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Evaluating XR Techniques in Air Travel Design for Early Technology Readiness Level

Samantha Astles[1], Shelley Kelsey[2], and Chantal Trudel[1]

[1]Carleton University, School of Industrial Design, 1125 Colonel By Drive, Ottawa, ON, Canada
[2]Centre for Air Travel Research, National Research Council of Canada, 1950 Research Private, Ottawa, ON K1V 1J8, Canada

ABSTRACT

This paper explores the benefits of implementing extended reality (XR) techniques, such as virtual and augmented reality, into the aircraft cabin design workflow. The study consists of two phases: first, we compare the lead researcher's first-hand experiences with virtual reality sketching and traditional sketching methods; and second, we evaluate the feasibility of using 3D sketches for design and evaluation. In this paper, we report on the results of phase one, in which we identify advantages and disadvantages of virtual reality for human-centered design based on first-person accounts. The data collected from phase one describes the researcher's qualitative experience of using VR tools for sketching and documenting the productive and unproductive factors for design. Phase 2 focuses on gathering feedback through the use of user-centric metrics regarding the acceptability and usability of XR sketching technique from two different user groups – designers and non-designers. Progres of phase 2 and proposed future work is discussed.

Keywords: Aircraft design, Virtual reality, Extended reality, Early stages of design, Industrial design, Human-computer interaction

INTRODUCTION

Designing for air travel can be a lengthy and expensive process, which interferes with rapid innovation (De Crescenzio et al., 2019; Haocheng et al., 2010; Moerland-Masic et al., 2020). Extended Reality (XR) is an emerging technology and a potential tool to support the creation of design concept sketches for remote review and evaluation (Nemire, 1998; Felip et al., 2020). In the field of air travel design, researchers, designers, and engineers have studied the use of XR (e.g., Virtual Reality, Augmented Reality) to support the design workflow by comparing XR techniques to traditional industrial design methods. Early steps in aerospace design, such as research and brainstorming, have largely employed traditional methods, including sketching concepts and eliciting user feedback on early development work (Moerland-Masic et al., 2020; Ban & Hyun, 2020). In recent years, XR tools have been adopted to augment the design process and help drive innovative solutions; such as using virtual

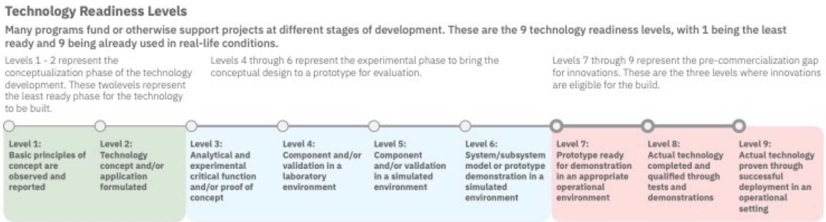

Figure 1: The technology readiness levels (TRL) with description of the design task.

(VR) and augmented reality (AR) for simulated architecture design (Milovanovic et al., 2012). To date, 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.

In response to this gap, the present study investigated the application of XR techniques to support the early stages of the aircraft design workflow 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 Technology Readiness Levels (TRL) framework (Fahimian & Behdinan, 2017). The study used VR as a tool for three-dimensional (3D) sketching and VR/AR hardware and software to engage users in evaluating the 3D design sketches generated using VR. The concepts generated were related to aircraft cabin concepts focused on a timely event—namely, creating design to support air travel during the COVID-19 pandemic.

BACKGROUND

The aircraft design process typically follows the Technology Readiness Levels (TRL) as a guideline for the development process and early design development task (Fahimian & Behdinan, 2017; Tschimmel, 2012). 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 ready for actual real-world use. In the TRL model (Figure 1), 40% to 60% of the design development time is spent on Level 3 to 4, where the tasks consist of brainstorming concepts, sketching, 3D modelling (with software), and prototype testing before entering an onsite simulation testing phase (Clergeaud et al., 2017; De Crescenzio et al., 2019).

The aircraft design process can be time-consuming and expensive, even before concepts are evaluated in real physical or high fidelity simulated environments. Some of the limitations of these methods include: the difficulties of collaborating remotely with team members to develop preliminary concepts (Haocheng et al., 2010), the prohibitive cost of conducting early evaluations or usability testing with participants (De Crescenzio et al., 2019), and the inability to conduct remote participatory design sessions (Clergeaud et al., 2017). These limitations were acceptable until the COVID-19 pandemic presented conditions that accelerated interest in new processes to support remote design across interdisciplinary teams and evaluation by end-users.

XR is a promising technology to help address some of the current issues in aircraft design. Given recent improvements in computer-aided design (CAD) for VR, sketching software now has the potential to enhance the early development phase of air travel design and 3D modelling by increasing cohesion and efficiency (Israel et al., 2009; Rahimian & Ibrahim, 2011; Ban & Hyun, 2020). For instance, 3D concepts can be realized early in the design process, and the designers can be more immersed at the conceptual stage of design. As opposed to passively viewing static 2D drawn concepts or rendered images, 3D images can be manipulated by the designers in real time (Israel et al., 2009; Rahimian & Ibrahim, 2011). The immersive aspect of virtual environments (VEs) can 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 for e.g., importing a classroom (Israel et al., 2009) or aircraft cabin environment in which a particular concept (i.e. a seat) being developed will most likely be placed.

Another advantage of XR technology is that it can support enhanced participation by designers and end-users during testing by providing an active conceptual model earlier in the design process. As part of obtaining user feedback, designers traditionally develop a prototype to present the idea to the participant to help them visualize, interact with, and think about the concepts (Israel et al., 2009; Ban & Hyun, 2020). Prototypes can facilitate and streamline conversation between the designer and users, 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 an increased time and cost investments to produce it. With XR, there is a potential for a reduction in both, the time it takes to develop a concept and the cost accrued due to the development process (Haocheng et al., 2010; Nemire, 1998; Rahimian & Ibrahim, 2011).

Apart from the above benefits, physical distancing measures due to the COVID-19 pandemic halted in-person collaboration and user evaluation studies, which made XR a more attractive option. Among other things, XR has the potential to 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 may benefit design teams to help them reach or diversify user participation to provide insight during the early stages of design development.

PHASE 1 - METHODOLOGY

The study was designed to mimic a typical design task in the TRL Level 3 to 4 of a designer working independently (i.e., not in a team-based environment) using traditional design practices and XR technology. The designer was the

Figure 2: The VR appartus: Logitech VR ink pen, HTC cosmos, and valve index Pro.

lead researcher (henceforth, "the researcher") who assessed and reflected on their own experience of using VR as a tool for design sketching.

The data collected from phase one consisted of the researcher's journal entries about their first-hand account with VR sketching versus traditional 2D sketching techniques. The design sketching brief was to generate aircraft cabin concepts with partitions between seats to physically separate passengers during the COVID-19 pandemic.

Independent Design Sketching Experience

The researcher developed a test set up 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 concept drawings. The sketching task was assigned a 130-hour time restriction for each medium (total of 260 hours).

Apparatus

Traditional 2D sketches were created 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).

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 × 1700 pixels per eye (2880 × 1700 pixels combined), a 90Hz refresh rate, and a 110- degree field of view (developed by HP Inc. model number 99HART000-00) (shown in Figure 2). The controller was a single Valve Index Pro that was used as an eraser tool (or undo/redo actions) and acted as a secondary pointing device for navigating the user interface throughout the study (shown in Figure 2). 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) (shown in Figure 2). 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 used was Gravity Sketch (ver. 2021).

Procedure and Analysis

The researcher kept a document to record memos about their experience throughout the sketching process. The memos were time-stamped and wrote the detailed the event-code that occurred while sketching (e.g., technical issues), the activity-code completed while drawing (e.g., free drawing, tracing, rendering, etc.), and the think-code about what the researcher was doing and/or thinking during the task. The memos provided insight on the advantages and disadvantages of using VR versus traditional sketching methods.

The memo of the activity provided a first-hand recording of elements that influenced the researcher's experience of using VR techniques in contrast to traditional methods in the design workflow. Using qualitative research software NVivo (version 2020), themes and patterns in the memos were first uncovered using the word frequency query tool to identify reoccurring keywords. The researcher then organised the common keywords and summarised the time and event themes illustrated in an infographic.

RESULTS

This study explored the user experience of design sketching in VR compared to traditional methods. The following sections present preliminary results based on the researcher's memos about their sketching experience. Findings include identification of factors that contributed to a productive and unproductive sketching session for both traditional 2D sketching and VR sketching.

Sketching Outcomes

A total of four concept sketches, two 2D sketches and two 3D sketches (shown in Figure 3), were deemed by the researcher to be of acceptable quality for use in the following phase of the study, discussed later in this paper. The researcher had memos documenting their sketching experience throughout the various segments of the sketching workflow as well as factors that impacted it. The 2D sketching experience was divided into two linear infographics representing a *Productive* session versus an *Unproductive* session (Figure 4). The same procedure was followed for the 3D sketching experience, though the experience was summarized in three infographics; one *Productive* sketching session and two *Unproductive* sketching sessions.

One *Unproductive* session related to *Internal Factors* (e.g., dilemmas in the simulation) and the other to *External Factors* (e.g., hardware issues) that influenced the sketching session (Figure 5). These infographics identify and explain some of the advantages and disadvantages the researcher identified with the various drawing tasks and stages of the sketching workflow.

Traditional 2D Sketching Experience

A *Productive* 2D sketching session ran for roughly five hours, as shown in Figure 4. There were small breaks during the session, lasting 15-30 minutes, during which the researcher planned next steps to take after they returned

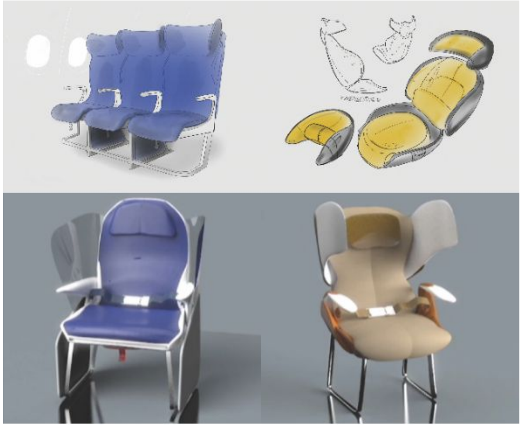

Figure 3: Final selected sketches used for phase two of the study.

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 spent not 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 consisted 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 of the scenario (e.g., a human figure for scale or airline cabin fuselage to clarify the environmental setting). These tasks were often challenging since they made 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 two or more hours of a *Productive* session was spent rendering and finishing the sketch by applying colour and shading.

An *Unproductive* 2D sketching session lasted on average 2.5 hours or less. These sessions were shorter, as the researcher did not want to spend too much time sketching non-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 of perspective lines[1]. 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 these issues took anywhere from one minute to half an hour each time, and the trend was that the researcher took a break afterwards before resuming sketching

Overall, sketching time in 2D environment was largely 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 produce design ideas.

[1]Drawing construction perspective lines helps the designer to construct the volume and form to match the perspective vanishing points.

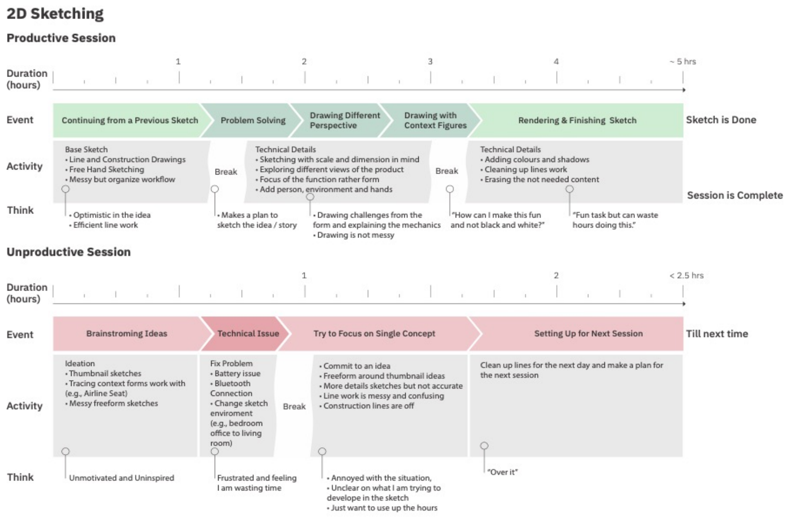

Figure 4: Infographic displaying the summary of the 2D sketching workflow xperience.

VR 3D Sketching Experience

The second half of this exploration involved recreating the design described above, this time using VR sketching. There was an initial learning curve involved in sketching in VR compared to traditional methods—namely, using the software and 3D sketching techniques. The researcher had several years of experience prior to this study developing drawings using 2D techniques, but VR sketching was a new experience and required an 'onboarding' stage. Sketching in VR posed limitations similar to those a designer might face when learning how to develop CAD in a 3D modeling program for the first time. In the early stages of the researcher's VR sketching, while they were still learning the basic tools of the Gravity Sketch software, they created multiple designs that appeared very robust and featured hard edges.

As shown in Figure 5, a *Productive* 3D sketching session in VR was one that had few interferences to the workflow. The session started with developing a 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 (Paes & Irizarry, 2018). These breaks were considered important to avoid fatigue or injuries since the researcher was anticipating sketching sessions of 4+ hours each. 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).

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

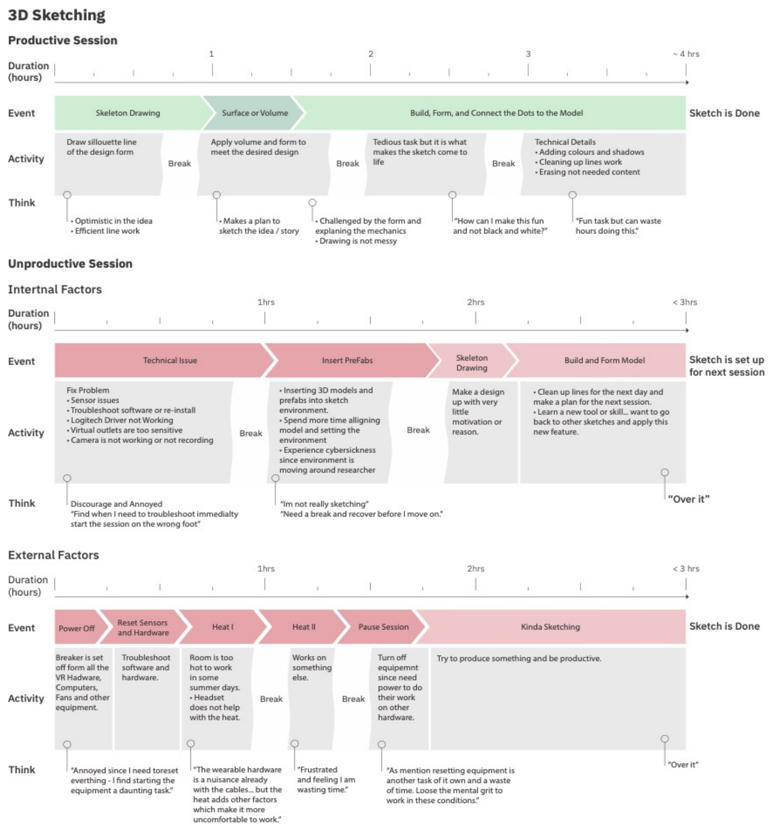

Figure 5: Infographic displaying the summary of the VR sketching workflow experience.

to make the final design more life-like and avoid robust or flat forms in the design. This task was the most time consuming and tedious to complete since it required manipulating 3D model polygons, edges, points, and solids volume to appear as the desired shape and form.

An *Unproductive* 3D sketching session due to *Internal Factors* was one where the researcher's sketching was interrupted by software issues. The researcher's memos indicate that these sessions had immediate technical issues, such as the software needing to be updated, cameras not recording the VR sketching simulation, sensors not detecting the hardware, Logitech VR Ink pen not being recognized in the VE, and the Logitech Ink pen driver not responding to the VIVE software.

Additional dilemmas caused by *Internal Factors* arose in some sketching sessions where the researcher inserted a prefabricated CAD model. Setting up the models in the VE presented challenges with aligning the CAD parts since there were no planes in the VE. 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; Keshavarz et al., 2015). While sketching with the prefabricated set-up in the

Figure 6: Example of researcher drawing an anthropometric sketch.

VE, the researcher was constantly moving the prefabricated parts to be able to sketch in specific areas, thus creating the illusion that the environment was moving while the researcher was sitting still. When the researcher became too nauseous to keep sketching, they took a 15-minute break.

Some *Unproductive* sessions were interrupted by *External Factors*, such as those related to the location in which the VR sketching occurred. VR sketching was done in the researcher's apartment due to physical distancing protocols related to COVID-19. An *External Factor* was the environment's 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 thus sketched for shorter time periods, taking many breaks, or postponing the session to a day when the ambient temperature was more tolerable.

DISCUSSION

This paper discuss the procedure and the researcher first-hand account of developing early concept for aircraft design using VR compared to traditional 2D methods. Based on the researcher's experience, VR sketching has the potential to support designers to brainstorm concepts that facilitates more human-centered needs in the early stage of the TRL model using more intuitive techniques compared to traditional 2D sketching methods. While first learning the VR sketching techniques to draw the chair, the researcher applied the dimension of their own office chair into their drawing (Figure 6). Outlining their office chair created a skeleton form of the seat to the approximate scale of an air cabin seat size and dimensions. This technique allowed the researcher to draw in 3D an orthogonal layout of the seat height and width based on accurate measurements and proportions. Drawing an orthogonal layout by referencing a real source object as an 'underlay' allowed the researcher to create more anthropometric appropriate skeleton sketches.

This discovery suggests that VR sketching could benefit from using mixed reality to create an outline or skeleton of sketch dimensions referencing ergonomic dimensions and proportions while drawing. Designers could then sketch concepts around anthropometric requirements for a product design, revealing future potential to introduce human factor procedures, such as including anthropometric requirements, earlier in the brainstorming stage of the design workflow (De Crescenzio et al., 2019).

The 3D skeleton sketch demonstrated perhaps the most valuable aspect of VR sketching: creating anthropometrics sketches for human-centered design.[2] Anthropometric data is used to design products to meet ergonomic and other human factors requirements. Therefore, a potential benefit of VR sketching for human-centered design, in the scenario where a user is in a VR simulated testing set-up, is that they have the ability to draw around their own body and add their design criteria to meet anthropometric requirements. The work of Crescenzago et al. (2019) identified that a more efficient human-centered design testing medium is needed, one that affords the user to "foresee the capability of a specific cabin interior design of meeting the user's expectations, including the needs related to comfort and well-being" (pp. 772; De Crescenzio et al., 2019).

Using VR as a tool is 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. During the researcher's experience, the main disruption to their workflow was the pairing issues with the Logitech VR Ink Bluetooth. Although the device interrupted the overall workflow, the use of the pen made the sketching experience more intuitive while drawing the orthogonal forms around them.

The 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) (Pham & Stuerzlinger, 2019). 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.).

VR software and hardware are designed to have natural affordances so that the user will feel immersed in the simulation (Ban & Hyun, 2020). To make drawing a more immersive experience, the Logitech developed the VR Ink Pen is designed like a pen for users to sketch in VR. Currently, there is little information available on the ergonomic benefits of using this device for drawing in VR. Most input devices have been examined 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 (i.e., Fitt's Law) in AR and VR but also explored the ergonomic benefits of using either design (i.e., controller versus mouse versus stylus) (Pham & Stuerzlinger, 2019). 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] Anthropometry is the systematic measurement of the physical properties of the human body .

Next Steps – Phase 2

The sketches developed in Phase 1 of this study, shown in Figure 3 were implemented into a second phase of the study, where a remote end-user reviewed the 2D and 3D design sketches. The next step involved comparing feedback from two participant groups, designers and non-designers, who viewed and evaluated both the traditional 2D illustrations and the 3D sketches independently and asynchronously. All participants reviewed the sketches remotely, and their evaluations of the designs were obtained via an online survey using the System Usability Scale (SUS) (Brooke, 1986). The designers completed an additional questionnaire called the Technology Acceptance Model (TAM) (Davis, 1989) to assess their experience with the ease and usability of embedding XR techniques in the design workflow. The participants used 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.

The second phase of this study is still ongoing and the next step will be the analysis of the collected data. From these data we aim to further validate the acceptability and usability of the XR techniques as a drawing tool for sketching. In particular, the designer group results will help to identify if XR can be used to share 3D drawn concepts remotely and if XR has a place in the design workflow. The non-designer group results will help to identify if XR can provide a more accessible usability testing method and whether users can be involved in the earlier design stages by reviewing XR concepts that avoid the need to have them onsite for user testing. The findings from the second phase of this study will be described in follow up paper. The results of both phase 1 and 2 may provide insight into best practices for embedding XR techniques within the aircraft design and evaluation process.

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