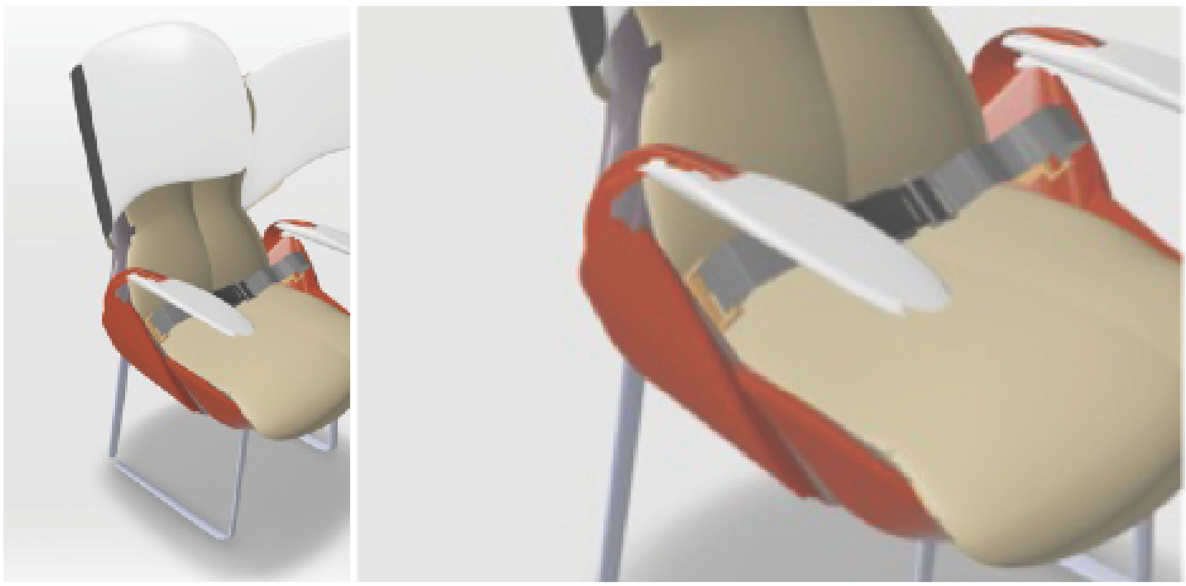

FIGURE 8 THE AR RENDER MISSING POLYGONS AND SURFACES AROUND THE COMPLEX CURVE

An animated video of the sketch rotating for 20 seconds was created by rendering in KeyShot. Once completed, the video was imported to Adobe Software, which produced a rendered version of the video for the stereo pattern, i.e., separate views for the left and right eye. An example of the stereo pattern is shown in Figure 9.

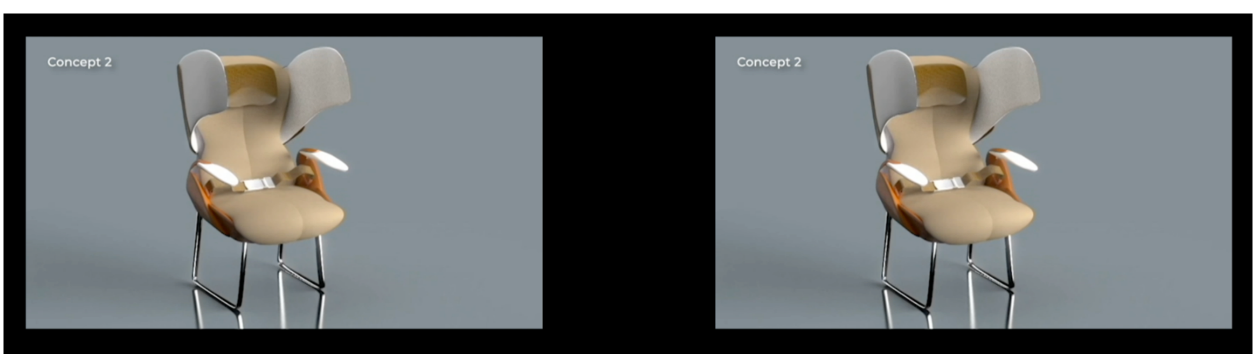

FIGURE 9 STEREO VIDEO FOR VR VIEWING

Though publishing the 3D sketches for VR viewing took roughly eight hours, the steps to create the VR simulation were not laborious. Rendering the animation and stereo video required the researcher to simply set up how the sketch will be viewed in VR; most of the eight hours was the time needed for the computer to render the output. The researcher, in theory, could have conducted other tasks in the workflow during this time.

3.2.4 Memos procedure

The researcher kept a journal (Figure 10) to record the memo notes throughout the sketching process to document each sketching session experience. The memo notes the time of the sketching experience, events-code that occurred while sketching (e.g., technical issues), the activity-code completed while drawing (e.g., free drawing, tracing, rendering, etc.), and what the researcher was doing and/or think-code during the task. The memos provided insight on the advantages and disadvantages of using VR versus traditional sketching methods. The codes helped identify categories and themes described in the Results (Chapter 4, section 4.1).

Date: mm.dd.yyyy	**Time (min)**	0:00	20	40	60	80	100	120
MEDIUM	**Event-Code**							
	Activity-Code							
	Think-Code							

FIGURE 10 THE MEMOS TO DOCUMENT THE SKETCHING EVENT, ACTIVITY, & THINK

The memo and comprehensive journaling activity resulted in "ideas about codes and their relationships as they strike the researcher" (p. 127) to illustrate the researcher's experience [39]. The memo and journaling activity provided a first-hand recording of elements that influenced the researcher's experience of using the VR techniques in contrast to more traditional methods in the design workflow. Using qualitative research software NVivo (version 2020), these themes and patterns were first uncovered using the word frequency query tool to identify reoccurring keywords in the notes. The researcher organised the common keywords and summarised the time and event themes illustrated in an infographic in section 4.1.

3.3 Phase two: participant feedback of traditional 2D and XR mediums

In this phase, a survey was distributed to two user groups, designers and non-designers. The survey accompanied the mediums to collect participants' insights on the potential usefulness and level of acceptance for reviewing concepts through an XR system versus traditional 2D sketches.

3.3.1 Study design

Participants viewed the concepts in the two mediums in random order—to reduce the potential bias from priming effects—and then completed a questionnaire (in Qualtrics) with questions about their experience with each medium. The concepts were presented in the Qualtrics platform as follows:

> *Medium 1, 2D*: A PDF gallery of the 2D concepts published with the built-in Qualtrics gallery viewer; and

> *Medium 2, 3D*: An online VR simulation option and an AR option to view the 3D concepts through the Unity3d platform. Multiple VR and AR options allowed participants to engage with the concepts depending on their equipment and their

preference for the review. The participants worked remotely and independently by using their personal computer, their own VR HMD to view the VR simulation, and/or their smartphone to view the AR option of the 3D sketches. Participants also had the option to choose which XR method (VR and/or AR) to experience the 3D medium.

3.3.2 Participants

The study was conducted with two target user groups to review the sketches, designers and non-designers. Participants were recruited through social media (e.g., Slack, Facebook). The researcher also recruited participants through their network (email and social media). The demographics of these two groups are described below. A total of 40 designer participants were recruited, 20 male and 20 female, from various fields of design with different levels of experience. For this study, the definition for non-designers are participants from the general population who could be hypothetically called to participate in an air travel design user testing session. There were 41 non-designer participants, 27 female, 13 male, and one who wished not to identify.

3.3.3 Overview of the procedure

The questionnaire used branching logic, where the researcher asked different questions depending on whether the participant was a designer or a non-designer. In Figure 11, the logic design of the survey is illustrated; the trajectory of the study will be explained in more detail in the following sections. The reason why there is a different path for each user group is that the non-designers did not complete the Technology Acceptance Model questionnaire since the questions are for the designers. The TAM questionnaire focused on how the designers perceived the usability and ease of use of XR systems for their design workflow, which was irrelevant for the non-designer group

FIGURE 11 QUESTIONNAIRE LOGIC DESIGN IN QUALTRICS

Design of questionnaire branching logic

The Qualtrics questionnaire (Appendix A, p.123) opened with information about the study and a confirmation ‘Yes’ or ‘No’ question for participants to provide their consent to participate. Selecting ‘No’ closed the questionnaire with a thank-you statement. Selecting ‘Yes’ continued to the questions.

The first section of the questionnaire asked participants to answer demographic questions (age and gender), followed by their familiarity with XR technology and their frequency of using XR systems using a scale. Lastly, participants were asked to identify if they were a designer in a 'Yes' or 'No' question. If they said ‘No’, they were asked to identify their occupation, and then the questionnaire continued with the logic for the non-designers. If they said ‘Yes, they were asked to specify their field of design and years of experience, and then the questionnaire continued with the logic for the designers.

Following the consent and demographic questions, the participants were then presented with the concepts either in a PDF slideshow viewer (2D sketches) or in a VR and AR (Figure 12) simulation (3D sketches). After viewing the first medium, a System Usability Scale (SUS) was displayed to the participant. The SUS asked participants to provide feedback on their viewing experience. The participant then viewed the other medium and repeated the SUS. For the non-designer group, the questionnaire would end once they completed the second round of the SUS. After viewing both mediums and completing the SUS for each medium, the designer group, were asked to complete an additional Technology Acceptance Model (TAM) questionnaire to gauge their perceptions on the potential usability of using XR systems in their workflow.

FIGURE 12 THE 3D SKETCHES FOR THE VR AND AR SIMULTION

3.3.4 Data analysis

In the Qualtrics survey, all participants, designer, and non-designers, were asked to complete the SUS survey after viewing each sketch medium. Only the designer group completed the TAM questionnaire in the survey. The following describes the SUS and TAM procedure used to analyze the data associated with each survey.

System Usability Scale (SUS)

The System Usability Scale (SUS) has been an industry standard since its inception in 1986 in HCI and VR studies [40]. It is described as a reliable, low-cost survey that can be used to assess system usability [41]. The SUS was used to identify potential differences in the experience of viewing the 2D sketches when compared to the 3D sketches of the two groups. The intention was to provide insight on each groups' experience of using traditional versus XR mediums for viewing sketches. Since the medium was presented in a random order to the participants, a matrix of results would help identify if seeing one medium before the other might also influence the experience of viewing the next medium.

The SUS questionnaire is based on the following questions:

1. *I found the system easy to use.*
2. *I found the system unnecessarily complex to use.*
3. *I think that I would like to use this system frequently.*
4. *I think that I would need the support of a technical person to use this system.*
5. *I found the various functions in this system were well integrated.*
6. *I thought there was too much inconsistency in this system.*
7. *I would imagine that most people would learn to use this system very quickly.*
8. *I felt very confident using the system.*

9. *I needed to learn a lot of things before I could get going with this system.*

The participants had the choice to select from five scaling options; highly disagree (1), disagree (2), neutral (3), agree (4) and highly agree (5). The SUS scores are calculated by standard SUS calculations, as explained below:

- X = the sum of the scores for all the questions from the scale results.
- All the questions with negative sounding items (e.g., 2, 4, 6, 9) were balanced to match the positive times (i.e., highly disagree was flipped to highly agree) to mitigate the potential for participants to select responses automatically.
- The SUS Score was calculated as follows = (X) x 2.5.

Once a SUS score was calculated for each question, the average, median, minimum, and maximum SUS values were calculated. In the Results section, the evaluation of the data was based on the traditional SUS analysis procedure [41, 42].

Technology acceptance model (TAM) questionnaire

In addition to the SUS, the designer group completed a Technology Acceptance Model questionnaire to assess the designers' 'technology acceptance of XR' to support design workflows. The Technology Acceptance Model (TAM) is a questionnaire developed by Davis (1989) that evaluates people's perceptions on the implementation of new technologies [43, 44]. For this study, we use statements derived from the model to assess the designers' Perceived Usability (PU) and Perceived Ease of Use (PEU) of the XR system [43, 45]. The questions are set up with a scale response, highly disagree (1), disagree (2), neutral (3), agree (4) and highly agree (5) to rate their answer [44].

There are two TAM questionnaires:

TAM for Intent Technique Performance: This was completed by all the designers to identity their perception of the *potential of using an XR system* in their workflow. Below are the items they were asked to rate.

Perceived Usefulness (PU) Items of Technique Performance

Using XR techniques in my job would enable me to accomplish tasks more quickly.

Using XR techniques as a tool would improve my job performance.

Using XR techniques in my job would increase my productivity.

Using XR techniques would enhance my effectiveness on the job.

Using XR techniques would make it easier to do my job.

I would find XR techniques useful in my job.

Perceived Ease of Use (PEU) Items of Technique Performance

Learning to operate XR techniques as a tool would be easy for me.

I would find it easy to get XR techniques to do what I want them to do.

My interaction with XR techniques would be clear and understandable.

I would find XR techniques to be flexible to interact with.

It would be easy for me to become skillful at using XR techniques.

I would find XR techniques easy to use.

TAM Actual Use Performance: Only designers *who had already implemented XR* into their workflow completed this questionnaire. Below are the items they were asked to rate.

Perceived Usefulness (PU) Items of Actual Use Performance

Using XR systems improves the quality of the work I do.

Using XR systems gives me greater control over my work.

XR systems enable me to accomplish tasks more quickly.

XR systems support critical aspects of my job.

Using XR systems increases my productivity.

Using XR systems improves my job performance.

Using XR systems allows me to accomplish more work than would otherwise be possible.
Using XR systems enhances my effectiveness on the job.
Using XR systems would make it easier to do my job.
Overall, I would find the XR systems useful in my job.

Perceived Ease of Use (PEU) Items of Actual Use Performance
I find it cumbersome to use XR systems.
Learning to operate XR systems is easy for me.
Interacting with XR systems is often frustrating.
I find it easy to get XR to do what I want it to do.
XR systems are often rigid and inflexible to interact with.
It is easy for me to remember how to perform tasks in XR systems.
Interacting with XR systems requires a lot of my mental effort.
My interaction with XR systems is clear and understandable.
I find it takes a lot of effort to become skillful at using XR systems.
Overall, I find XR systems easy to use.

The analysis of this data used descriptive statistics to identify the average score of the designer's response. Cronbach's alpha was used to measure the internal consistency of the designers' responses to determine reliability in each item's score [46]. Cronbach's alpha reliability score needs to be above 0.70 [47] with the equation provided below.

$$\alpha = \frac{N\overline{c}}{\overline{v} + (N-1)\overline{c}}$$

3.4 In summary

The methodology of the study consists of two phases to analyze the usability and viability of using XR systems in the airline design workflow. Phase one was an exploratory research phase to gather qualitative insight on the researcher's experience sketching in VR. Documenting this first-hand experience can help identify the advantages and disadvantages of using VR as a tool for design, with the goal of reporting on best practices in VR sketching. Phase two was designed to collect quantitative results using the SUS and TAM scales to gauge participants' experiences (designers and non-designers), in viewing traditional 2D sketches versus 3D sketches developed in VR using VR or AR. The next chapter presents the results from both phases of the study.

Chapter 4 Results

This chapter presents the results of the two phases of this research. As a reminder, phase one focused on the researcher's self-recording of their own user experience of sketching in VR compared to traditional methods and presenting these mediums for evaluation. Phase two focused on non-designers and designers' reviewing the sketches produced and measuring their experience using a SUS and a TAM questionnaire.

The goal of the study was to explore how XR techniques can be implemented into the early stages of the airline design workflow. The methodology of this research was designed to investigate the following research questions:

1. *What is the user experience of design sketching in VR like compared to traditional methods?*
2. *What advantages and disadvantages does XR (VR/AR) offer in the early stages of design workflows?*
3. *Considering the limitations of physical distancing measures during the COVID-19 pandemic, what are the potential benefits and barriers of using XR (VR/AR) for remote design?*

Overall, the findings from this exploration of XR techniques identify the advantages and disadvantages of XR as a tool for sketching and the usability of XR techniques for remotely engaging users in evaluating early design concepts. For example, in phase one of the study, VR sketching allowed the researcher to draw to scale in a 3D space around their body to create a skeleton anthropometric sketch (described in more detail in 5.1.2) supporting human factors considerations in the design process. However, developing VR sketches also had disadvantages with the difficulties of publishing 3D medium sketches efficiently compared to traditional 2D medium techniques (section 4.2). In phase two, the researcher found that the non-designer participants rated the usability of XR higher compared to the designer group (section 4.3.2). The TAM questionnaire also revealed that the designers saw learning XR techniques as a barrier in adopting the technology as part of their design workflow (section 4.3.3). This chapter presents the detailed results of phase one: sketching in VR compared traditional methods and phase two: participant feedback using traditional 2D versus XR mediums.

4.1 Phase one: sketching in VR compared traditional methods

Phase one was driven by the following research question: *What is the user experience of design sketching in VR like compared to traditional methods?* The following sections explore the researcher's firsthand experience with sketching in traditional methods (section 4.1.1) and sketching in VR (section 4.1.2), in anticipation of the subsequent section about how the resulting sketches were prepared and distributed for phase two.

4.1.1 Traditional sketching: 2D medium

The initial sketching session of phase one used traditional 2D techniques for a total of 130 hours, during which the researcher developed ideas for new airline cabin seating solutions. The researcher's 2D sketching process and experiences were journaled in memos, as presented in Chapter 3 (section 3.2.4). It should be noted that the researcher entered the session already familiar with the sketching approach and hardware, as they had prior training in sketching for design as well as several years of professional experience working as a designer.

During the 130 hours, the researcher developed roughly 16 ideas through sketching; six of these were deemed (by the researcher) to be of sufficiently high quality to share with the participants. In other words, some ideas were sketched and then discarded at the researchers' discretion. Of the six sketched ideas that were retained, only two ideas (Figure 13) were shown to the participants in the next phase of the study, as discussed in section 4.3. A detailed breakdown of how the researcher spent their time during the 2D sketching session is provided next.

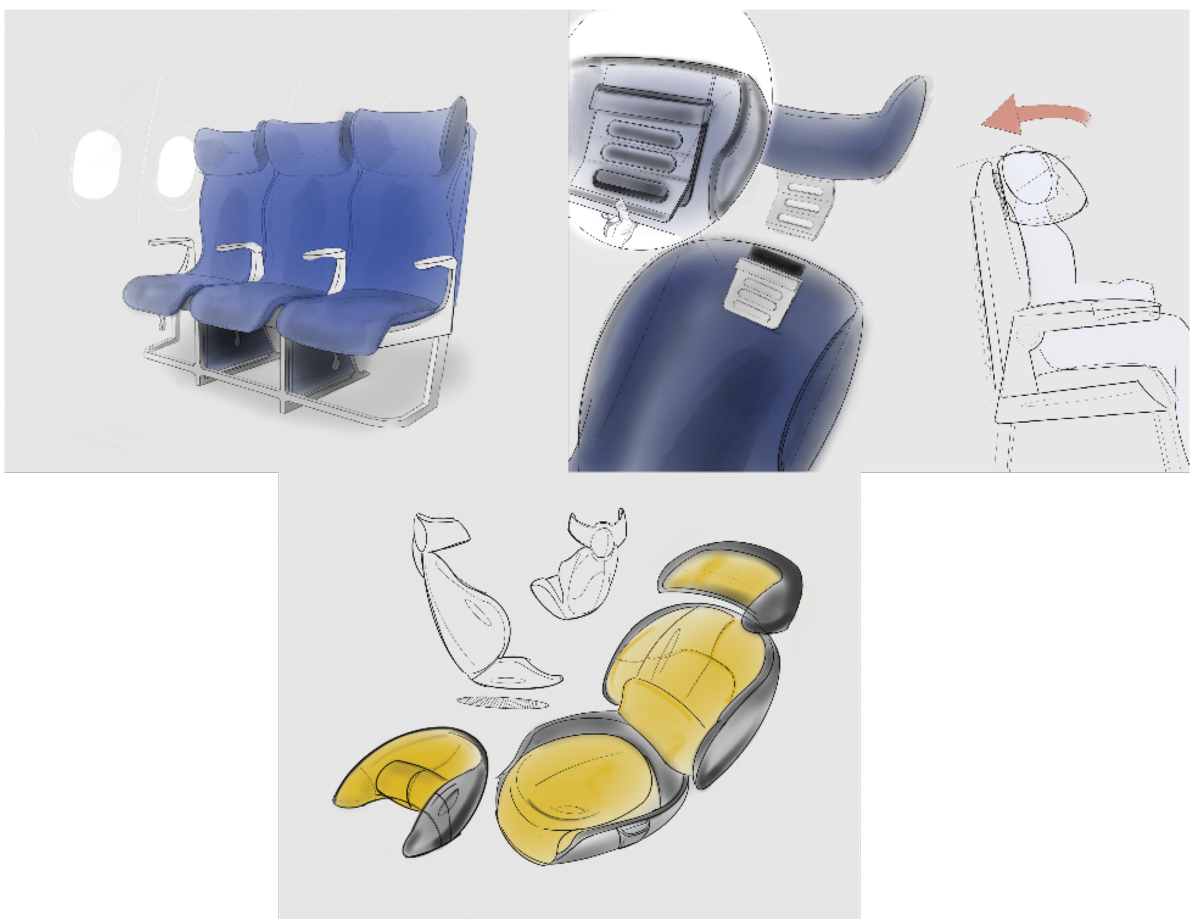

FIGURE 13 THE 2D MEDIUM SKETCHES DEVELOPED IN PHASE ONE OF THE STUDY

Breakdown of the 2D sketching experience

The researcher's workflow to develop an idea in 2D was as follows: (1) rough freeform sketching to generate ideas; (2) cleaning lines and adding context items (e.g., human figure) and perspective to the drawing to create the final form of the idea; and (3) rendering to bring colour and more dimension to the drawing. This workflow does not represent a single sketching session per se, but rather how the task of sketching typically unfolded. Generating ideas while sketching can help hone a design and develop potential solutions, but it is expected that some of these initial sketches will most likely be discarded [14]—hence why the researcher fully drew out only a couple of the initial 16 ideas they sketched. Another note is that the above workflow can also be disrupted by external factors to the experience, such as hardware issues with the sketching tool or the impact of the environment while drawing.

A breakdown of the researcher's activities while sketching in 2D is presented in Figure 14. To summarize, of the 130 hours, roughly 30 hours were spent brainstorming ideas while sketching and 47 hours were spent line sketching, where the drawings' form and structure were developed. Roughly 50 of the remaining hours were spent making the drawings cleaner (e.g., stronger lines) and rendering, which entailed adding colour and shading/shadows to bring context and volume to the sketched form. Another 3 hours were spent using Photoshop, mostly doing additional cleaning of the lines, and rearranging the sketch layout on the artboard for presentation (e.g., cropping the image on the page).

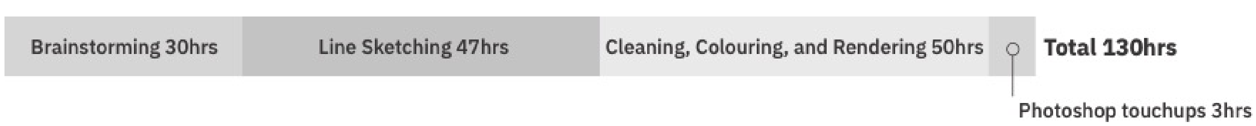

FIGURE 14 BREAKDOWN OF THE 130 HOURS SPENT SKETCHING IN 2D

2D sketching techniques

Sketching in 2D has its share of limitations, such as a small area available for sketching on the drawing space (i.e., the paper or artboard size). Design sketching relies heavily on drawing in perspective and using vanishing points. Drawing with the laws of perspective and vanishing points is fundamental to making sketches understandable and rational to the plot space [48]. This technique helps make the drawn geometry rational for the viewer to visualize the perceived item and environment created on the 2D medium.

The disadvantage of this technique for design sketching is perspective lines tend to be exaggerated so the 2D image can be perceived to a scale and with depth of its volume. Drawing construction lines to the vanishing points helps the designer to construct the volume and form to match the perspective vanishing points. The issue that occurred during phase one of 2D sketching is that some of the sketches became overwhelming to follow the lines, made the sketches messy to work with, and the development of these construction lines were a time-consuming process.

In Figure 15, a sketch is shown that features construction lines. In this sketch, the lines are disorganised, hard to understand, and made the task of sketching more of a challenge rather than being a useful tool to communicate ideas. This hindered the researcher's productivity, and the original idea was discarded to pursue an easier design to draw and communicate using the 2D medium.

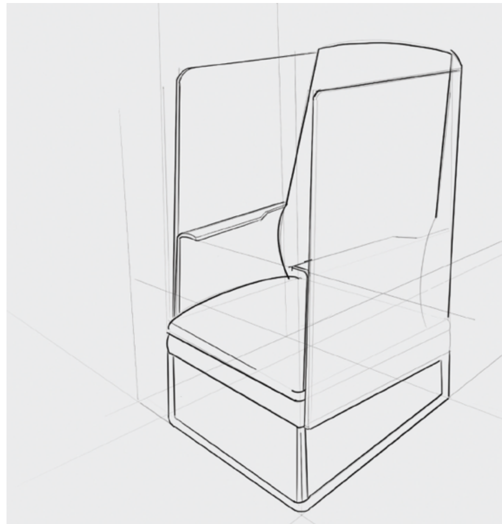

FIGURE 15 EXAMPLE OF USING VANISHING POINTS IN A SKETCH

Overall, most of the time on task in phase one was spent on applying techniques to make the design ideas viewable in a 2D medium. This included ensuring the idea could be communicated through images, rather than spending the time to produce a useful design solution. The next section will provide a summary of the 2D sketching workflow by time spent during working sessions.

2D sketching experience

The researcher documented their experience in memos that commented on the experience of sketching throughout the various segments of the sketching workflow (as described above) as well as factors that impacted it. The 2D sketching experience is divided into two linear infographics representing a *productive* session versus an *unproductive* session, as described below. The rational for showing these two sessions is to identify the advantages and disadvantages of drawing tasks or stages during the sketching workflow (Figure 16).

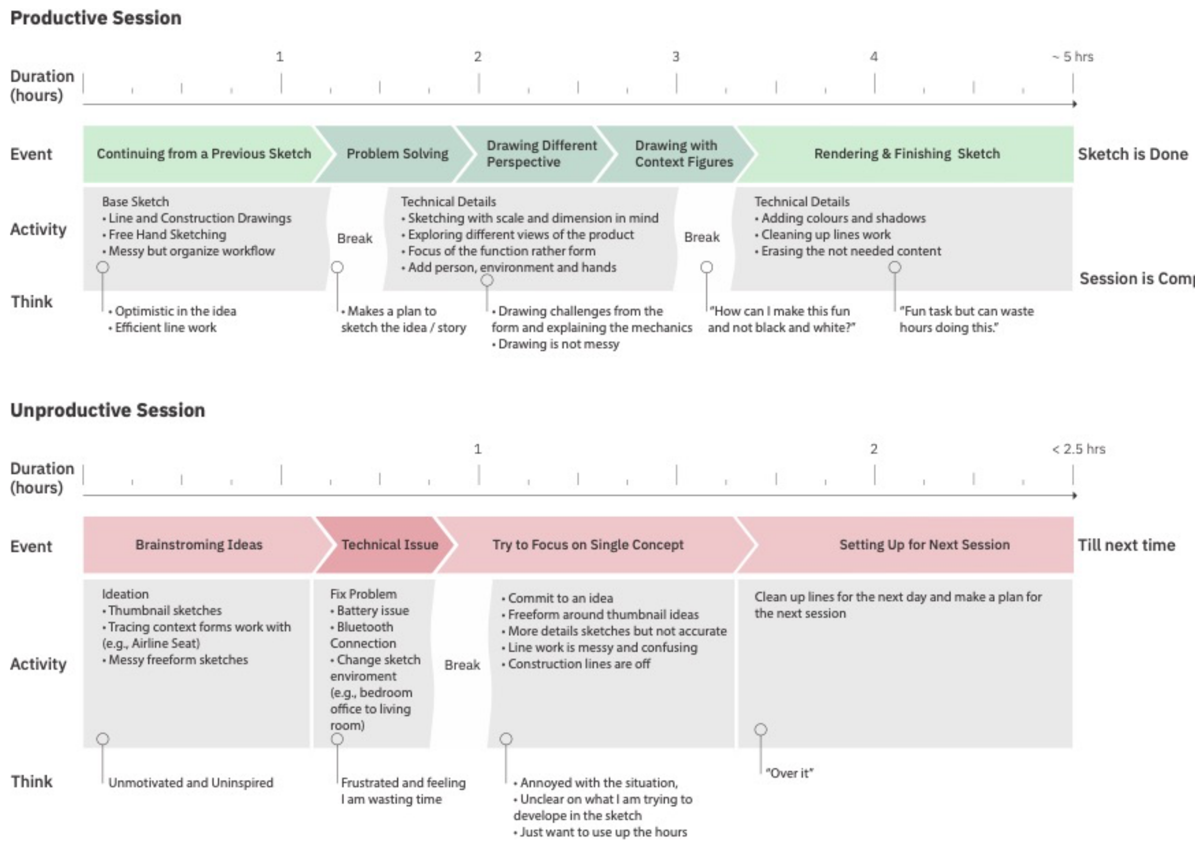

FIGURE 16 SUMMARY OF THE PRODUCTIVE AND UNPRODUCTIVE 2D SKETCHING SESSION

A *productive* sketching session (Figure 16) ran for roughly five hours. There were small breaks during the session, lasting 15-30 minutes, during which the researcher planned next steps to take after they returned from the break. Most *productive* days of sketching were spent working on an existing idea or working on ideas from a previous sketching session.

Nearly half of a *productive* session, usually 2.5 hours, was not spent on developing the idea but rather refining the sketch to better communicate the design. This entailed problem-solving and decision-making regarding how the sketch would tell the story of the design, without the need for text. This aspect of sketching consists of several tasks, including: creating drawings in different perspectives and views; focusing on the functional features of the design; and adding contextual images to make sense in the scenario (e.g., a human figure for scale or airline cabin fuselage for users to understand the environment). These tasks are often challenging since they make the image more complicated to draw; on a *productive* day of sketching, these dilemmas did not consume too much of the researcher's time and the workflow remained efficient. The remaining time, two or more hours of a *productive* session, was spent rendering and finishing the sketch by applying colour and shading to complete the sketch.

An *unproductive* session (Figure 16) lasted for an average of 2.5 hours or less, in part because the researcher did not want to spend too much time sketching unproductive concepts instead of trying to produce creative solutions. Half of the session was spent brainstorming ideas by sketching small rough sketches of concepts (i.e., thumbnail sketches) and freeform drawings of ideas that resulted in disorganized or messy line drawings from the construction perspective lines. During this time, there were some external disruptions to the workflow, such as power issues with the iPad, issues with the pens' Bluetooth connection, and software issues with the sketching application. Resolving the issue took anywhere from one minute to half an hour and the trend was that the researcher took a break before resuming sketching.

To make the sketching session more productive, the researcher spent the remaining time, roughly 1 hour, focusing on a single idea to be explored further in the next stage of the sketching workflow. Once a concept was thought out, the researcher started sketching the idea in preparation for the next session.

Overall, sketching in 2D time was mostly spent ensuring that the drawings were clean and represented the ideas the researcher was trying to communicate. Most of the time was spent trying to communicate the story rather producing design ideas. In design, it is important to be able to communicate ideas for users to understand, but arguably much of that time may be spent stylizing rather than producing concepts. In terms of 2D sketching, designers need to spend much of the workflow ensuring that their ideas can be communicated in this medium, which is limited in terms of techniques. These techniques in 2D are compared to those in 3D sketching in the next section.

4.1.2 Virtual reality sketching: 3D medium

The second half of phase one involved creating the same design as in phase one, an airline seating solution, however this time the designer used VR sketching instead of 2D sketching. There was an initial learning curve involved in sketching in VR compared to traditional methods, namely in using the software and 3D sketching techniques. As mentioned earlier, the researcher has several years of experience developing drawings using 2D techniques; but VR sketching was a new experience, and so required an 'onboarding' stage. The researcher produced roughly 10 seating sketches within the 130 hours; two sketches (Figure 17) were kept and used in the next phase of the study (described in section 3.3). The following section further discusses the learning curves of sketching in VR and the researcher's 3D sketching experience.

FIGURE 17 FINAL 3D SKETCHES SHARED WITH PARTICIPANTS IN PHASE TWO OF THE STUDY

Learning VR sketching techniques

Sketching in VR posed the same limitations that a designer faces when learning how to develop CAD in a 3D modeling program for the first time. In the early stages of the VR sketching, the researcher developed multiple designs that appeared very robust and featured hard edges, because of learning the basic tools of the Gravity Sketch software. In Figure 18, a solid chair is shown (on the left) where there is little curvature to its form while the second image (on the right) shows curves but is only constructed with surfaces.

While learning the new tools and techniques of VR sketching, an additional issue that occurred was drawing a straight line and connecting lines after. In attempting to draw a perfect straight line, the line tended to skew or curve unintentionally. When sketching in a VE you do not have drawing planes unless placed there in advance. Thus, while the researcher was free hand sketching in 3D, they needed to estimate where the ink of the virtual pen was placed and move in the VE based on how their arm or body was moving, which may not align with their intended goal.

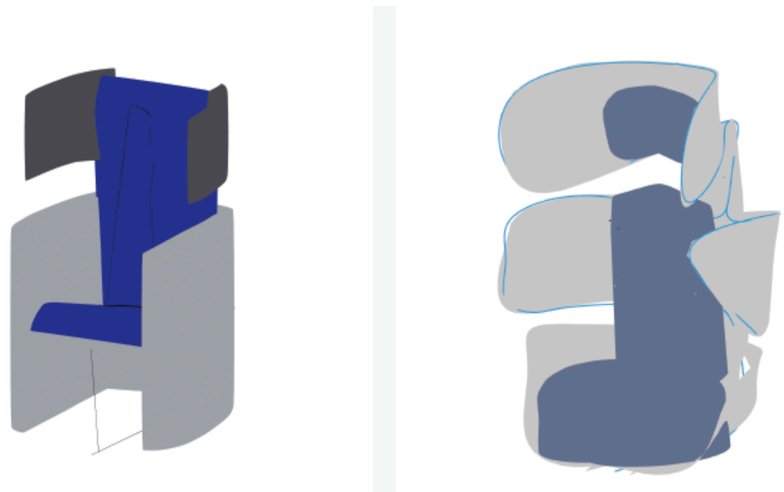

FIGURE 18 FIRST AIRLINE CHAIR DESIGN WITH 3D IN GRAVITY SKETCH.

When sketching in 2D, your drawing artboard, such as a tabletop, provides an automatic axis plane to draw on, a spatial constraint, and physically eliminates the error of depth placement awareness while drawing. Therefore, sketching in 2D it is easy to connect the lines and draw them nearly straight without a ruler. In Figure 19 a common sketching exercise is shown where a designer pulls lines as a method to build the muscle memory to draw straight lines. The image on the far left shows the 2D version of the exercise where the lines are all connected and are mostly straight. The two images on the right show the VR version and it does not have the same results. The middle image shows the lines are not as straight as the 2D version and the illusion that they are connected. When you view the sketch from a different perspective, the image on the far right, the lines are skewed and are not connected.

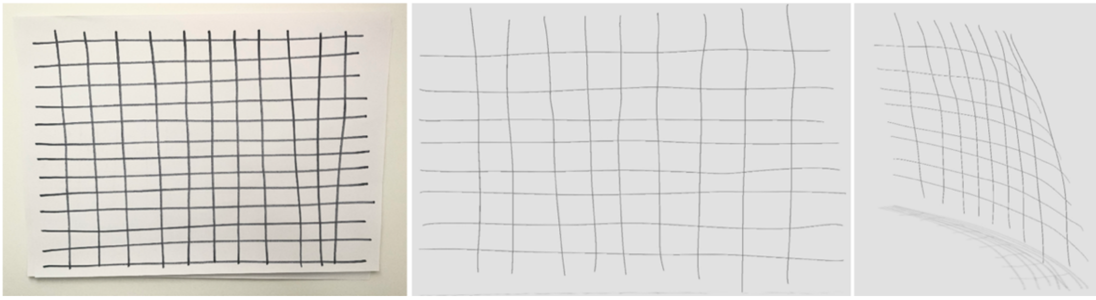

FIGURE 19 EXAMPLE OF HOW THE LACK OF CONTROL SKETCHING IN VR APPEARS

Freehand sketching in VR poses issues in making accurate drawings. However, while learning the VR sketching techniques, in one of the first attempts to draw a chair, the researcher applied the dimension of their office chair into their drawing. While drawing the outline of the chair, which is the skeleton form (described further in the next section), the researcher drew the outline of their chair to scale to approximate the same anthropometric dimensions of an air cabin seat (Figure 20). This allowed the researcher to draw an orthogonal layout of the seat height and width based on real dimensions and proportions.

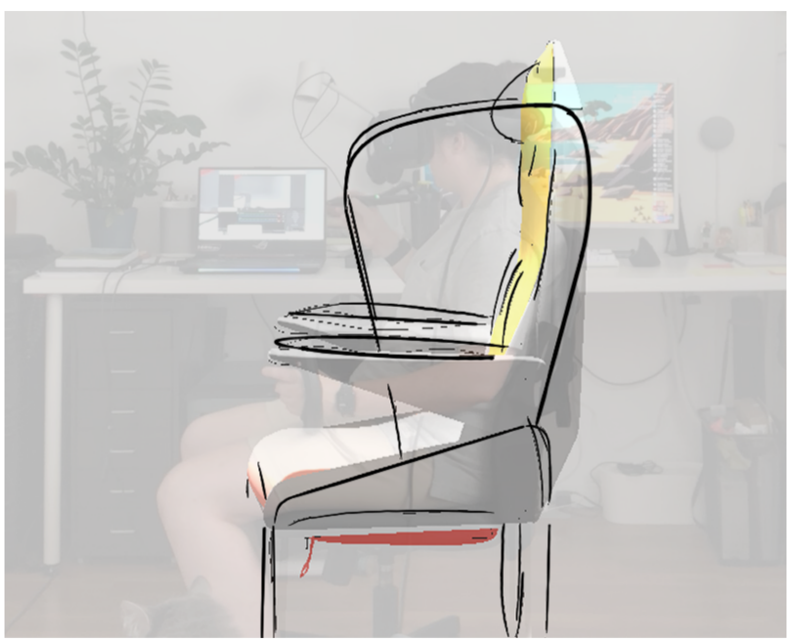

FIGURE 20 EXAMPLE OF RESEARCHER DRAWING AN ANTHROPOMETRIC SKETCH

Drawing an orthogonal layout by referencing a real source object as an ‘underlay’ allowed the designer to create more anthropometric appropriate skeleton sketches. This discovery revealed that VR has the potential benefit in making use of mixed reality (MR) to create an outline/skeleton of sketch dimensions referencing ergonomic dimensions and proportions while drawing. Thus, designers can sketch concepts around approximate anthropometric requirements for the product. This technique has future potential to specifically support physical ergonomics in the design workflow. This is explored further in section 5.1.2 of the Chapter 5.

Breakdown of the 3D sketching experience

A breakdown of how the researcher spent the 130 hours sketching in 3D is displayed in Figure 21. In summary, the first 15 hours was used as an onboarding session to become familiar with sketching in VR and the featured tools in the Gravity sketching software. A total of nine hours were lost to troubleshooting the software or hardware issues (e.g., lighthouse sensor not detecting the hardware or software). Roughly 31 hours were spent setting up the scene, which entailed placing the prefabricated CADs in the VE (e.g., airline fuselage) and making rough skeleton sketches of the design. The remaining time, roughly 75 hours, was spent sketching as per the workflow discussed above (i.e., rendering and finishing the sketches). Once the sketches were completed, several issues occurred while publishing the final sketch which will be discussed in section 4.2. The task of publishing the 3D sketches ended up going beyond the assigned 130-hour timeframe. The challenge of distributing the 3D medium sketches is further described in the next section.

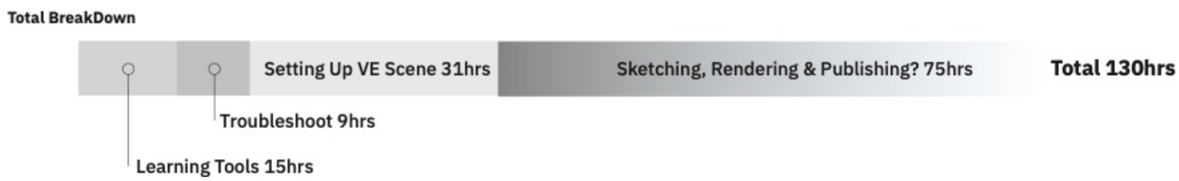

FIGURE 21 BREAKDOWN OF THE 130 HOURS SPENT SKETCHING IN 3D

3D sketching workflow

Since sketching in the 3D medium was a new learning experience for the researcher, there was a different workflow than for the 2D sketching. As mentioned, some time was spent with the initial onboarding, i.e., learning the techniques and tools of the software. With this time, a procedure for sketching in 3D, as described below, was created and followed for the remaining 130 hours of sketching.

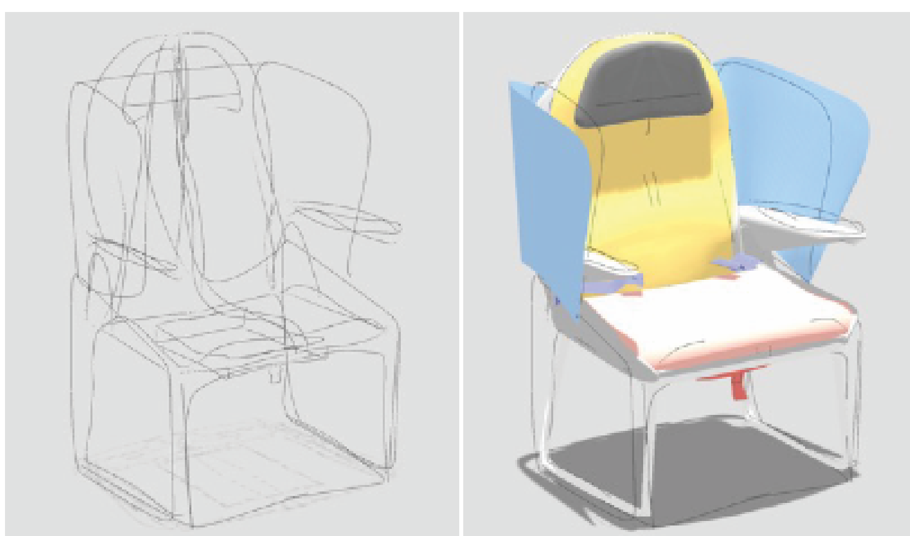

FIGURE 22 EXAMPLE IMAGES OF VR SKETCHING WORKFLOW.

Initially, the researcher created a 3D drawing of the chair base by developing a skeleton sketch of the design form (left image of Figure 22). A skeleton is a line drawing where the curvature and silhouette of the design volume are mapped out. To develop the skeleton, a freeform sketching technique was used with the mirror tool in Gravity Sketch software, which creates a reflected duplicate of the sketch based on an assigned center plane, thus a symmetrical form is drawn out efficiently. Features like the mirror tool demonstrated to the researcher how VR sketching could be more efficient compared to 2D sketching on a paper or tablet.

Once the researcher had created a skeleton sketch, the next step was to develop the volume and form of the sketch (right image of Figure 22). This step involved inserting the surface and volume parts to create the illusion of a solid body on the sketch. Surfaces were drawn out and added to the chairs to represent features such as the textile components of the design. The last step was inserting the solid forms to create the remaining solid features (e.g., the tube lines for the legs of the chair). Once all parts were inserted, the remaining time was spent sculpting or manipulating the surface and volume to place it in the correct position to make the design complete to the researchers' discretion.

3D sketching experience

Recall that the researcher's experiences in their 2D sketching sessions were categorized as either *productive* or *unproductive*; the same procedure was followed for the 3D sketches, with a summary of memos presented in Figure 23. The 3D sketching experience has been summarized in three infographics*:* one *productive* sketching session and two for *unproductive* sketching sessions, where for the *unproductive* sessions, one scenario related to *internal factors* (dilemmas in the simulation) and the other to *external factors* (hardware issues) that influenced the sketching session. Each is described in turn below.

A *productive* sketching session in VR had no interference to the workflow. The breakdown of a *productive* session is shown in Figure 23. The session started with developing the skeleton sketch and the silhouette of the design. This task typically lasted an average of one hour. It should be noted that the researcher took a 15-minute break every 45 minutes since VR headsets are known to cause eye strain and neck pain if worn for long periods. Since the researcher was anticipating sketching for 4+ hours per session, these breaks were considered important to avoid fatigue or injuries.

The next step of a *productive* 3D sketching session was inserting the surface and volumes into the sketch to make a near final form of the design. This was done by laying out 3D parts (either as a solid or surface) where its silhouette closely matched the desired form of the final design (e.g., a solid rectangle cube 3D part for the bottom seat cushion). Additionally, during this step, the researcher assigned colours to the part which you can see in Figure 22. The reason why each part was assigned a colour was to define the section or layer to insert the final product colour, material, and finishes (CMF) to the 3D sketch and make the rendering task more efficient.

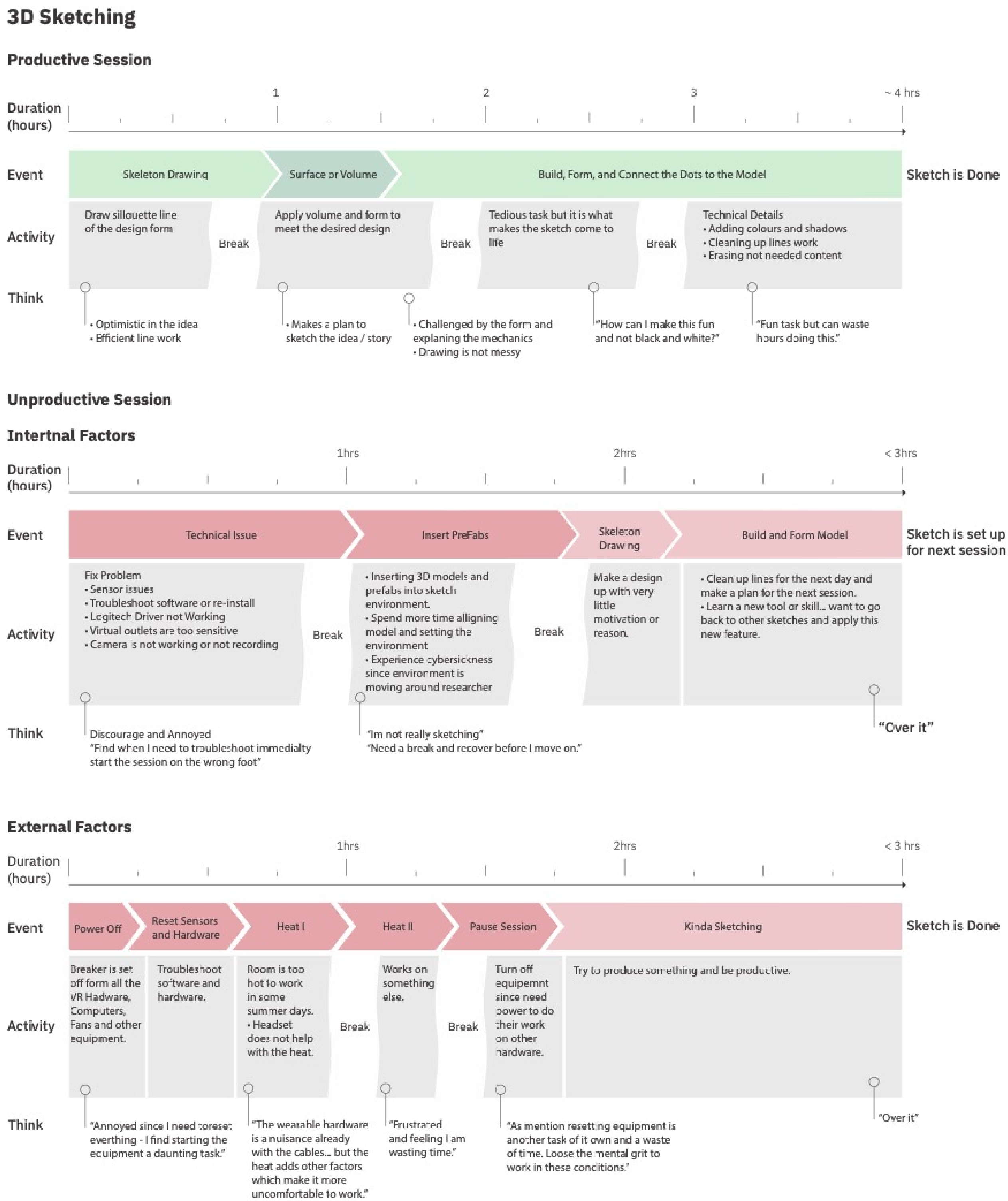

FIGURE 23 SUMMARY OF A PRODUCTIVE AND UNPRODUCTIVE 3D SKETCHING SESSION.

Once a rough form of the design in the 3D sketch was made, the final task involved manipulating the surface and solid parts to complete the design. This task was done by sculpting the volume and manipulating the edges of the parts to create the final desired curvature. The goal of this phase was to make the final design more life-like and avoid robust or flat forms as discussed previously in the technique section. This task was the most time consuming and tedious to complete since it required manipulating the 3D model polygons, edges, points, and solids volume to appear to the desired shape and form. In a *productive* session the researcher completed this task within the 2.5 hours and the 3D medium sketch was not considered completed until rendered in KeyShot.

In contrast to a *productive* session, an *unproductive* 3D sketching session due to *internal factors* was one where the researcher's sketching was interrupted by issues with the software. As summarized in Figure 23, the researcher's memos indicated that these sessions had immediate technical issues, such as the software needing to be updated, the cameras were not recording the VR sketching simulation, the sensors were not detecting the hardware, the Logitech VR Ink pen was not being recognized in the VE, and the Logitech Ink pen driver was not responding to the VIVE software. To resolve these issues, the researcher was required to uninstall and reinstall the software, which created a one-hour delay in the sketching session.

The memos showed that once the software was working again, the researcher usually experienced a lack of motivation and delayed resuming the sketching session by taking a short break. When the researcher returned to the sketching session, the researcher then had to reset the sensitivity on the VR Ink pen, which took time to complete since the process requires multiple haptic tests to reset the sensors. To illustrate, Figure 24 shows random spots of VR ink in the VE; this happened since the buttons and touch pad on the Logitech Ink Pen were so sensitive to the user's physical touch that the VR ink essentially 'dripped' into the VE, similar to how the ink of a pen can bleed onto paper. The ink spots were resolved by adjusting the touch sensors of the Logitech pen using the classic 'turn it off and on again' approach.

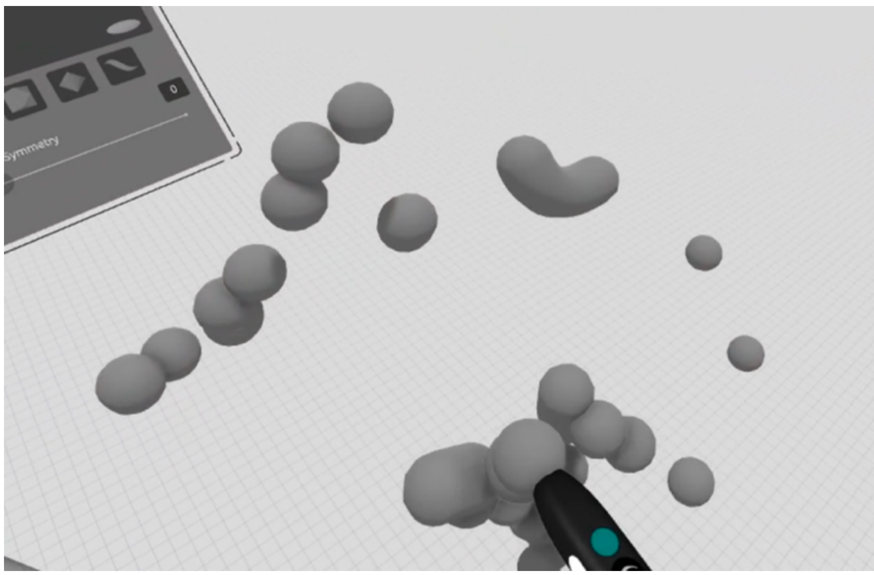

FIGURE 24 VR INK BLEEDING FROM SENSOR SENSITIVITY OF THE LOGITECH INK VR

Additional dilemmas related to *internal factors* were issues with using prefabricated CAD parts. In some sketching sessions, the researcher inserted a prefabricated CAD model. For example, Figure 25 shows an insert of an air cabin interior, including the fuselage and seats. Setting up the models in the VE presented challenges with aligning the CAD parts since there are no planes in the VE. The researcher had to manipulate the position and placement of the multiple CAD parts until they were in the desired position. This task was tedious since it was difficult to align the prefabricated parts in a rational position, to match that of a real inflight interior, and to properly cement the part to the ground plane since the CAD part's bottom surface was not able to recognize the VE ground plane.

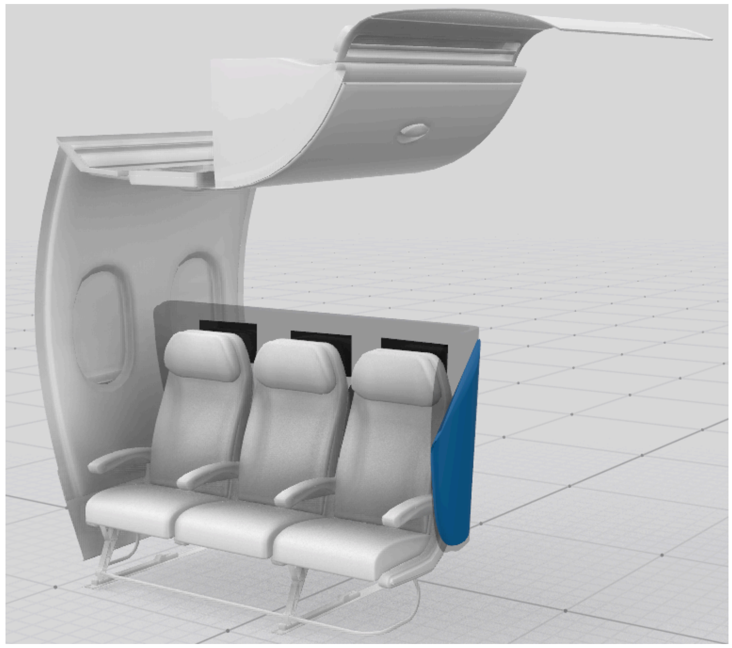

FIGURE 25 EXAMPLE OF USING PREFABRICATED CAD MODELS FOR A 3D SKETCH

Additionally, constantly moving the prefabricated CAD parts and sketching with their presence in the VE caused the researcher to experience cybersickness due to Vection, a motion sickness that occurs when a person's perceived environment is moving around them while they are sitting in place (similar to the motion sickness experienced in a vehicle) [49]. While sketching with the prefabricated set up in the VE, the researcher was constantly moving the prefabricated parts around them to be able to sketch in specific areas, thus creating the illusion that the environment around them was moving while they were sitting still. When the researcher was too nauseous to keep sketching, they took a 15-minute break. According to the researcher's memos, some 3D sessions were *unproductive* due to *external factors*, which included events outside of the VR simulation that disrupted the sketching session. The summary of these occurrences is presented in Figure 23.

The location that the VR sketching occurred was found to be an *external factor* that produced *unproductive* sessions. VR sketching was done remotely in the researcher's apartment due to physical distancing protocols related to COVID-19. Additional VR equipment, computers and electronics were needed to conduct this research; however, the apartment's power supply was not adequate to sustain the requirements. When circuit breakers were set off, the researcher had to reset all the sensors to the equipment, which often triggered other software limitations as discussed above, disrupting the workflow.

A second *external factor* was the environment, specifically the ambient temperature. The researcher completed the 3D sketching between June and early September 2021; the summer heat caused issues with wearing the VR HDM because the working environment was too hot to work in for a session of 120 minutes or longer. The researcher sketched for shorter time periods, taking many breaks, or postponing the session to a day when the ambient temperature was tolerable to work in.

Overall, an *unproductive* sketching session for both *internal* and *external factors* lasted for less than 3 hours. The time that was spent sketching involved making skeleton forms of the design and strategies of what the researcher planned to complete during the next session. Once a sketch was complete the next step was to publish the final drawing. This phase of the workflow brought up additional limitations to 3D sketching compared to the 2D sketching workflow.

4.2 Publishing the sketches

The goal of design sketching is to share ideas that words alone do not adequately express. Once the researcher completed the sketching in phase one, the goal of phase two was to distribute the drawing to designers or non-designers (i.e., users) for feedback. Publishing 2D sketches was simple and entailed exporting the sketch into an image format (e.g., PNG, JPEG, IMG) and then either printing or emailing the image to the designer or non-designer for review (see Figure 26 for a task list). This task took a maximum of one minute to complete for the three sketches.

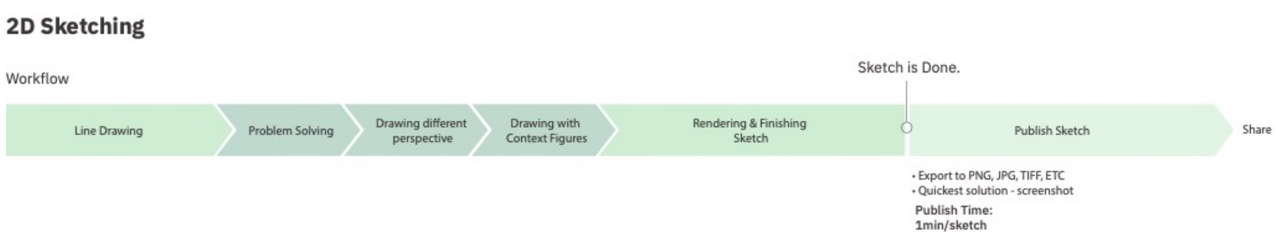

FIGURE 26 FINAL 2D SKETCHING WORKFLOW

For 3D sketches, however, there were several unforeseen issues when it came to publishing. In Figure 27, additional tasks are listed for publishing both AR and VR simulations to make the sketches viewable. To share AR and VR sketches, the researcher was required to apply the digital rendering of the CMF. This was completed using the software KeyShot, a rendering software for designers and engineers, where a 3D texture, colours and material are applied to the 3D sketch to give it the appearance of the desired finished model (Figure 17). This task alone took roughly an hour to complete per sketch.

FIGURE 27 FINAL 3D SKETCHING WORKFLOW

The second issue the researcher faced with publishing the 3D sketch was making it possible for multiple users to view it in AR or VR. Publishing a 3D model for either AR or VR has a different procedure to support viewing the models on a smartphone for AR simulation and using an HMD for viewing the VR simulation. These issues were significant, and are discussed in more detail in the following section.

In summary, phase one of the study identified the techniques and workflow of using 3D sketching as a design. There are disadvantages of sketching in 3D with there being more *external* and *internal* factors that may interfere with the sketching session compared to the traditional 2D sketching. The most insightful finding from the 3D sketching experience, that is an advantage, is the ability to draw out anthropometric skeleton sketches. Moving forward, the following sections presents the results of phase two of the study.

4.3 Phase two: engagement with the XR system

Phase two of the study evaluated the user experience of viewing and evaluating the sketches that were developed in phase one of the study. The two user groups in this study were designers and non-designers. Each group completed a remote review session of the sketches and completed a survey created in Qualtrics. These sections provide the results of: 1) participants' familiarity with XR technology; 2) the System Usability Scale (SUS) results for the 2D sketches; and 3) the designer group's responses to the Technology Acceptance Model (TAM) questionnaire related to XR use for their work.

Characteristics of the designer group

A total of 40 designer participants were recruited for the survey; 20 male and 20 female from various fields of design whom all had different levels of experience. Most of the designers fall within the age range of 25-34 (26 of the 40) with the age distribution of the participants shown in Figure 28. Most designers had a bachelor's degree (24 out of 40), while 13 had completed a master's degree, 2 participants completed a high school diploma, and 1 completed a college degree (Figure 29).

In the questionnaire (discussed further in section 4.3.3), the designers were asked to identify their field of work and years of experience. Overall, 18 of the 40 participants identified that they work in Industrial Design; 6 indicated they had 1-3 years of experience and 6 identified they had 3-10 years of experience. The following fields of design were the most represented in this study: Industrial Design, Engineering, Human-Computer Interaction, and UX Design. The entire distribution of field and years of experience of each designer group on page 104)_

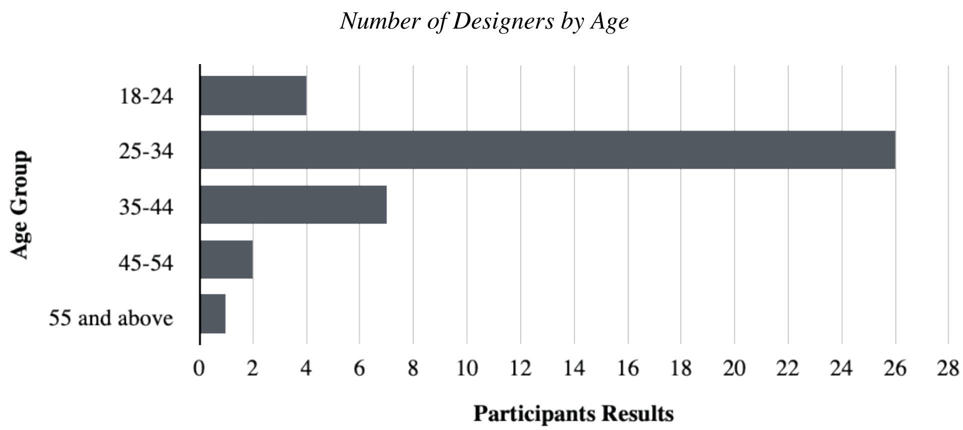

FIGURE 28 AGE DISTRIBUTION OF THE DESIGNER GROUP

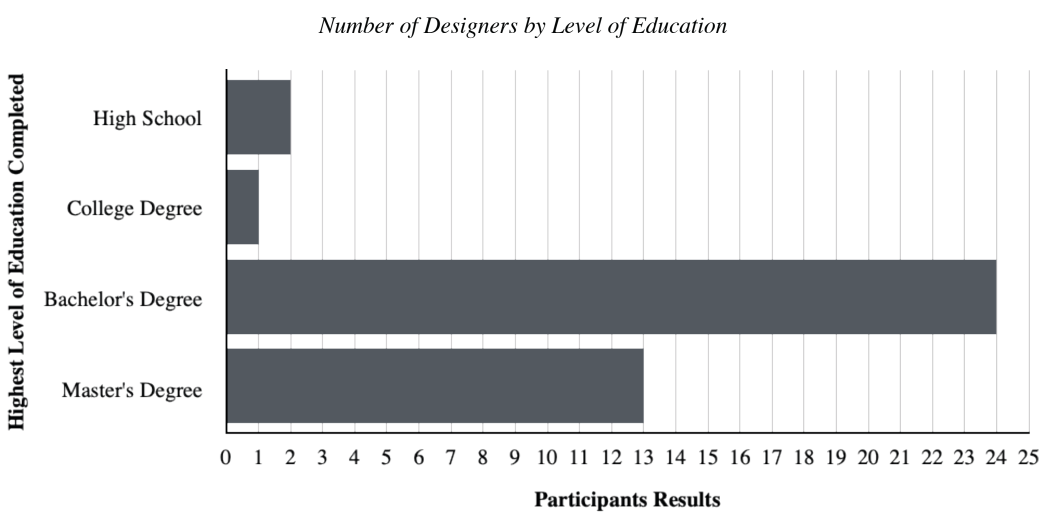

FIGURE 29 EDUCATION COMPLETED DISTRIBUTION OF THE DESIGNER GROUP

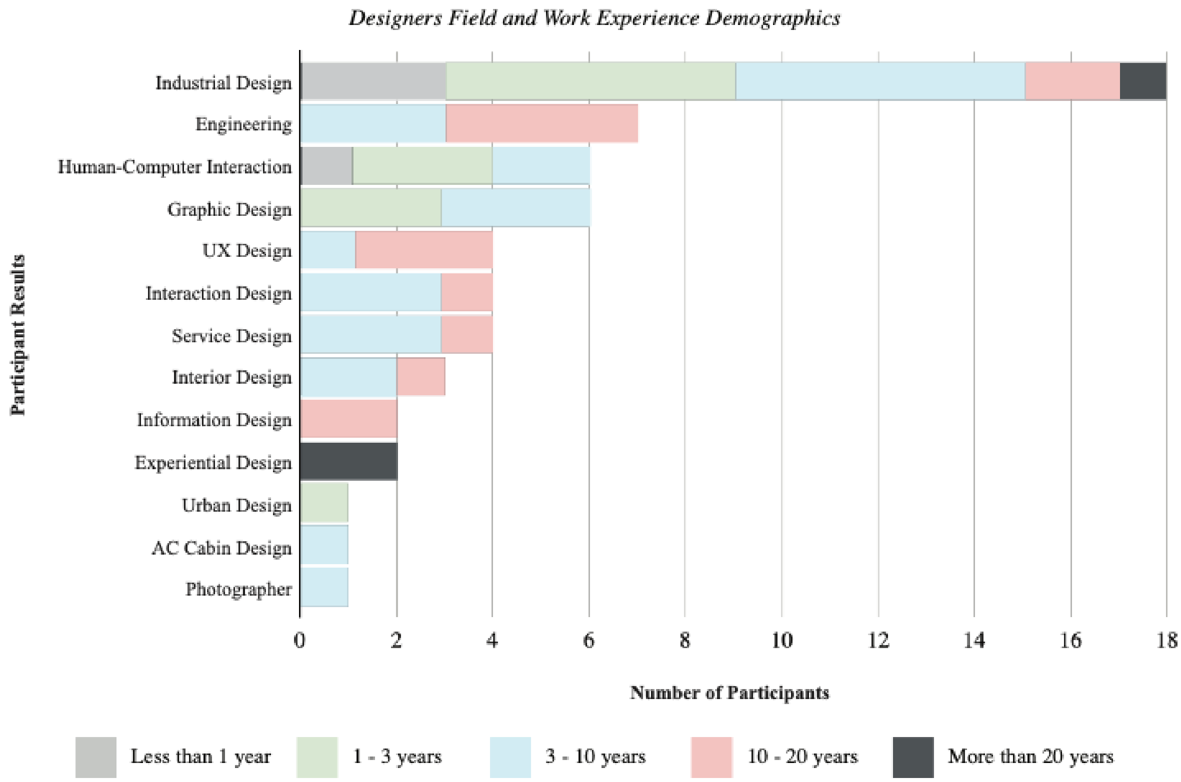

FIGURE 30 DESIGN EXPERIENCE AND FIELD OF WORK OF THE DESIGNER GROUP

Characteristics of the non-designer group

For this study, the definition for non-designers are participants from the general population who could be hypothetically called to participate in an air travel design user testing session. There were 41 participants, 27 female, 13 male, and one who wished not to identify. The majority of the non-designer group, 21 of the 41, fell within the 25-34 age range (Figure 32). The distribution of the highest level of education completed by the non-designers is as follows: 21 out of 41 completed a bachelor's degree, 14 a master's degree, 3 a PhD, 2 a college
follows: 21 out of 41 completed a bachelor's degree, 14 a master's degree, 3 a PhD, 2 a college
degree, and 2 completed high school (Figure 31).

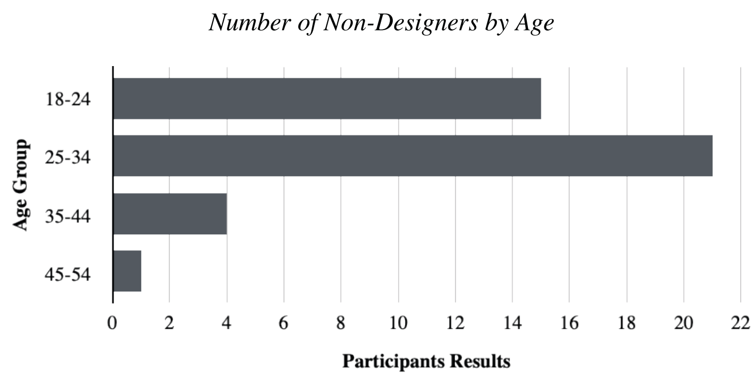

FIGURE 32 AGE DISTRIBUTION OF THE NON-DESIGNER GROUP

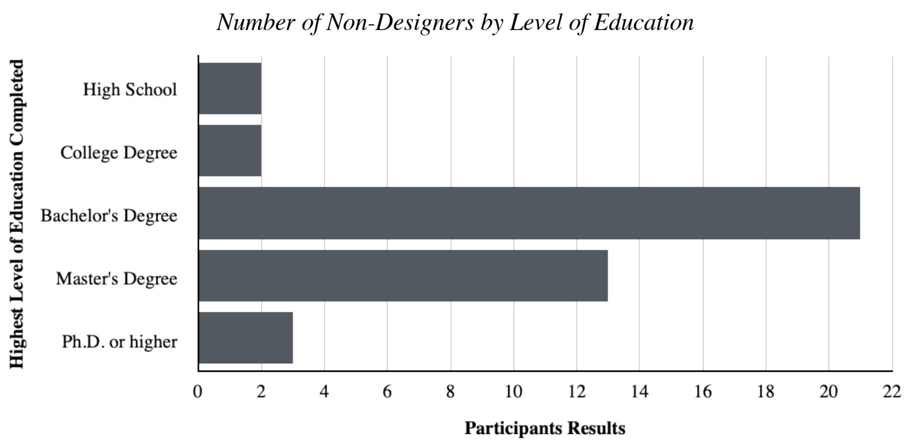

FIGURE 31 EDUCATION COMPLETED DISTRIBUTION OF THE NON-DESIGNER GROUP

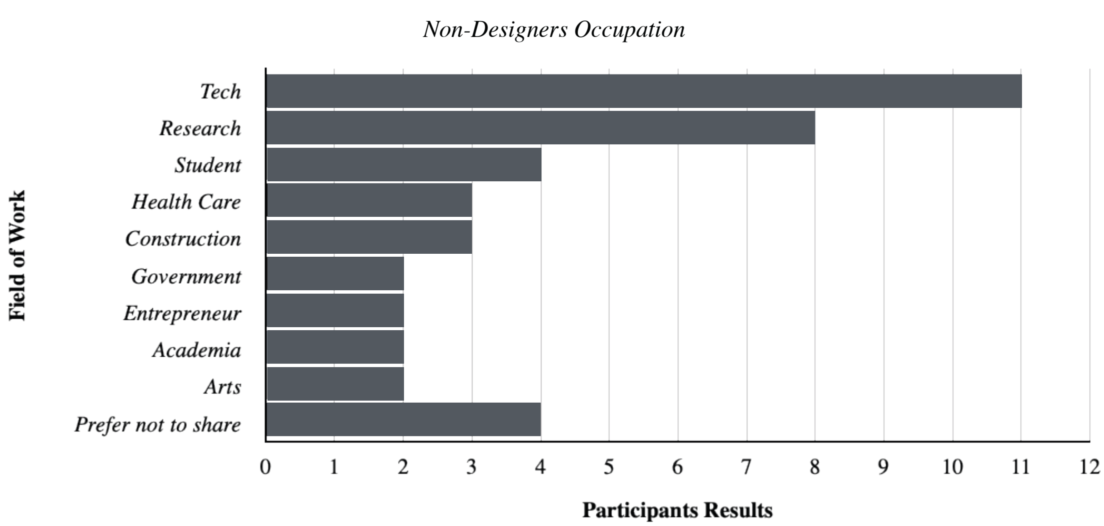

FIGURE 33 FIELD OF WORK CATEGORIES OF THE NON-DESIGNER GROUP

Compared to the designer group, the non-designer participants were asked to identify their occupation. Since their careers are more sporadic, the results were summarised into umbrella terms related to their field of work. Of this group, 11 of the 41 occupations were related to working in technology-related work, and the next large group 8 of the 41 identified as researchers (Figure 33).

4.3.1 Familiarity with XR (designers and non-designers)

Participants from both groups were asked about their familiarity with VR, AR, and XR and their frequency of use of these technologies. This set of questions was used to capture users' knowledge of the terminology (e.g., VR versus AR, XR as an umbrella term encompassing both VR and AR) and their frequency of use in the technologies.

Designer group familiarity

The designers were asked to identify how familiar they are with VR, AR and XR technology identifying which statement was most relevant to them; *I am aware and frequently use…*; *I am aware and occasionally use…*; *I am aware but never use them…*; and *I have never heard of…*. The familiarity results of the designer group are shown in Figure 34.

Overall, the designer participants in the designer group (N= 40 participants, 20 male and 20 female) were familiar and occasionally use both VR (n=17) and AR (n=20), but over half had "*…never heard of XR"* (n=21). The unfamiliarity score of the term XR was not was unexpected since the term XR is widely used in research and development (especially for the field of HCI and UX Design). The researcher assumed that XR would be a term participants would have come across at some point in their career or education.

Designers were asked to identify their frequency of how they use VR, AR and XR by selecting a statement that was most relevant to them: *Once a day*; *Once a week*; *Once a month*; *Once a year*; and *Have yet to experience*. The results of the designers' responses regarding their frequency of use of the technologies is shown in Figure 36.

In Figure 23, XR technology scored the highest identifying that a large number of designers from this group had yet to use the technology or did not know they had used this technology, not being familiar with the umbrella term for VR/AR term (score of 28/40). Looking more closely at the participants who reported using XR (i.e., from *Once a year* to *Once a day*) HCI or UX was part of their work experience and they had completed a Master's-level education or higher. This finding suggests that familiarity with XR is common for work and study related to HCI and UX.

According to the results, most designers have never heard of XR. This is not surprising given it is a term perhaps more often used in research and development, and the designers were mostly from an industrial design and engineering background. However, the designers were familiar with AR and VR, reporting they occasionally use it in their workflow with *"Once a year"* being the most cited response. The designers that reported using the technologies frequently work in the fields of Industrial Design, Engineer, Interior Design, HCI, UX, Interaction, Graphic and/or Aircraft Cabin Design. The designers who used the technologies with the least frequency identified as working in Service Design, Experiential Design, Urban Design, and/or Photography.

Non-designer group familiarity

The non-designers group (N=41 participants; 27 female, 13 male, and 1 prefer not to say) responded to the same question as the designers about their familiarity and frequency of VR, AR, and XR technology and use. Their responses are shown in Figure 35. Similar to designers, the majority of the non-designers (28/41) had *"never heard of...*" XR. None of the non-designers claimed to be "*aware and frequently use…*" or "*aware of … but never used*" XR. Of the non-designer participants 3/41 were "*... aware and occasionally use...*" XR technology. Looking further into these participants, they identified as working in the Tech field.

Overall, most non-designers stated that they are mostly familiar with both VR and AR technology. Regarding VR and AR use, nearly half used it occasionally (VR 21/41 and AR 20/41). Surprisingly, 18/41 participants responded, "*I have never heard of VR*". Looking further into these participants, they identified their occupation in the fields of Health Care, Arts, Construction, Government, or Student.

Non-designer participants' responses regarding the frequency of their VR, AR, and XR use are displayed in Figure 37. The majority of the non-designers' responses skewed toward infrequent use (e.g., *Once a month*, *Once a year*, or *Never use*). Two non-designers indicated using the technologies once a day; these participants reported working in the fields of Information Technology and holding a master's degree. A total of 38 of the 41 non-designers "*Have yet to experience XR*".

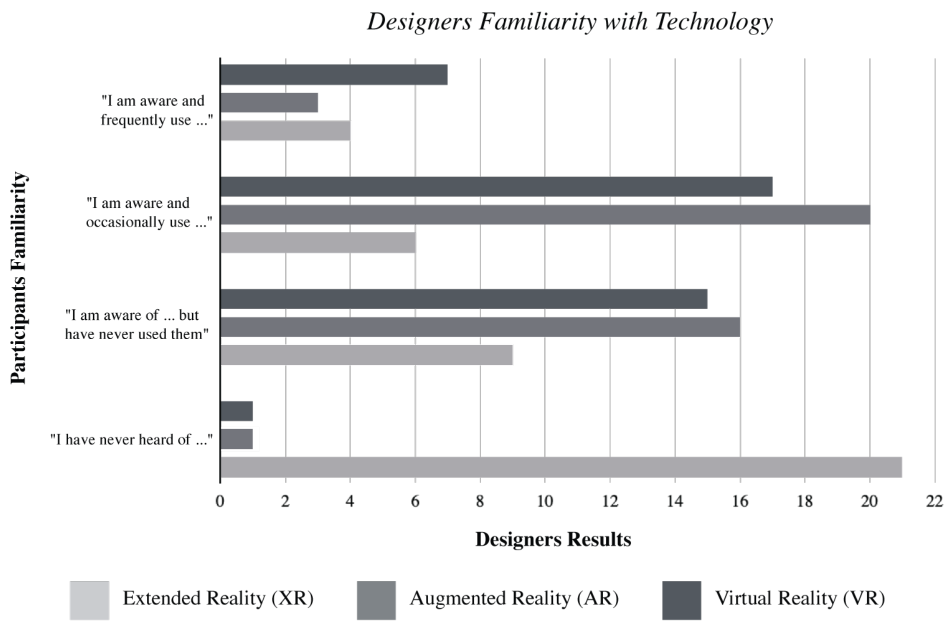

FIGURE 34 DESIGNERS GROUP RESULT OF THEIR FAMILIARITY OF VR, AR, AND XR.

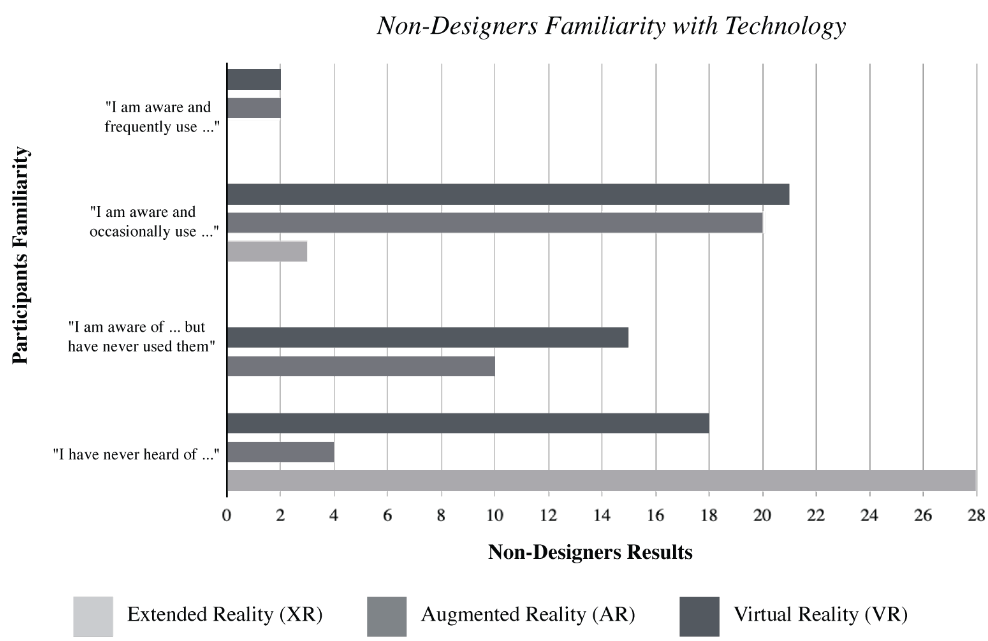

FIGURE 35 NON-DESIGNERS GROUP RESULTS OF THEIR FAMILIARITY OF VR, AR, AND XR.

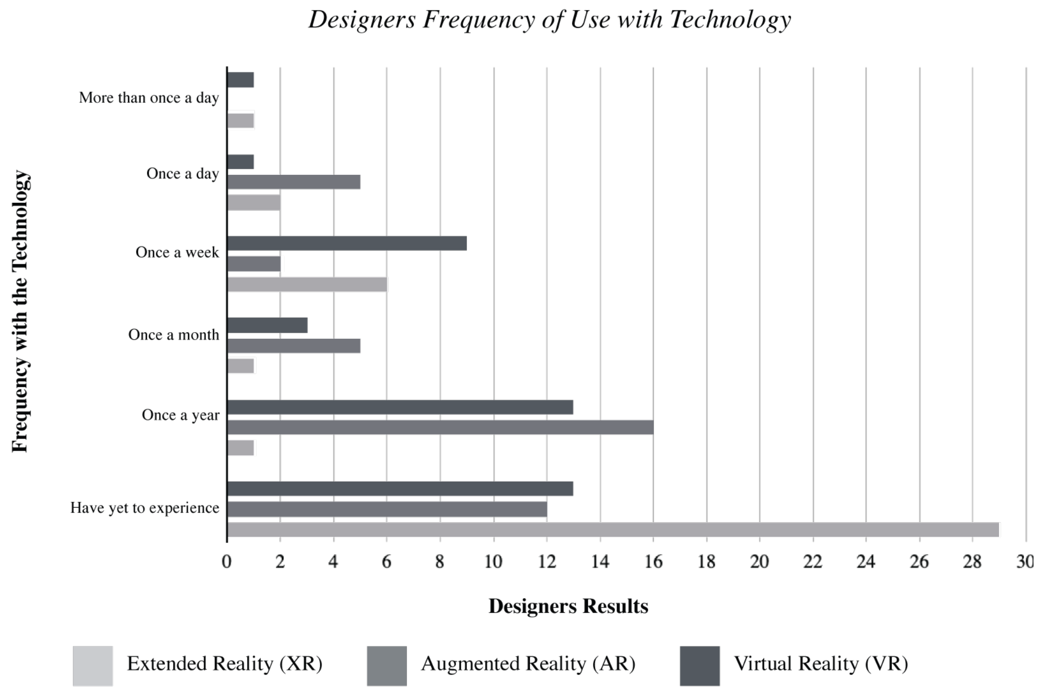

FIGURE 36 DESIGNER GROUP RESULTS OF FREQUENCY USING VR, AR, AND XR

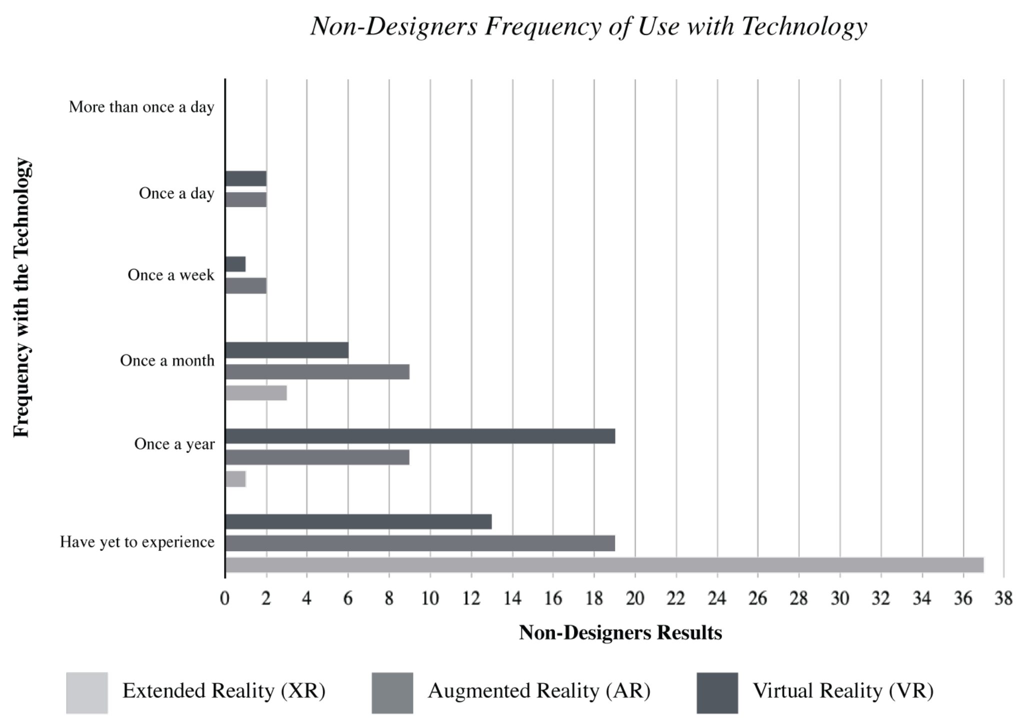

FIGURE 37 NON-DESIGNER GROUP RESULTS OF THEIR FREQUENCY OF USING VR, AR, AND XR

Overall, both groups' reported familiarity with VR, AR, and XR and the reported frequency in using these technologies suggested that they are mostly unfamiliar with the concept of XR technology but familiar with VR and AR. In other words, most users had at least some experience with XR, whether for recreational or work use. These results were reassuring in the context of this study, as an ongoing concern was that users would not be able to use the AR or VR application to evaluate the sketches in phase two Fortunately, there were assessment of the 3D sketches.

4.3.2 System Usability Scale results for designers and non-designers

After reviewing the sketches in the 2D and 3D viewing systems, both groups of participants completed a SUS to rate their experience with the viewing medium (Table 1). A SUS survey evaluates how a user perceives a system's usability and was used here to assess the usability reviewing 2D and 3D sketches. Traditionally, a passing score for SUS to determine if a system is perceived to be usable is when the average score is above 68. With the 2D system, the designers scored a mean of 66.79 (or an average rating of 3.33 out of 5 on the SUS) and a mean of 62.57 (3.12) for the 3D system; indicating that the designers found the system of viewing the 2D sketches more usable compared to that of the 3D system. In contrast, the non-designers found that the system for viewing the 3D sketches was more usable with a score of 72.64 (or 3.63 rating) compared to the 2D sketch system that scored 69.04 (or 3.45 rating). The non-designer group rated the usability of both systems (2D and 3D medium) higher and both have a passing score compared to the designer group.

TABLE 1 DESCRIPTIVE STATISTICS FOR SYSTEM USABILITY SCALE (SUS)

Item	Group	Mean	S.D	Median	Max	Min
2D Medium	Designers	66.79	15.60	68.75	90	40
	Non-Designer	69.04	18.18	73.75	90	32.5
3D Medium	Designers	62.57	17.08	65.00	90	30
	Non-Designer	72.64	13.53	75.00	90	42.5

In Figure 38, a box plot compares the overall SUS score for the 2D medium and 3D medium for both groups of participants. Any median score above the 3rd quartile (or the red line in Figure 36 which represents a score of 68) represents a positive and acceptable system [41]. Overall, non-designers rated the 2D and 3D mediums to be usable with a mean score for both mediums above 68. The designer group rated the 2D and 3D mediums lower than the passing score, with means of 66.79 for the 2D medium and 62.57 for the 3D medium (1.21 and 5.43 points below the desired 68 approval score).

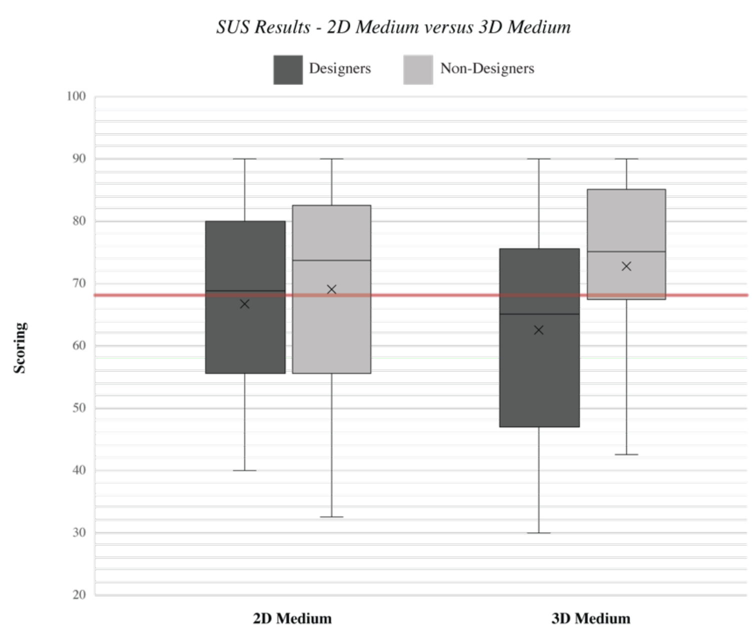

FIGURE 38 SUS SCORE COMPARING THE 2D AND 3D VIEWING SYSTEM FOR BOTH GROUPS

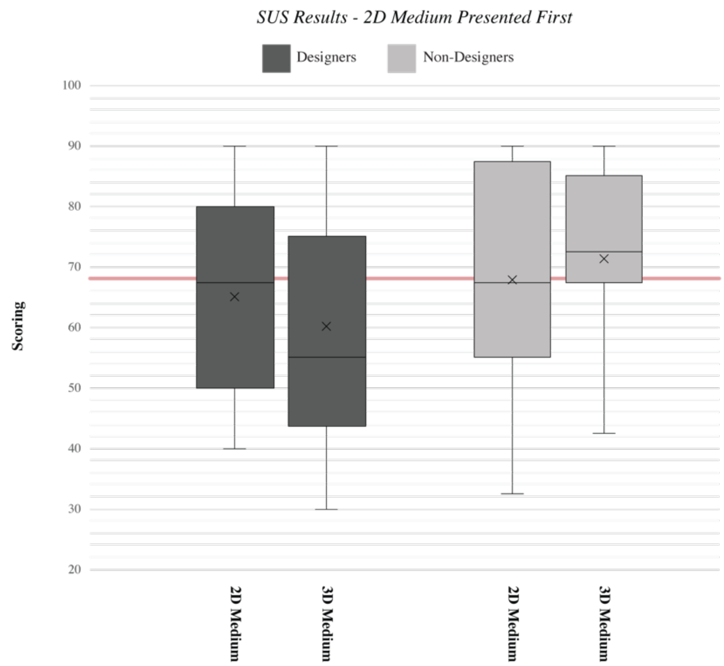

FIGURE 40 SUS RESULTS WHEN THE 2D MEDIUM WAS PRESENTED FIRST TO PARTICIPANTS

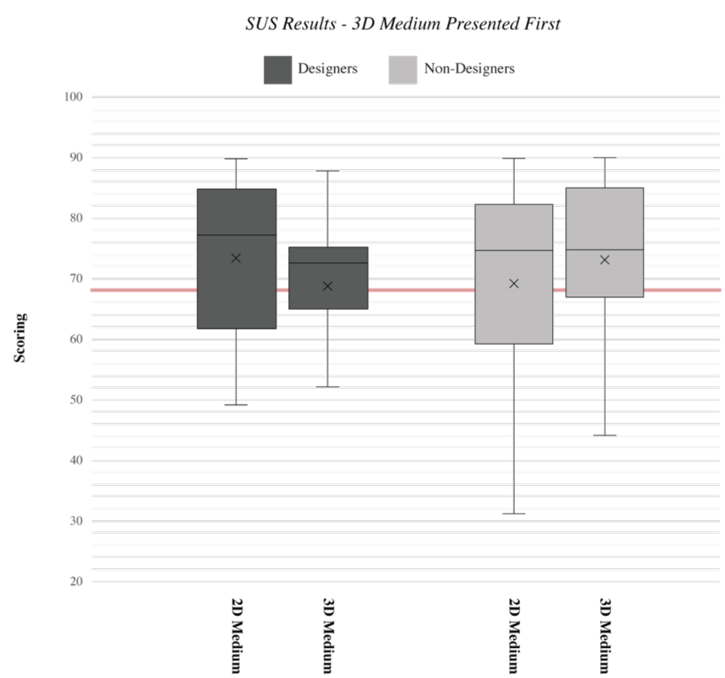

FIGURE 39 SUS RESULTS WHEN THE 3D MEDIUM IS PRESENTED FIRST TO PARTICIPANTS

As mentioned in Chapter 3, section 3.3.1, 2D and 3D sketches were presented to users in random order; thus the order that the system was presented may influence the participants rating. In Figure 40, the results of the SUS are shown for both groups when the 2D sketches were presented first. When presented first, the 2D system scored slightly below the third quartile (score of 68) where the average score is 65.00 for designers and 67.88 non-designer (median for both is 67.5). When presented with the 2D medium first, the designer group rated the usability of the system when viewing the 3D sketches below the third quartile with a score of 60.10 (median = 55.00).

In Figure 39. the results of the SUS are shown, for both groups, when the 3D sketches were presented first. Overall, both mediums, for both groups, scored higher and above the 68 score compared to when the 2D system was shown first. For the non-designer group, the 3D system rating scored an average of 73.75 (median = 75.00), while the 2D system rating scored an average of 69.76 (median =75.00). For the designer group, the 3D system rating scored an average of 68.80 (median =72.50), while the 2D system rating scored an average of 71.38 (median =75.00).

In summary, the designers found the 3D system to be less usable compared to the 2D system while the non-designers rated the 3D system higher regardless of the distribution of the mediums in the random distribution. The non-designer group seems to rate the XR experience higher compared to the traditional 2D method. In Figure 41 shows the side-by-side comparison of both SUS results depending on the order of the medium presentation for both the designers and non-designers. The designers rated the 2D system similar to the non-designer group but seemed to take a pessimistic view of the 3D system experience. It should be noted that all the results from the SUS did have a score above the neutral scale rating, thus the result does have a mostly higher positive perception rating according to the SUS rating system (mostly agreeable and or above neutral stance).

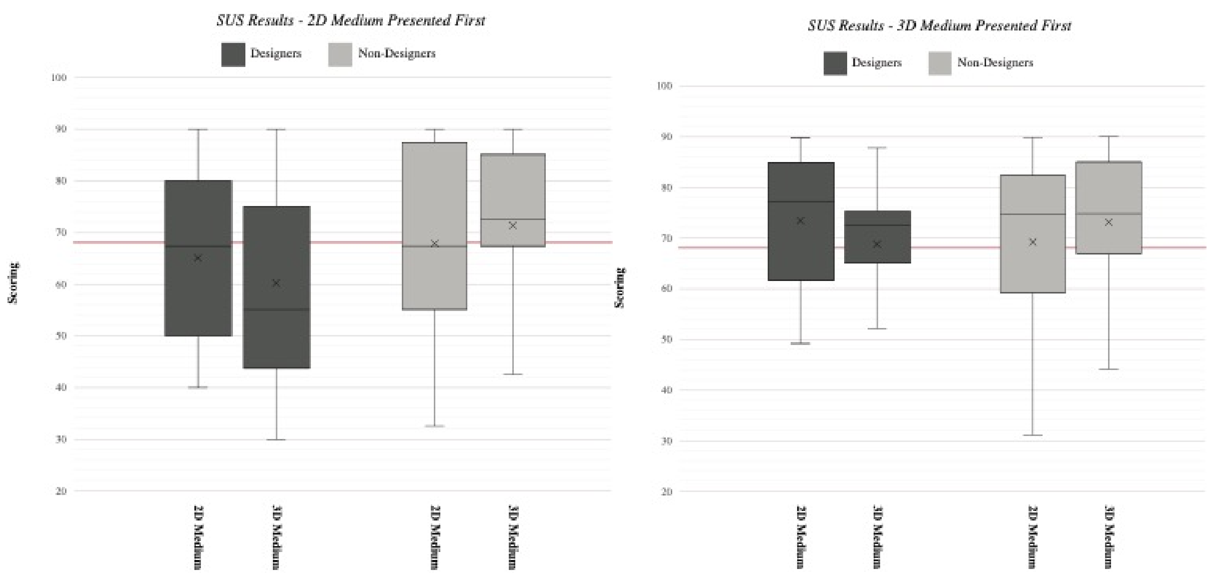

FIGURE 41 SIDE-BY-SIDE COMPARISON OF THE SUS OF BOTH MEDIUM PRESENTATION ORDER

4.3.3 Designers Technology Acceptance Model questionnaire results

The designer group completed an additional questionnaire in phase two to gain a better knowledge of their perception on the acceptance of the technology for their existing workflow. This part of the investigation was conducted using the statements extracted from the Technology Acceptance Model (TAM) where the designers rated their perception of the usefulness and ease of use of XR technology by providing a scale response (see section 3.3.4 for details). Two sets of questionnaires were distributed to the designers: Perceived Acceptance of the XRs System Technology Techniques (where only 31 of the 40 designers contributed), and Perceived Acceptance base of Actual Use of XR System Technology Techniques (where only 9 of the 40 designers contributed). The 9 of the 40 designers who contributed to the Actual Use of XR System Technology reported that they work in the field of Industrial Design, HCI, Interaction Design, Interior Design, Graphics Design, UX Design, and Engineering (Table 2). The 8 of 40 designers who did not complete the TAM questionnaire of the survey are those who did not identify their field of design or work in Industrial Design, HCI, Graphic Design, and Service Design; it is presumed that participants decided to withdraw at this phase of the study. The designers rated their perception results on a 5-point-scale rating, where 1 is Highly Disagree, 3 is Neutral, to 5 where they Highly Agree with the statement.

TABLE 2 PARTICIPANTS DESIGN FIELDS WHERE THEY DO APPLY XR TECHNIQUES TO WORKFLOW

Design Field	Has actual use of XR in their design workflow
Industrial Design	3
Human-Computer Interaction	3
Interaction Design	3
Interior Design	3
Graphic Design	2
UX Design	2
Engineering	1

*NOTE THAT SOME DESIGNERS WORK IN MULTIPLE FIELDS OF DESIGN

The questions documented in Table 3 show the results for the first survey, *Perceive Acceptance of the Technology Techniques* (N=31). The question regarding the Perceived Usefulness (PU) scored an average 3.40 rating (S.D. 1.18). Thus, the overall PU of 3D systems in their workflow was just above the "*Neutral*" score (3-point rating). The Cronbach's alpha is measured at 0.92 for the PU questionnaire, which shows that the rating of the designers has relatively high internal consistency, where any score above 0.70 is an acceptable reliability coefficient score (see section 3.3.4 for details). The Perceived Ease of Use (PEU) scored an average of 3.62 (S.D. 0.98) thus a rating below "*Somewhat Agree"* (4-point score rating) with the statements. The PEU Cronbach's alpha is measured at 0.88 for the PEU questionnaire.

TABLE 3 DESCRIPTIVE DATA FOR TAM QUESTIONNAIRE OF XR SYSTEM TECHNIQUES

Item	Mean	S.D	Median	Max	Min	Cronbach's α
Perceived Usefulness (PU) Items of Technique Performance						
Using XR techniques in my job would enable me to accomplish tasks more quickly.	3.29	1.16	4	5	1	-
Using XR techniques as a tool would improve my job performance.	3.41	1.33	4	5	1	-
Using XR techniques in my job would increase my productivity.	3.29	1.24	4	5	1	-
Using XR Techniques would enhance my effectiveness on the job.	3.48	1.12	4	5	1	-
Using XR techniques would make it easier to do my job.	3.19	1.22	3	5	1	-
I would find XR techniques useful in my job.	3.74	0.99	4	5	1	-
Overall Perceived Usefulness (PU)	**3.40**	**1.18**	-	-	-	**0.92**
Perceived Ease of Use (PEU) Items of Techniques Performance						
Learning to operate XR techniques as a tool would be easy for me.	3.90	0.94	4	5	2	-
I would find it easy to get XR techniques to do what I want it to do.	3.32	0.97	3	5	2	-
My interaction with XR Techniques would be clear and understandable.	3.48	1.09	4	5	1	-
I would find XR Techniques to be flexible to interact with.	3.64	0.83	4	5	2	-
It would be easy for me to become skilful at using XR Techniques.	3.61	1.14	4	5	1	-
I would find XR Techniques easy to use.	3.77	0.84	4	5	2	-
Overall Perceived Ease of Use (PEU)	**3.62**	**0.98**	-	-	-	**0.88**

In looking at the PU, the questions had a relatively high standard deviation (S.D. 1.18) compared to PEU (S.D. 0.98). The lower the standard deviation, the more consensus in the designers' responses. The statements that had the lower standard deviations are as follow: for PU "*I would find XR techniques useful in my job.*" (mean = 3.74); and for PEU "*Using XR Techniques in my job would increase my productivity.*" (mean = 3.74); and "*I would find XR techniques to be flexible to interact with."* (mean = 3.64).

Overall, the median score of almost all the statements for PU and PEU received a 4-point rating (*Somewhat Agree*). The only one that received a lower median score of a 3-point score (*Neutral*) was PU's "*Using XR techniques would make it easier to do my job*" and PEU's "*I would find it easier to get XR techniques to do what I want it to do*". The designers who rated the statements with consistent 4-to-5 point ratings were those who continued to the next set of questionnaires that explore their PU and PEU base of Actual Use of XR System Technology Techniques for their workflow.

Table 4 shows the results of the 9 designers who contributed to the final TAM questionnaire Perceived Acceptance base of Actual Use of XR System Technology Techniques. Overall, the average score for PU was 4.07 (S.D. 0.99) and PEU 3.60 (S.D. 0.81). The Cronbach's alpha for PEU is measured at 0.87 and for PEU is 0.81, thus both are above the acceptable measure demonstrating relatively high internal consistency. The PU that had the highest rated score were the questions with a median score of either 4 or 5. The TAM statements that scored the highest average of 4.33 is *"Using XR systems will improve my job performance."* (S.D. 1.11) and *"Overall, I would find the XR system useful in my job."* (S.D. 1.00). The PEU that scored lower compared to PU, were statements in the questionnaire that asked about the learnability of using XR such as "*Learning to operate XR systems is easy for me.*" scored an average 2.55 (S.D. 0.52); and *"I find it takes a lot of effort to become skillful at using XR Systems.*" scored an averaged of 2.88 (S.D. 0.92). The highest rated statement of the questionnaire was "*Overall, I find XR Systems easy for me to use.*" with an average score of 4.44 (S.D. 0.72).

TABLE 4 DESCRIPTIVE DATA FOR TAM QUESTIONNAIRE OF ACTUAL USE XR SYSTEM TECHNIQUES

Item	Mean	S.D	Median	Max	Min	Cronbach's α
Perceived Usefulness (PU) Items of Actual Use Performance						
Using XR systems improves the quality of the work I do.	4.22	1.09	5	5	2	-
Using XR systems gives me greater control over my work.	4.22	0.97	5	5	3	-
XR systems enables me to accomplish task more quickly.	4.11	1.16	5	5	2	-
XR systems support critical aspects of my job.	3.88	1.05	4	5	2	-
Using XR systems increases my productivity.	3.66	1.11	4	5	2	-
Using XR systems improves my job performance.	4.33	1.11	5	5	2	-
Using XR systems allows me to accomplish more work than would otherwise be possible.	4.22	0.83	4	5	3	-
Using XR systems enhances my effectiveness on the job.	3.66	1.00	4	5	2	-
Using XR systems would make it easier to do my job.	4.11	0.78	4	5	3	-
Overall, I would find the XR systems useful in my job.	4.33	1.00	5	5	2	-
Overall Perceived Usefulness (PU)	**4.07**	**0.99**	-	-	-	**0.87**
Perceived Ease of Use (PEU) Items of Actual Use Performance						
I find it cumbersome to use XR systems.	3.66	1.22	4	5	2	-
Learning to operate XR systems is easy for me.	2.55	0.52	3	5	2	-
Interacting with a XR systems is often frustrating.	3.44	1.33	4	5	1	-
I find it easy to get XR to do what I want it to do.	3.88	0.92	4	5	2	-
XR systems is often rigid and inflexible to interact with.	3.55	1.33	4	5	1	-
It is easy for me to remember how to perform tasks in XR systems.	4.11	0.78	4	5	3	-
Interacting with XR systems requires a lot of my mental effort.	3.66	1.00	4	5	2	-
My Interaction with XR systems is clear and understandable.	3.77	0.83	4	5	3	-
I find it takes a lot of effort to become skillful at using XR systems.	2.88	0.92	3	5	1	-
Overall, I find XR systems easy to use.	4.44	0.72	5	5	3	-
Overall Perceived Ease of Use (PEU)	**3.60**	**0.81**	-	-	-	**0.81**

Overall, the designers who completed both surveys rated both the PU and PEU with mostly high agreement ratings on the scale with exception to the statements regarding the learnability which scored below a 3 (Neutral) score. Designers who only completed the first TAM questionnaire rated the statement that included keywords such as “learning” and “becoming skillful” higher compared to the 9 of the 40 designers who had actually used XR in their work. This reflects the same learning curve the researcher experienced with sketching in VR and making the 3D medium available for users to view in VR and AR discussed in section 3.2.3.

Moving forward, the evidence garnered form this study identify the benefits and barriers that XR technology currently holds for the current design process. The results from the sketching exploration identify trade-offs in using 3D sketching as a technique, while the design survey shows that XR may allow for more accessibility for non-designers to be involved in the design process but shows the hesitancy from designers in adopting and learning the XR system techniques. The interpretation of the result with regards to the research question, mention in section 1.2, will be discussed in the next chapter.

Chapter 5 Discussion

In aerospace, the demand for innovation by exploring emerging technology is continuously evaluated if these technologies benefit the existing design and development workflow [5, 4, 10]. Additionally, analysing new tools adapted from already existing design processes can help decrease the impact of possible unprecedented challenges so that they do not disrupt the project's plan. Specifically, current challenges in aerospace design that have been challenged due to COVID-19 are the need to continue designing and working with research participants remotely. Both designers and participants from the general public must be involved in the development process without the need to be onsite. This limitation with existing bottlenecks in traditional aerospace design methods makes the design process time-consuming and expensive. It is difficult to collaborate remotely with team members to develop preliminary concepts; the cost of conducting early evaluations or usability testing with participants is prohibitive; and there is a need for a robust process to conduct remote participatory design sessions [2, 4, 5, 8].

The research conducted in this study experimented with the potential benefits of implementing XR techniques in the early level of the TRL model, precisely level 2-3. From the researcher's experience coupled with the survey results reported in this study, promising practices in using VR sketching for remote sketching and applying VR and AR as a method to share ideas with users were identified. The following chapter discusses the implication of these findings from both phases (see Chapter 4 for full results) and promising practices in XR to support design workflows. The chapter concludes with XR's research contribution for remote studies, the limitations of the study, and future work.

5.1 Promising practices in XR for design

The following section discusses the implications of the findings from each phase of the study regarding previous literature (see Chapter 2 for the full literature review). Each sub-section responds to a research question (see section 1.2 of Chapter 1).

5.1.1 Is it possible to design sketch in VR?

The emergence of VR as a tool for design, specifically for sketching, has been popularised in recent years as a technology that could replace traditional sketching techniques and merge the workflow task of sketching to CAD modelling [6]. The experiment in phase one of the study was designed to explore and document the experience of VR sketching for early brainstorming compared to traditional methods—and the benefits and disadvantages of each. The literature review in Chapter 2 identified potential benefits of using VR as a design tool, including: a 3D medium approach offers increased capacity for creativity and complex problem-solving [14]; virtual spaces provide more spatial freedom compared to traditional 2D sketching methods [15, 16]; and sketching to scale as well drawing in a simulated environment can better match the context to the product and provide a more immersive experience while drawing [11, 14]. The potential disadvantages of using VR sketching included drawing for accuracy [6] and ergonomic limitations due to the hardware [34]. From the results of phase one (see section 4.1), the researcher identified several promising practices in using VR sketching for brainstorming concepts. The following paragraphs discuss the factors that can impact the sketching workflow in VR compared to traditional techniques.

Overall, the researcher found that the demands of learning the VR technique disrupted their ability to be creative while sketching, and several internal and external factors affected the 3D sketching workflow. Israel *et al.* (2009) identified that the process of moving around in 3D can allow the designer to be more creative since they can find solutions and inspiration in the design while interacting with the 3D model [14]. Based on the phase one results, drawing in 3D did not promote more creative thinking while sketching. The researcher's focus while VR sketching was on making the sketch better with their developing VR sketching skills rather than on sketching to find creative design solutions. The researcher spent roughly 15 hours learning the techniques and tools of the Gravity Sketch software before producing a sketch that they considered to be near the same level of quality as their 2D sketches (Figure 13 and Figure 17). As discussed in the literature, VR sketching may be more challenging to sketch for accuracy [6]. From the researcher's experience, this is true during the learning phase of the VR sketching session. While freehand drawing, the drawing results showed that the lines of the form sketch in VR had some difficulty connecting (shown in Figure 20) and that the researcher did lack control of the drawing while sketching in VR. Additionally, adding the volume and surface to the sketch was the task that consumed most of the researcher's time while drawing in VR. The majority of the time spent in VR sketching was sculpting the 3D form to make it appear as the desired design of the product, rather than iterating multiple unique or creative solutions.

The results of phase one showed *internal* and *external factors* that disrupted the researcher's design workflow while sketching in VR (discuss in section 4.1.2 and show in Figure 23). The majority of interruptions during the workflow were hardware issues and ergonomic limitations. *External factors* that disrupted the workflow were the devices' sensors not connecting and the environment where the sketching was taking place was too hot to work while wearing the HMD hardware. Though these limitations caused *unproductive* sessions, the researcher was mindful of these events and scheduled time breaks during the sketching session to ensure productivity while drawing and resetting the hardware sensors.

An *internal factor* that disrupted the workflow that the researcher did not anticipate was the cybersickness when pre-fabricated models were placed in the sketching VE. Since the researcher mainly was sketching stationary (i.e., sitting in place) due to the physical limitations of the researcher's room size, to navigate around the 3D sketch, they grabbed the 3D sketch or the VE in the VR simulation around them, which induced Vection, a form of motion sickness [49]. In the research conducted by Israel *et al.* (2009) [14] and Rahimian and Ibrahim (2011) [36], moving within a VE or around the 3D drawing can make the cognitive task to mentally process the image less overwhelming and more intuitive compared to 2D techniques—in other words, they did not account for the user working stationary. In this exploratory research, pre-fabricated models were inserted into the VE to allow the researcher be more immersed and to visualise how new partition barriers could be designed for existing airline interiors. Though the pre-fabricated models were effective in this regard, the experience of cybersickness was not anticipated, which caused sketching sessions to be delayed until the researcher could continue and focus on design.

The limitations of the *external* and *internal factors* that disrupted the VR sketching workflow were events that can be avoided by being mindful of the time spent in VR. Looking at the linear infographics of both the 2D and 3D sketching sessions (Figure 16 and Figure 23), the researcher was able to work productively for 1-2 hours, even on days with the disrupting factors. From the researcher's experience, creating sketches in the 3D simulation was not as productive for creative and iterative solutions when VR sketching from scratch as using it to explore previous ideas drawn out with the traditional 2D techniques. The VR sketching was mainly spent modifying the design instead of creating a unique solution. The best workflow identified from phase one was using 2D sketching to brainstorm multiple designs and then adapt the narrowed down design solution in VR to explore its volume, form, and dimension in the immersive setting. A similar workflow was identified in the research by Ban and Hyun (2020), where their design sketching process was moving between VR and 2D sketching on a Wacom to make their workflow time-efficient and not get caught up on the techniques of sketching in VR [6].

Though VR may not be the best medium for creating design solutions from scratch, an insight the researcher identified from their VR sketching workflow (see section 4.1.2) was that it was useful for developing a skeleton silhouette of the airline seat that fit their ergonomic measurements. The following sections describe the benefits of using VR for the human-centered design process.

5.1.2 VR sketching for human-centered design

Phase one of the study defined a workflow for 3D sketching (summarized in section 4.1.2), which helped the researcher to be efficient during their VR sketching session. From the workflow, making a skeleton sketch in VR helped to create a silhouette of construction lines of the chair. The process of drawing this skeleton sketch demonstrated the most valuable part of VR sketching: creating anthropometric sketches for human-centred design (shown in Figure 19). The definition of anthropometry is the systematic measurement of the physical properties of the human body [50]. For design, anthropometric data is used to help design products to meet ergonomic needs and design with human factors front-of-mind. Anthropometric-based sketching can make human factor and/or centred design more efficient in the early concept development phase, revealing early insights or accelerating ideas related specifically to human dimensions and proportions.

Currently, the traditional methods of 2D sketching only create a stylised idea of a design. The 2D sketch lacks the knowledge of how the user will fit into the design, and this can only be explored through more detailed dimensioned orthogonal or 3D CAD software using mannequins (i.e., Autocad Orthogonal, Solidworks HumanCAD, HumanCAD-MQSW), or at a later stage of the workflow (i.e., when a physical prototype is built for user testing). In the VR sketching exploration, as described in section 4.1.2, the researcher was able to draw partition walls around themselves to explore 'fit' first-hand around their chair and bodily dimensions. Thus, the 3D medium can quickly afford designers and users the experience of how a design feels so they can identify the satisfactory and unsatisfactory design details before moving forward to more detailed drawings and models or the next (costly) design stage of building the physical prototype.

Additionally, a potential benefit of VR sketching for human-centred design is the scenario where the user is in a VR simulated testing set up and they can sketch on top of their own body and add their own design criteria to meet their comfort needs. The work of Crescenzio (2019) identified that creating a more efficient human-centered design testing medium for users can "foresee the capability of a specific cabin interiors design of meeting the user's expectations, including the needs related to comfort and well being" (pp.772) [4]. In this study, the researcher drew the seat design dimensions around their own body and office chair dimensions. For human factors design, especially for the airline industry, an industry-standard size that should fit an acceptable range of the population can be used as a point of reference. Using VR sketching can allow designers and researchers to sketch around pre-set anthropometric measures to create ideas that will work for a target user and/or challenging environments. An example would be to draw an airline seating solution around dimensions that would accommodate users at the upper and lower constraints of anthropometric measures and how interaction in the seat could accommodate their needs and make the flight experience more comfortable.

A study conducted by Daigle et al. (2020) explored airline accommodation for people living with obesity [51]. Their research identified that current airline interior space design does not meet most passenger comfort for air travel since emerging airline designs focus on consuming more of the environment space to fit more passengers per flight [51]. Based on the present study, the implementation of VR could help airline designers develop solutions that could serve the comfort of all users (e.g., persons living with obesity, people of different statures, children, etc.) and test the designs in a simulated aircraft to see how these designs can fit into the limited aircraft space. Thus, this technique can help designers better understand the users' access, clearance, reach and physical comfort in sitting and walking while travelling inflight.

5.1.3 Non-Designers involvement in the design workflow through XR

Human-centered design not only focuses on the user while designing but also on their participation in the design process for testing. Due to physical distancing restrictions implemented during COVID-19, this study's research was designed for the participants to complete from home. Previous literature has identified that VR and AR have been tested as a method for participants to work remotely [9] and asynchronously [5]. In the SUS survey assessment of viewing the two-sketch medium system, the non-designer group rated the 3D system higher than the traditional 2D sketching medium. A notable insight from this experiment is that XR has the potential to allow non-designers to be involved with the work process remotely (in response to Research Question 2, *"...what are the potential benefits and barriers of using XR (VR/AR) for remote design?"*.

Currently, for non-designers to be involved in the design process, they must participate in a user testing session or a product testing session, which has barriers regarding the availability of participants to partake in the sessions (e.g., if their schedules align with the project timeline) and having them on site to conduct the test. These reasons and more can make the logistics of user involvement in the design workflow almost unachievable or risk causing delays in the workflow. This study showed that the non-designer participants could view sketches using XR remotely.

As mentioned, XR has the potential for the user to be involved in the design process by providing them with early design sketches at an earlier stage and requesting feedback on the concept before it enters the phase where more advanced design and fabrication may be involved. Non-designer insight from the SUS showed that regardless of whether the 2D or 3D medium sketches were presented first, the usability of the XR system still scored higher more often than the traditional methods. Using the XR system may make non-designer users more enthusiastic to provide insight independently and remotely and provide insight on designs early on, as early as in the ideation sketching phase of the design workflow. User feedback on a design is currently only presented to end-users when a nearly finished porotype is ready to be shown. It is much harder to make changes to the plan at this stage than in the early stages of the design process.

The only barrier to using XR to facilitate user involvement is that not all users have a VR headset to view the simulation. AR can be the solution to this dilemma. In this study, most of the participants used AR not VR; of the designer group, 29 out of 40 used AR to view the 3D sketches, and of the non-designer group, 23 of out 41 used AR. As mentioned in section 3.2.2, the dilemma with AR is that it does have limitations in publishing large polygon models and may cause some details of the design to be missing in the AR simulation. Unfortunately, this dilemma may be an added learning curve to the design workflow and require more awareness of 3D mediums and the drawing outputs for publishing for XR viewing. This consideration may influence the acceptability of adopting the technology for some designers' existing workflow.

5.1.4 Does XR have a place in the early stages of the air cabin design workflow?

This study sought to identify promising practices of XR tools and techniques for the early stages of the design workflow. Above, we discussed some of the advantages that XR has over traditional methods. A key advantage was that XR can benefit the design workflow in the application of sketching in VR to develop anthropometric sketches that can help iterate more human-centred design concepts during the brainstorming phase of the design workflow. As well, using VR/AR is a viable method to share concepts with non-designers compared to passively viewing 2D sketches.

To revisit our response to Research Question 2, *Does XR have a place in the early stages of the air cabin design workflow?*, for non-designers, yes, there is enough evidence to suggest that XR can make the process more efficient for this group of users to be involved in the design work. As for designers, in phase two, the SUS showed that designers rated the 3D system as less usable compared to the non-designers, and in the TAM questionnaire, the perceived usability and ease of use was rated lower when learnability was probed in the statement. Thus, XR only has a place if designers are willing to use the tools.

The TAM questionnaire for the *Perceive Acceptance of the Technology Techniques* showed that designers (N=31) perceived the usefulness and ease of use of the XR system relatively above neutral after their survey experience (see section 4.3.3). This pool of participants combined designers with and without prior experience using the XR system for their workflow. Therefore, results related to perceived usefulness and ease of use have a novelty bias since only 9 of the 31 designers had used XR at some point in their design career.

The second TAM questionnaire responses from the nine designers who had used XR tools rated the overall usefulness of the XR system relatively high (4.07 out of 5) and the ease of use lower (3.60 out of 5). The results section 4.3.3 showed that in the question in the TAM questionnaire where the keyword *learning* was present, the designers rated both usefulness and ease of use the lowest.

The widespread usability of XR techniques is feasible only if the tool is easy to learn. In phase one of the study, the researcher noted it took roughly 15 hours to learn the techniques of VR sketching, but only around the end of the 130 hours of assigned sketching time did their 3D sketches start to appear to have the same stylised quality of their 2D sketches (see section 4.1.1). The nine designer-participants who had used XR for work and rated the learning question lower on the TAM questionnaire may be aware or have experienced a similar dilemma as the researcher. In the TAM questionnaire of perceived usability, where all 31 designers contributed, the responses to the question, *I find it takes a lot of effort to become skilful at using XR Systems*, scored an average of 2.88 (below neutral). Looking into how the participants responded to this question, all nine participants with prior experience mostly responded with a rating below 2 (*somewhat disagree*), while the other 22 rated a score above 4 (*somewhat agree*). In other words, the learning curve in developing designs using XR techniques may not be readily apparent while viewing the 3D sketch in VR/AR. Still, the nine designers showed with their lower rating on the learnability of the system that VR may be less valuable than using traditional 2D techniques. Research by Trudel (2020) suggested that VR applications need to include considerations in their design development to support the learning challenges associated with VR techniques compared to techniques using traditional tools (pp. 4) [52]. In Trudel's research, a VR research and development model is proposed to assess and support the design development of VR techniques for surgical training. The purpose of using VR is for the surgical learners to achieve mastery of the techniques that would be used in real life during surgical procedures—but VR adds a layer of learning the interaction techniques, before simulated surgical learning can begin. Fundamental to achieving any level of mastery is time and appropriate resources, which may vary between individuals based on their characteristics and abilities [52].

For the case of XR being adopted into the airline design workflow, its success depends on whether the designer is willing to build the skills and take the needed time to learn the techniques. Dahl et al. (2020) discussed the concept of *employee-driven innovation*, an umbrella term for employees' active participation in the development of new solutions [53]. *Employee-driven innovation* is when employees seek to explore potential benefits in new technology on their own time to improve their work processes. The conditions for employee-driven innovation are different in various organizations. Still, there are some key standard cultural features like engagement, trust, autonomy, safety, tolerance, and openness that promote employees' exploration of different workflow avenues of new products or systems.

Thus, is XR feasible for designers in the design process? It is, but it requires a trade-off of time and effort for the designers to build the skills and techniques to use the XR to its fullest potential. In this study, the XR techniques required roughly 150 hours for one sketch to be VR- and AR-ready for users to view, while the traditional methods only took 130 hours. In summary, for designers to adopt and accept any new technology into their workflow will require time to learn how to use the tools to benefit their work and satisfy their desired design goals for the project.

5.2 How to apply XR techniques into the early design workflow

The researcher's firsthand experience from this study has identified a promising best practice of applying XR techniques into the existing Design workflow shown in Figure 42. Overall, using traditional sketching techniques is best for the iteration of multiple concepts and the brainstorming phase of the design workflow (the green in Figure 42). Once a design direction is identified, the designer can the apply XR techniques (now in the blue of Figure 42). The design can be developed further in a 3D medium for early evaluation; this entails recreating the 2D sketch with VR sketching and following the workflow identified in section 4.1.2. With drawing in VR, the designer can develop the design and brainstorm the concept further by applying anthropometric sketching theory to the process as discussed in section 5.1.2. Once the 3D sketch is considered ready to be reviewed, a VR and AR simulations can now be developed to distribute to the users to evaluate the preliminary concepts remotely and provide feedback on the current state of the design solution. Once feedback has been retrieved and applied to the design concept, the design can move to the next step of development, when a physical prototype can be developed for onsite testing.

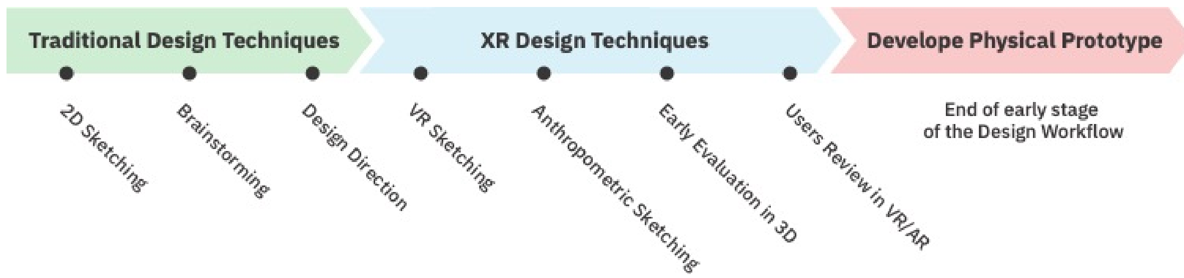

FIGURE 42 DESIGN WORKFLOW WITH THE IMPLEMENTATION OF XR TECHNIQUES

5.3 Research contribution of XR for remote studies

The study design demonstrates the potential of using XR techniques as a methodology for the user to participate remotely and asynchronously. Having the participants use an XR method (VR or AR) to contribute independently and from their workspace aligns with the identified benefits discussed in Chapter 2 Background and literature review. The benefits of using XR as a tool for research include; the ability for the participants to contribute to the study on their own schedule and avoid the scrutiny of the planning logistics of onsite user testing sessions [9]; the participant can still contribute meaningful insight regardless of the quality of the VR hardware that they own (Google cardboard versus HTC Vive Pro) [5]; and VR and AR simulation of early design concepts can help reduce the cost and production time to produce physical porotypes used for the soul-purpose of gaining user feedback of the CMF and usability of the product design [2, 4].

A unique finding from this experiment is that the non-designer group was able to use XR independently with no technical issues and in the SUS showed that they prefer using the XR system to view the concepts rather than the traditional 2D sketch system. A non-designer participant sent a follow up email after they conducted study with enthusiasm of their experience with the following quote: "*It was cool having a plane seat in my room. Did not know AR can do this and it was fun to see.*" Additionally, the participant included a video of their interaction with the chair in AR, shown in Figure 43, where the participant's friend pretends to sit and fall on the augment chair.

FIGURE 43 EMAILED VIDEO FOOTAGE OF PARTICIPANT INTERACTING WITH THE AR CHAIR

5.4 Limitations

In each phase of the research, some limitations need to be acknowledged that may have driven the results. For phase one, the independent sketching experience was conducted by the researcher working independently and remotely. The data collected in the journaling memos of the researcher's experience is subjective of the events that occurred during the 2D and 3D sketching sessions and may not be generalised for other designer experiences. Additionally, the method used to publish the 3D sketches for VR and AR simulation viewing was limited to the software and computing capabilities available to the researcher working from home.

There are numerous methods to develop a publishable AR and VR simulation. The publishing method used for this research was based on the researcher's experience with the tools in Keyshot, Unity3D, and Blender software to work with 3D sketches exported from Gravity Sketch.

In phase two of the research, one of the limitations of the data collected for this study is the sample size of both groups for the SUS survey. Like most surveys, the data collected may lack validity depending on the timing of distribution, participant size, and how the distribution of the study was conducted. The discretion that decided when the survey collected enough participants was when the research saw that the designer group gender distribution was identical (N=40, 20 female and 20 male). Ending the distribution of the survey for this condition affected the non-designer group size, with primarily female participants (N=41, 27 female, 13 male, and one who wished not to identify). Though gender was not examined as a factor for the results, the rationale for the participant to share this information was for the researcher to be aware if the data was non-homogenous. The participant size goal was to have a nearly even distribution of participants; thus the results could represent the population and not have a gender bias.

For the TAM questionnaire of the 40 designer participants, only 31 continued to complete the first questionnaire, "*XR System Techniques"*, and only 9 participants completed the "*Actual use of XR System Techniques*" questionnaire. As mentioned in the results, section 4.3, most of the participants that did not complete the TAM selected that their field of design is not Industrial Design or Engineering. It is presumed that these participants found the questioner statements were irrelevant to their field and thus did not complete the survey.

Additionally, the TAM questionnaire only had 31 participants to provide insight, which is not a large enough participant pool to make a conclusion on the user acceptance of the technology following the Davis TAM model methods [43]. Ideally, both TAM questionnaires would have a minimum of 50 participants to draw statistical significance of the user perception of XR techniques for the design workflow.

The goal of the participants' insight from this study was to better understand their perception of XR as a tool for the early stage of the design workflow. The SUS and TAM show a quantitative evaluation of the participant experience using the techniques but lacks qualitative analysis. To better judge how XR can impact the design process for designers and non-designers would involve collecting more heuristic data by interviews. The original plan of this study was to conduct interviews with 5 participants from each group to gain more insight into their perception of XR for design, but this plan was deferred due to timing and lack of participants volunteering for these interviews. The next step of this research is to complete these interviews for future publication and gain designers' views on how XR can be placed in the design workflow for future work.

5.5 Future work

The finding of this research is the starting point of an ongoing research project, Aviation Future Initiative, a collaboration with the National Research Council (NRC) and the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR). Their research aims to identify how XR implementation into their workflow can improve their design process for both the designers, researchers, and future participants for future user testing studies. Moving forward from the research would entail testing XR in the next step of the design workflow, which on the TRL and Double Diamond model is having participants test and interact with a prototype version of the design.

The most conceivable next step of this study is to apply the VR sketches into a more dynamic VR simulation that allows more user interaction (as in to be able to move around and interact in VR). This will allow for more interaction while viewing the sketch rather than the current static viewing of the stereoscopic simulation (as described in section 3.2.3).
In this study, we evaluated if the user could view and evaluate 3D medium sketches using either VR or AR techniques independently and remotely. Moving forward will be to assess if users of both groups will be able to view a more complex simulation, which may require higher quality VR hardware and more willingness from participants to install/set up the simulation.

The next step for airline VR sketched concepts is to evaluate if these 3D medium drawings could be used with existing aircraft interior simulations that the NRC and DLR are currently using for testing – test if the VR drawings could work cohesively with the existing sophisticated testing software. In the work of Haocheng *et al.* (2010), software simulated the ground handling area to investigate human factors considerations in airport workers' handling of passengers' luggage from baggage vehicle into the plane, and the researchers reported issues related to various CAD formats [8]. The software did not run as smoothly as they anticipated since some of the CAD models provided did not share the same file formats (e.g., STL, OBJ, FBX, SLDPRT). This created limitations in what they could run in the simulation and limited what 3D models could be tested. Due to this error the software was never launched for professional use.

Using VR simulation lacks tangible interaction when reviewing a prototype. For obvious reasons developing a 3D prototype will provide more tactile but, as mentioned in section 2.1.3, is not widely practiced since there is an immense cost to produce physical prototypes. The study conducted by Felip *et al.* (2020), discussed in section 2.3, created a simulation to evaluate a chair design using mixed reality techniques [2]. Felip *et al.* designed their study where the participant would wear a VR headset to view a visual simulation of the design but still have a physical chair for the user to touch and interact with. The implication from the Felip et al. study is that VR and MR techniques have the potential to help produce low-fidelity prototypes that can be augmented digitally. Galan et al. (2021) explore this concept further by researching the adaptability and flexibility that VR offers with tangible and haptic feedback to review household product characteristics using different visual methods [54]. The study was designed to evaluate two different presentation means; a real setting versus a VR simulation with passive haptic feedback (MR). Data was collected from 128 participants to evaluate their interactions with tangible elements combined with VR. The results revealed that the presentation means did not influence the overall product assessment. Gala et al.'s findings imply, similar to Felip et al., that using MR techniques shows promise to conduct user testing for product design using virtual simulation techniques.

Chapter 6 Conclusion

The goal set out by this research is to evaluate the advantages and disadvantages of using XR techniques in the early development phase of air travel design. The literature research has shown how some XR systems can replace traditional methods used in the design workflow, such as focusing on the early development sketching, prototyping and evaluation stages of the early design process. Additionally, the literature review identifies a gap in the research of VR sketching for the early phase of brainstorming concepts and sharing these 3D medium sketches with users for review.

In summary, phase one of the study identifies the dilemmas where VR technology currently stands as a tool for developing 3D sketches with developing accurate sketches, being creative during the process, and publishing the drawings to share with others for review. The use of VR sketching does have other benefits, with its ability for the designers to be immersed in the VE and sketch around their figure or existing products to create an anthropometrics outline that is to scale - which cannot be done using traditional sketching techniques. Phase two insight shows that non-designers rated the SUS of the 3D medium system higher than the 2D system. In contrast, the designer participants only rated the 3D system higher when it was shown first in the design review. Both groups overall placed both medium experiences as a positive interactive experience. Still, the designer group was able to recognise the potential negative impact of the learning curves involved in using XR technology for their workflow through their responses from the TAM questionnaire.

This research was designed to investigate the practical implementation of XR as a tool for a design workflow. The following discusses the key findings from the results, the limitations of the study, as well future work of this research.

6.1 Summary of key findings

Overall, this study identifies the perks and dilemmas XR may have as a tool in the early stage of the design workflow. The following is a summary of the key findings from this research:

1. *What is the experience of design sketching in VR compared to traditional methods?*

   The researcher discovered that using VR for sketching shows the potential to efficiently draw with a more 'human-centred design' mind-set by creating anthropometric skeleton sketches that reflect real world ergonomic conditions. The 3D sketching techniques present learning curves in drawing in 3D, which interfere with being creative and finding solutions while drawing. Additionally, VR sketching sessions can be easily disrupted compared to traditional methods; internal factors such as cybersickness and external factors such as the sketching environment temperature need to be considered. But these dilemmas can be preventable with pre-awareness of these events and making plans to make them preventable.

2. *What advantages and disadvantages does XR (VR/AR) offer in the early stages of design and TLR workflows?*

   Evidence shows that XR can make human-centred design more efficient and accessible for non-designers to be involved in the workflow. This benefit is an asset for air cabin design workflow since VR allows designers to easily sketch out concepts that reflect anthropometric considerations in an air cabin. Additionally, the ability to share concepts remotely through VR/AR with end-users creates more accessibility for the users to share their thoughts on the design, which hopefully can help generate more solutions to a make the inflight experience more comfortable. However, VR has a disadvantage in publishing accessible content efficiently for users to view 3D sketches, but publishing in AR has proven to be a more feasible method.

As for the participants' experiences in viewing sketches in VR/AR, the non-designers rated the usability of the 3D medium system to be more usable compared to traditional methods of 2D sketches. The designers group rated the traditional 2D medium system to be more usable compared to the XR option. Designers are aware of the learning curve involved with building their skills and working with XR as a tool. Thus, designers accepting XR technology into the air cabin design workflow may not be adopted or work effectively as traditional techniques (such as iterating ideas using 2D sketching methods).

3. *Considering the limitations of physical distancing measures during the COVID-19 pandemic, what are the potential benefits and barriers of using XR (VR/AR) for remote design?*

   Both VR and AR have proven to have the potential opportunity of sharing early design concepts with end-users remotely. Using XR allows non-designers to have more accessibility to view the design and provide feedback in the earlier stage of the workflow compared to traditional onsite user testing sessions. Barriers to using XR are the time and tools to publish the sketches to be viewable in a VR or AR simulation and work on the variety of HMD available on the market (i.e., Oculus and Google Cardboard HMD).

6.2 Final remarks

Imagining the opportunities of XR for the design workflow, with a focus on developing ideas and early prototypes, can be endless since the emerging technology techniques show many hopeful insights into the replacement of many traditional methods in the design process. Though XR technology may seem appealing to adopt with the impression of the technology being feasible, it is crucial to understand the users, both designer and non-designer, perception of the technology and if the XR system is easy to manage independently and remotely. This study identifies the perks of the user experience while sketching in VR and how VR/AR can bring non-designers closer to the design workflow. This asset should be enough to attract aerospace designers to adopt XR technology to make their design projects more collaborative with the user they are tasked to design for to find the best design solution for the users' needs for air travel.

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Appendix A Pre-Screening Questionnaire

Appendix A.1 Consent Form

Name and Contact Information of Researchers:

Samantha Astles, Carleton University, Master of Human-Computer Interaction

Email: samantha.astles@carleton.ca

Supervisor and Contact Information:

Prof. Chantal Trudel, Carleton University, School of Industrial Design.

Email: chantal.trudel@carleton.ca

Phd. Shelley Kelsey, Carleton University, School of Industrial Design and National Research Council

Email: shelley.kelsey@nrc-cnrc.gc.ca

Project Title:

Evaluating XR Sketching as a Technique in Air Travel Design and Early Stages of the Technology Readiness Level (TRL) Method.

Carleton University Project Clearance:

Clearance #: 115459   Date of Clearance: June 23, 2021

Invitation:

We are asking you to complete this survey because of your experience as a designer or a general user capable to provide design feedback on concept sketches in air travel design. This survey is being conducted by Samantha Astles a Carleton University, Candidate for a Master of Applied Science in Human-Computer Interaction (samantha.astles@carleton.ca, working under the supervision of Chantal Trudel and Shelley Kelsey

Objectives and Summary:

The purpose of this study is to evaluate the effectiveness of reviewing design concepts remotely, specifically through two mediums: traditional 2D slideshows of rendered concepts and 3D Extended Reality (XR) simulations of sketches drawn in a virtual reality (VR) model. You have the option on viewing the VR model with your own VR head mounted display or using you smartphone to view it with Augmented Reality (AR). We are interested in understanding your thoughts on the use of these mediums for developing design concepts and participating in evaluating concepts. The concepts you will be reviewing focus on aircraft designs in response to the COVID-19 pandemic. Please note these concepts are fictional and will not be implemented into production as a future product. After viewing the concepts, you will be asked to complete a short 5-to-10-minute System Usability Survey (SUS). If you are a Designer, you will be asked to also complete a short Technology Acceptance Model (TAM) survey. At the end of the survey, you will be invited to participate in a 30-minute interview session over a video call chat that will be scheduled at your convenience. This interview session is optional if you wish to continue helping us with this study.

Compensation:

By participating in the survey, you will be automatically entered into a draw for $50 Amazon Gift Card, chances of 1 in 100. Interview participants will also be entered in a separate draw for the chance to win another $50 Amazon Gift Card, chances of 1 in 20. To participate in the interview, you will be asked to leave your name and preferred email for contact. This information will be kept confidential and will not be affiliated with your response to the survey.

Risks and Benefits:

Please note the VR simulation will involve viewing the concept in a static model, thus cyber or motion sickness should not be present, or at the very least, should be limited. The VR simulation has no locomotion or traveling but will require minor head movement. If you have a history of experiencing cybersickness, it is advised to not participate in the VR simulation of the survey and to do the AR option instead.

If you do experience cyber or motion sickness in the VR simulation, please do not feel obligated to complete the survey. In the unlikely event that you experience extreme cybersickness and continue to feel ill after the survey, and you are a member of the Carleton University Community, we invite you to contact Carleton University's Health and Counseling Services at: 613-520-6674, or the Distress Centre of Ottawa and Region at 613-238-3311 (http://www.dcottawa.on.ca) for counselling services. If you are not a member of Carleton University, it is advised that you reach out to your family physician or contact the nearest Healthcare Clinic. It is advised to not drive or operate a vehicle if you are experiencing sever cybersickness.

Anonymity and Data Storage:

Your data will be stored and protected by Qualtrics in Loudoun County, Virginia, but may be disclosed via a court order or data breach. The data collected in this survey is anonymous. The results of this study may be published, but your particular contributions will be anonymous. After the survey is downloaded, all the research data will be encrypted and stored in the researcher's password-protected computer and any hard copies of data will be kept in a locked cabinet in the researcher's home. After the study is completed, we will retain your anonymous data for future research use for a period of 5 years.

For the interview recording, your data will be stored and protected by Zoom in their serves hosted in Mountain View, California. In-session" data, such as the audio, video and chat transcript from the interview, will be stored locally on the researcher's computer. Operation data, such as meeting and performance data, will be stored and protected by Zoom on servers located in Mountain View, California, but may be disclosed via a court order or data breach.

Your response to the survey will be coded to keep your identity confidential for the research and thesis report. Your identity will not be anonymous if you choose to participate in the compensation raffle to win the gift card and to participate in the interview phase.

Withdrawal procedure:

You can withdraw at any point throughout the survey and will still receive the compensation. All your data will be discarded and deleted from the research.

To withdraw from the survey and interviews, you can connect with the researcher via email, at Samantha.astles@carleton.ca, within 2 weeks of your data being collected in the survey consent. The researcher will remove and delete/destroy your name after the compensation draw for the gift card is complete and distributed.

REB Review and Contact Information:

This project was reviewed and cleared by the Carleton University Research Ethics Board. If you have any ethical concerns with the study, please contact the Carleton University Research Ethics Board by email at ethics@carleton.ca.

Direct consent:

☐ Yes, I voluntarily agree to participate in this study.

☐ No, I do not wish to participate in this study.

Appendix A.2 Demographics

Q1. What is your age range?

☐ 18 – 24

☐ 25 – 34

☐ 35 – 44

☐ 45 – 54

☐ 55 – 64

☐ 65 and above

Q2. What gender do you identify as?

☐ Male

☐ Female

☐ Non-binary / third gender

☐ Prefer not to say

Q3. What level of education have you completed?

☐ High School

☐ College Degree

☐ Bachelor's Degree

☐ Master's Degree

☐ Ph.D. or higher

☐ Trade School

☐ Prefer not to say

Q4. Do you work in the field of Design?

☐ Yes

☐ No

** Only participants respond <u>No</u> to the question above, "Do you work in the field of Design?" will be prompted to the following question:*

Q5. What is your occupation?

[insert text box] *participant will key in their occupation*.

**Only participants that answer <u>Yes</u> to the question "Do you work in the field of Design?" will be prompted to the following question:*

Q6. What field of design do you work in? (select as many as needed)

☐ Architecture

☐ Engineering

☐ Graphic Design

☐ Game Design

☐ Human Computer Interaction

☐ Industrial Design

☐ Information Design

☐ Interaction Design

☐ Interior Design

☐ Service Design

☐ User Experience Design

☐ Other and please specify: [insert text box]

**Only participants that answer <u>Yes</u> to the question "Do you work in the field of Design?" will be prompted to the following question:*

Q7. How many years of experience do you have in the field of design?

☐ Less than 1 year

☐ 1 - 3 years

☐ 4 - 10 years

☐ 11 - 20 years

☐ More than 20 years

Appendix A.3 Familiarity and frequency of VR/AR/XR

Q8. How familiar are you with the concept of Virtual Reality (VR) technology? Please choose the response that best describes your familiarity:

☐ "I am aware and frequently use VR."

☐ "I am aware and occasionally use VR."

☐ "I am aware of VR but have never used them."

☐ "I have never heard of VR."

☐ None of the above

Q9. How frequently do you use Virtual Reality (VR) technology?

☐ More than once a day

☐ Once a day

☐ Once a week

☐ Once a month

☐ Once a year

☐ I have yet to experience VR

Q10. How familiar are you with the concept of Augmented Reality (AR) technologies? Please choose the response that best describes your familiarity:

☐ "I am aware and frequently use AR technology."

☐ "I am aware and occasionally use AR technology."

☐ "I am aware of AR but have never used this technology."

☐ "I have never heard of AR."

☐ None of the above

Q11. How frequently do you use Augmented Reality (AR) technologies?

☐ More than once a day

☐ Once a day

☐ Once a week

☐ Once a month

☐ Once a year

☐ I have yet to experience VR

Q12. How familiar are you with the concept of Extended Reality (XR) technologies? Please choose the response that best describes your familiarity:

☐ "I am aware and frequently use XR technologies."

☐ "I am aware and occasionally use XR technologies."

☐ "I am aware of XR but have never used this technology."

☐ "I have never heard of XR."

☐ None of the above

Appendix B Design Review and System Usability Scale (SUS) Survey

For this section the participant has reviewed two design concepts presented in two different mediums. The 2D sketches was presented in a PDF gallery slideshow within the Qualtrics survey platforms. The 3D virtual reality sketches were accessible by a link to a 3D simulation viewing platforms via Unity3d Publishing Developers platform and online emulator using a head mounted display (HMD) owned by the participant and the participant also had the option to view the 3D virtual sketches using their smart phone where they can scan a QR to view an Augmented Reality (AR) version of the design.

**The logic of the survey design is that the participant will view the design on one medium, then proceed to the SUS survey. Once this is complete, they will then view the design in the alternate medium and then proceed to the same SUS survey. After these tasks are completed, general participants will submit the survey and be asked if they would like to participate in a follow-up interview. Designer participants will be asked to complete an additional TAM survey, submit, and also asked for their participation in a follow-up interview.*

Q13. For the following section, please select which statement matches your experience while reviewing the design in the two mediums:

SUS Survey

	Highly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Highly Agree
I found the system easy to use.					
I found the system unnecessarily complex to use.					
I think that I would like to use this system frequently.					
I think that I would need the support of a technical person to be able to use this system.					
I found the various functions in this system were well integrated.					
I thought there was too much inconsistency in this system.					

I would imagine that most people would learn to use this system very quickly.					
I felt very confident using the system.					
I needed to learn a lot of things before I could get going with this system.					

* *The following question is to reassure the research which medium was presented to the participant first for their results section.*

Q14. What was the medium presented to you first?

☐ 2D PDF Sketches

☐ 3D VR Sketches

Q15. Which Extended Reality option did you view the 3D medium?

☐ I used the VR option only.

☐ I used the AR option only.

☐ I used both the VR and AR options.

Appendix C Technology Acceptance Model (TAM) Questionnaire

Q16. For the following sections, please select which statement matches your opinion on using XR technologies - Virtual Reality (VR) and Augmented Reality (AR) as a tool for the design.

Usefulness Items of Technique Performance (Revised 6 Davis Version, 1989)

	Highly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Highly Agree
Using XR techniques in my job would enable me to accomplish tasks more quickly.					
Using XR techniques as a tool would improve my job performance.					
Using XR techniques in my job would increase my productivity.					
Using XR Techniques would enhance my effectiveness on the job.					
Using XR techniques would make it easier to do my job.					
I would find XR techniques useful in my job.					

Ease of Use Items of Techniques Performance (Revised 6 Davis Version, 1989)

	Highly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Highly Agree
Learning to operate XR techniques as a tool would be easy for me.					
I would find it easy to get XR techniques to do what I want it to do.					
My interaction with XR techniques would be clear and understandable.					
I would find XR techniques to be flexible to interact with.					
It would be easy for me to become skillful at using XR techniques.					
I would find XR techniques easy to use.					

Q17. Do you currently use Extended Reality (XR) technologies in your work? (XR is an umbrella term that refers to Virtual Reality, Argument Reality, Mixed Reality, and more.)

☐ Yes

☐ No

* *Only participants that respond <u>Yes</u> to the question above, "Do you* currently use XR technologies in your work? *will be prompted to the following question:*

Q18. For the following sections, please select which statement matches your perception of using XR technologies - Virtual Reality (VR) and Augmented Reality (AR) as a tool for your work.

Perceived Usefulness Items Systems (Davis Method, 1989)

	Highly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Highly Agree
Using XR systems improves the quality of the work I do.					
Using XR systems gives me greater control over my work.					
XR systems enable me to accomplish task more quickly.					
XR systems support critical aspects of my job.					
Using XR systems increases my productivity.					
Using XR systems improves my job performance.					
Using XR systems allows me to accomplish more work than would otherwise be possible.					

Using XR systems enhances my effectiveness on the job.					
Using XR systems would make it easier to do my job.					
Overall, I would find the XR systems useful in my job.					

Perceived Ease of Use (Davis Method, 1989)

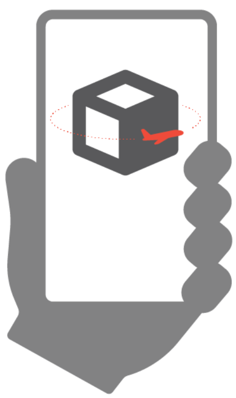
	Highly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Highly Agree
I find it cumbersome to use XR systems.					
Learning to operate XR systems is easy for me.					
Interacting with a XR systems is often frustrating.					
I find it easy to get XR to do what I want it to do.					
XR systems is often rigid and inflexible to interact with.					
It is easy for me to remember how to perform tasks in XR systems.					

Interacting with XR systems requires a lot of my mental effort.					
My interaction with XR systems is clear and understandable.					
I find it takes a lot of effort to become skillful at using XR systems.					
Overall, I find XR systems easy to use.					

Appendix D Study recruitment poster

Air Travel Design Review Survey

Evaluating Sketches presented in a 2D and 3D Medium

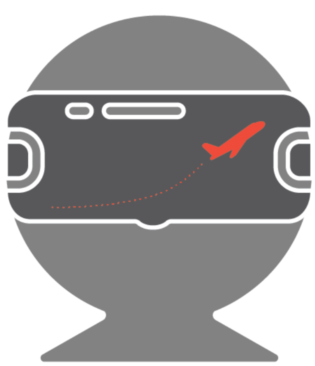


Survey Link:
https://carletonu.az1.qualtrics.com/jfe/form/SV_88iUCR2sGRMYw2a

This is a 15-minute online survey where we asked you to evaluate two air travel design concepts presented in two different mediums - a slideshow showing 2D sketches and a 3D Virtual Reality and/or Augmented Reality simulation showing 3D sketches.

This survey is being conducted by Samantha Astles at Carleton University, candidate for a Master of Applied Science in Human-Computer Interaction (samantha.astles@carleton.ca) working under the supervision of Professor Chantal Trudel and Dr. Shelley Kelsey.

To participate in the survey, it require you to have access to a VR Head Mounted Display (HMD): a Google Card Board HMD used with your smartphone, Oculus Quest or Rift, HTC, and more. As a compensation, your name will be entered in a raffle (1/100) to win a $50 Amazon Gift Card. If you have a history of cybersickness, it is advised that you should not participate in the VR potion of the Study.



The ethics protocol for this project has been reviewed and cleared by the Carleton University Research Ethics Board. If you have any ethical concerns with the study, please contact the Carleton University Research Ethics Board-B by email at ethics@carleton.ca.

Project number 115459.

Please contact the researcher, Samantha Astles, for more details on this study at samantha.astles@carleton.ca

Thank you for the support.

Appendix E Carleton University Ethics Clearance

Carleton
UNIVERSITY
Canada's Capital University

Office of Research Ethics
4500 ARISE Building | 1125 Colonel By Drive
Ottawa, Ontario K1S 5B6
613-520-2600 Ext: 4085
ethics@carleton.ca

CERTIFICATION OF INSTITUTIONAL ETHICS CLEARANCE

The Carleton University Research Ethics Board-B (CUREB-B) has granted ethics clearance for the changes to protocol to research project described below and research may now proceed. CUREB-B is constituted and operates in compliance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS2).

Ethics Clearance ID: Project # 115459

Principal Investigator: Samantha Astles

Co-Investigator(s) (If applicable): **Samantha Astles (Primary Investigator)**
Chantal Trudel (Research Supervisor)
Shelley Kelsey (Research Supervisor)

Project Title: **Evaluating XR Sketching as a Technique in Air Travel Design and Early Stages of the Technology Readiness Level (TRL) Method.**

Funding Source:

Effective: **June 23, 2021** Expires: **April 30, 2022**.

This certification is subject to the following conditions:

1. Clearance is granted only for the research and purposes described in the application.
2. Any modification to the approved research must be submitted to CUREB-B via a Change to Protocol Form. All changes must be cleared prior to the continuance of the research.
3. An Annual Status Report for the renewal or closure of ethics clearance must be submitted and cleared by the renewal date listed above. Failure to submit the Annual Status Report will result in the closure of the file. If funding is associated, funds will be frozen.
4. During the course of the study, if you encounter an adverse event, material incidental finding, protocol deviation or other unanticipated problem, you must complete and submit a Report of Adverse Events and Unanticipated Problems Form.
5. It is the responsibility of the student to notify their supervisor of any adverse events, changes to their application, or requests to renew/close the protocol.

6. Failure to conduct the research in accordance with the principles of the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans 2nd edition* and the *Carleton University Policies and Procedures for the Ethical Conduct of Research* may result in the suspension or termination of the research project.

Special requirements for COVID-19:

If this study involves in-person research interactions with human participants, whether on- or off-campus, the following rules apply:

1. Upon receiving clearance from CUREB, please seek the approval of the relevant Dean for your research. Provide a copy of your CUREB clearance to the Dean for their records. See [Principles and Procedures for On-campus Research at Carleton University]() and note that this document applies both to on- and off-campus research that involves human participants. Please contact your Dean's Office for more information about obtaining their approval.

2. Provide a copy of the Dean's approval to the Office of Research Ethics prior to starting any in-person research activities.

3. If the Dean's approval requires any significant change(s) to any element of the study, you must notify the Office of Research Ethics of such change(s).

Upon reasonable request, it is the policy of CUREB, for cleared protocols, to release the name of the PI, the title of the project, and the date of clearance and any renewal(s).

Please email the Research Compliance Coordinators at ethics@carleton.ca if you have any questions.

CLEARED BY: **Date: June 23, 2021**

[redacted]

Bernadette Campbell, PhD, Chair, CUREB-B

[redacted]

Natasha Artemeva, PhD, Chair, CUREB-B

Appendix F QR code for AR and VR simulations

Augmented Reality Viewing:

To view a 1:1 scale AR version on your smartphone, click on the AR icon in the top right corner of the simulator to access the QR or scan the codes below:

Virtual Reality Viewing:

A stereo video can be viewed on your Smartphone with a VR Cardboard Headset following the QR code that is below. Or, if you have a VR Headset, key in the following TinyURL into your VR web browser of choice: https://tinyurl.com/f37hw2a8