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Exploring the use of extended reality for user experience design in product-service systems

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Exploring the use of Extended Reality for user experience design in product-service systems

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Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends with it.

Albert Einstein

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SUMMARY

This dissertation aims to explore the use of extended reality (XR) as an approach to developing user experience (UX) for product-service systems. It included eight chapters to explore the research question: "How can designers use extended reality to develop the user experience for product-service systems?"

Chapter 1 introduces three immersive experiences in current user experience studies as examples (Section 1.1), and explains three relevant research topics of these experiences (Section 1.2). It then reviews the applications of extended reality in designing product-service systems in practices and the literature (Section 1.3) to propose the aim, the research question, and six sub-questions of this dissertation (Section 1.4). Section 1.5 then explains the theoretical background and research methodology to explore these research questions.

Chapter 2 answers sub-question 1 about the essence of immersive experience from users' and designers' viewpoints. Section 2.1 proposes a user-centered model of immersive experience from literature and case analysis to explain how the perception of immersion appears. It then suggested a design guideline based on this model. Section 2.2 focuses on mapping currently available XR platforms concerning the categories of experiences, as well as the Double-Diamond Model - a model of human-centered design processes.

Chapter 3 firstly in Section 3.1 answers the sub-question 2 by reviewing state-of-the-art XR technologies for UX studies. Section 3.2 then aggregates the insights from previous theoretical studies. It proposes a process to prototype experiences via XR to develop positive experiences for product-service systems, and thus paved the way to develop user experience via XR in the following case studies.

Chapter 4 investigates three case studies to understand how to ideate concepts via XR at the early design stage, specifically in conceptualization. These studies focus on comfort-relevant experience in the context of a long-haul flight, which is mainly stimulated by the security drive. In addition, the studies also compare the influence of different viewpoints and ways of interaction on the perception of "being comfortable".

Chapter 5 examines how to assess experiences via XR across user groups and concentrates on competence-related experiences. The experiences of "being competent" are selected as they are broadly applied in the field of education and training, a heated domain of XR applications. This chapter contains three case studies in the

context of true-to-life surgical training where a successful surgery depends both on proficient psycho-motor skills and mature self-management of surgeons. In addition, these studies also observe the influences of proficiency, cultural backgrounds, and technology familiarity on the perception of competencies.

Chapter 6 scrutinizes how to facilitate remote collaboration via XR. This chapter covers two studies in the context of remote teamwork but applied in manufacturing and healthcare. The experiences about asymmetric coordination are selected in that they reflected the needs of “be-related” in a complicated work, which can be driven both by security and novelty. Given relatedness as a universal need, these studies focus on the influences of different interfaces, either immersive or non-immersive, on the perception of the co-location, as well as task loads, usability, and presence.

Chapter 7 first reviews the lessons learned from the case studies and then probes how design teams integrate immersive experiences into their practices. Hence, four co-creation studies were developed which are in line with the conceptual process in Chapter 3. Section 7.2 aims to understand how designers craft immersive experiences within design projects. Section 7.3 targeted how to enhance the designerly thinking of a design process via immersive experiences. Section 7.4 discussed how suitable XR technologies are used as mediators to prototype different designable elements. Section 7.5 was a pilot study to review the concept of immersive co-design space.

Chapter 8 reflects on each sub-question from an overarching perspective, and then summarizes three sets of recommendations for design stakeholders who are interested in integrating immersive experiences in their work. This chapter then envisions a concept of a co-design community via immersion - ‘Design Metaverse’. At the end, the limitations of this work are discussed, as well as future research directions.

SAMENVATTING

Dit proefschrift is gericht op het verkennen van het gebruik van extended reality (XR) als een benadering voor het ontwikkelen van gebruikerservaring (UX) voor product-servicesystemen. Het bevatte acht hoofdstukken om de onderzoeksvraag te verkennen: "Hoe kunnen ontwerpers extended reality gebruiken om de gebruikerservaring voor product-servicesystemen te ontwikkelen?"

Hoofdstuk 1 introduceert drie immersieve ervaringen in huidige studies naar gebruikerservaringen als voorbeelden (Sectie 1.1), en legt drie relevante onderzoeksonderwerpen van deze ervaringen uit (Sectie 1.2). Vervolgens wordt een overzicht gegeven van de toepassingen van 'extended reality' bij het ontwerpen van productservicesystemen in de praktijk en de literatuur (Sectie 1.3) om het doel, de onderzoeksvraag en zes deelvragen van dit proefschrift voor te stellen (Sectie 1.4). Sectie 1.5 licht vervolgens de theoretische achtergrond en onderzoeksmethodologie toe om deze onderzoeksvragen te onderzoeken.

Hoofdstuk 2 beantwoordde deelvraag 1 over de essentie van immersieve ervaring vanuit het gezichtspunt van gebruikers en ontwerpers. Sectie 2.1 stelde een gebruikersgericht model van immersieve ervaring voor op basis van literatuur en case-analyse om uit te leggen hoe de perceptie van immersie tot stand komt. Vervolgens werd op basis van dit model een ontwerprichtlijn voorgesteld. Sectie 2.2 richtte zich op het in kaart brengen van de momenteel beschikbare XR-platforms met betrekking tot de ervaringscategorieën, evenals het Double-Diamond Model - een model van mensgerichte ontwerpprocessen.

Hoofdstuk 3 beantwoordde eerst in Sectie 3.1 deelvraag 2 door een overzicht te geven van state-of-the-art XR-technologieën voor UX-studies. Sectie 3.2 bundelde vervolgens de inzichten uit eerdere theoretische studies. Er werd een proces voorgesteld om prototypes te maken van ervaringen via XR om positieve ervaringen te ontwikkelen voor productservicesystemen, en zo werd de weg vrijgemaakt voor het ontwikkelen van gebruikerservaringen via XR in de volgende casestudies.

In hoofdstuk 4 werden drie casestudies onderzocht om te begrijpen hoe concepten via XR in de vroege ontwerpfase kunnen worden bedacht, met name in de conceptualisatiefase. Deze studies richtten zich op comfort-relevante ervaring in de context van een langeafstandsvlucht, die voornamelijk wordt gestimuleerd door de veiligheidsdrang. Daarnaast vergeleken de studies ook de invloed van verschillende gezichtspunten en manieren van interactie op de perceptie van "comfortabel zijn".

Hoofdstuk 5 onderzocht hoe ervaringen via XR kunnen worden beoordeeld over gebruikersgroepen en concentreerde zich op competentiegerelateerde ervaringen. De ervaringen van "bekwaam zijn" werden geselecteerd omdat ze breed worden toegepast op het gebied van onderwijs en training, een verwarmd domein van XR-toepassingen. Dit hoofdstuk bevat drie casestudies in de context van levensechte chirurgische training waar een succesvolle operatie afhangt van zowel vaardige psychomotorische vaardigheden als volwassen zelfmanagement van chirurgen. Daarnaast hebben deze onderzoeken ook de invloeden van vaardigheid, culturele achtergronden en vertrouwdheid met technologie op de perceptie van competenties geobserveerd.

Hoofdstuk 6 beschrijft hoe samenwerking op afstand via XR kan worden vergemakkelijkt. Dit hoofdstuk behandelt twee studies in de context van teamwerk op afstand, maar toegepast in de productie en de gezondheidszorg. De ervaringen met asymmetrische coördinatie werden geselecteerd omdat ze de behoeften weerspiegelden van "verwant zijn" in een gecompliceerd werk, dat zowel door veiligheid als door nieuwheid gedreven kon zijn. Aangezien verwantschap een universele behoefte is, richtten deze studies zich op de invloeden van verschillende interfaces, immersief of niet-immersief, op de perceptie van de co-locatie, evenals taakbelasting, bruikbaarheid en aanwezigheid.

In hoofdstuk 7 werden eerst de lessen uit de casestudies geëvalueerd en vervolgens werd onderzocht hoe ontwerpteams immersieve ervaringen in hun praktijk integreren. Daarom werden vier co-creatie studies ontwikkeld die in lijn zijn met het conceptuele proces in hoofdstuk 3. Sectie 7.2 heeft als doel te begrijpen hoe ontwerpers immersieve ervaringen creëren binnen ontwerpprojecten. Sectie 7.3 richtte zich op hoe het ontwerpend denken van een ontwerpproces kan worden versterkt via immersieve ervaringen. Sectie 7.4 besprak hoe geschikte XR-technologieën worden gebruikt als bemiddelaars om prototypes te maken van verschillende ontwerpbare elementen. Sectie 7.5 was een pilotstudie om het concept van immersieve co-designruimte te evalueren.

Hoofdstuk 8 reflecteerde op elke deelvraag vanuit een overkoepelend perspectief en vatte vervolgens drie sets aanbevelingen samen voor ontwerpstakeholders die geïnteresseerd zijn in het integreren van immersieve ervaringen in hun werk. Dit hoofdstuk stelde vervolgens een concept voor van een co-design gemeenschap via immersie - 'Design Metaverse'. Aan het eind werden de beperkingen van dit werk besproken, evenals toekomstige onderzoeksrichtingen.

CHAPTER 1

General Introduction

This chapter starts with short stories about three pieces of extended reality experiences for specific products or services. The first part introduces the background and development of the key terms in this research – *Product-Service Systems, User Experience,* and *Extended Reality*. Second, the author reviews the state-of-the-art Extended Reality in the development of product-service systems introducing the aim and the main research question (RQ) of this dissertation, as well as the sub-research questions (sRQs). The third section explains the theoretical background and research methodology. Eight research cycles (RC) support the sub-questions introduced previously. Finally, a reading guide provides the structure of the dissertation, and a flow chart explains the methods and procedures that are applied to it.

1.1. Prologue: Glances into Extended Reality Experiences

Before the author starts to elaborate on the scientific background of this dissertation, let's go through several experiences created via Extended Reality (XR) as follows:

1.1.1. Case One

Imagine that you are participating in developing a concept airplane for long-haul flights – Flying-V. This airplane has a V-shape fuselage and oval-shaped section, making it save up to 25% fuel per flight. So, it has a completely different floor plan than a normal aircraft. You will evaluate a virtual flight by wearing a headset: The plane takes off at 10 p.m. and lands at the destination around 6 the next morning. When you board the Fly-V, you discover a quiet sleeping zone next to your economy-class zone. So, you book a sleep block for four hours to take a relaxing nap during the night. After a few hours, a soft azure-tone light gradually turns on in the block to wake you up. While walking back to your seat, you stretch yourself at the exercise corner next to the staff rooms. On your seat, you start your laptop and review the presentation for today. You pull down the shelter on your seat to avoid disturbing the people in the next seats. To focus, you turn on a gentle greenish light on the rim of the headrest and show a "no disturb" sign on the outer screen of the shelter. Two hours later, your presentation is scrutinized and you feel satisfied but still a bit drowsy. So, you turn the shelter completely dark and start a meditation program. Gentle music with the sounds of creeks and forests starts, and soon you fall asleep again. At about 5 a.m., the breakfast service begins, so you push back your shelter and enjoy your morning decaffeinated coffee. Little boys and girls from the next seats cannot wait for their parents to finish their meals because they want to go to the playroom. You feel as energetic as these children due to the comfortable nap and meditation. "5:20", you look at your watch and decide to go to the hygiene room to refresh yourself. You wash your hands and face, then dry them up with a paper towel, and then reshape your hairstyle with a blower. In thirty minutes, you arrive at your destination full of energy and pleasure.

1.1.2. Case Two

Imagine that you are redesigning an operating room (OR) section in a hospital. You are invited to observe some operational procedures, so you put on a VR headset and "step" into a virtual OR. There is a group of medical students from the Netherlands learning teamwork in minimally invasive surgery. They are playing the roles of a surgeon, a nurse, and an anesthetist with their avatars and performing a cholecystectomy (gallbladder removal) on a digital patient. The 'surgeon' controls two instruments, while the 'nurse' holds the endoscopy to follow the surgeon's maneuvers. The virtual operating theatre is full of sounds from the radio, the pagers, and phones. The 'surgeon' seems difficult to concentrate on and becomes stressed. "Relax and focus on here. Now use this right-angled dissector to hold this part of the gallbladder and slightly pull it towards you", a remote mentor is supervising and guiding the group. The 'anesthetist' student is distracted by an avatar walking inside the OR, and then he shouts suddenly, "The blood pressure drops fast now". "Calm down. Check the vital signs then shift to the emergency protocol", the remote mentor instructs. The background music starts to play 'Sweet Child O' Mine' softly, a popular song among surgeons. The trainees start to take control of the chaotic and twirly situation. Two minutes later, the vitals are stable again. The students giggle and make jokes with each other. "You see, you can do it. Handling a situation in a real surgery follows similar principles. But be aware that the differences between real patients are large", the remote mentor commented. When the procedure is done, the team receives a report about their errors, posture economy, and individual assessment. The students can replay the procedure again and observe it afterward. In the 'next door' virtual OR, a group of trainees from India is performing laparoscopic surgery, where a remote supervisor is evaluating their surgical skills with a standardized form. You notice that the uniforms, the layout, and the devices here, as well as the vibe of the team, are quite different from the previous virtual OR. An OR needs to be highly flexible to meet diverse operational requirements from different cultures, but you can find that entangled cables and pipelines, as well as awkward postures, are common problems, which frequently hamper trainees' maneuvers. Improving these aspects might enhance surgeons' performance and well-being.

1.1.3. Case Three

Considering that you and a colleague are helping upgrade a small factory that produces customized gift sets, such as selected markers with engraved cases. Currently, the factory only uses a robotic arm to engrave the customized texts or images on cases, and it wants to install robotic arms and conveyors to deliver the cases from the beginning of the assembly line to ensure the accuracy and efficiency of production. The factory owns a small workshop with limited space, so you and your colleague first help the factory to configurate a proper layout of this new line via an AR application. Your colleague arranges the configuration on-site with the owner, while you have the authority to share robotic models from a digital catalog that can simulate the production. When wearing AR headsets, the three members of your team come to a shared space where all can see full-scale digital models shown in the workshop. You choose the robots that fulfill the production requirements and show them in the space, while your local co-workers directly manipulate and put them in proper positions to form a feasible layout via hand postures and vocal commands. You switch robots or demonstrate their functionalities if your co-workers ask you to. The co-workers check the compatibilities of sizes, scales, and ergonomics of the workstations, whereas you inspect the overview as well as the workflow. You all can check the layout both from giant-eye and real-size perspectives. To achieve this kind of coordination, each one can see the avatars of others through their virtual hands and heads, as well as the gaze beams. In addition, the collaborators discuss with each other via a live audio stream. The final configuration of the factory line consists of four conveyors and two robotic arms in a J-shape layout. It takes the team about an hour to finish this design. A few hours later, these parts are delivered from the warehouses to the factory. You ask your co-workers to share their scene camera, so you can see the details to guide them through the installation procedure. They first align the physical parts with their digital twins, and then you use your virtual hands and annotations to tell them how to connect cables and sockets. Finally, the sensor data of physical parts are synchronized with their digital twins, so you can supervise their status remotely and diagnose potential risks in advance.

Do the abovementioned cases come from some plots of science fiction or futuristic movies? The readers might wonder and find some familiar flavors in the narratives somewhere. They are nevertheless all about experiences generated by the technologies of *Extended Reality* (XR) from publications and case studies, which aimed at providing a good user experience in a product-service system. The vividness and wholeness of the example XR experiences sound attractive. Designers and researchers hence might gain new possibilities to explore product-service systems involving humans, technology, and their interactions. This dissertation attempts to understand how can designers generate positive experiences in product-service systems by prototyping corresponding experiences via XR.

1.2. Research Topics

1.2.1. Product-Service Systems (PSSs)

Throughout history, people have been closer and tighter interweaving into a large network, involving products, services, events, and other people (Lindebaum, 2015). Owing to the advancement of the economy and information technology, this trend become more prominent during the last decades, particularly in product-service systems. *Product-Service Systems (PSSs)* in this dissertation dub the social-technology structures with economic values, which are capable of fulfilling human needs (Mont, 2002). The intellectual roots of developing a product-service system are work science, work psychology, ergonomics, and human factors. All those disciplines were primarily triggered by a more or less economically-driven demand for improving working places, i.e., aiming at increasing performance and subsequently production (Karwowski, 2005). Humans are often viewed as necessary yet improvable parts of a large "machine", as shown in Chaplin's *Modern Time*.

Despite the focus of human-system interaction shifting toward human-centered perspectives, the general objective to increase performance remains stable. For example, the ISO-9241-11 (2018) re-iterated and further popularized the pursuit of performance in usability by calling for efficiency and effectiveness. Satisfaction, signifying a generally positive attitude towards a product or a system, was framed as a by-product of performance other than self-contained, independent merit (Lindgaard & Dudek, 2003). In product-service systems, satisfaction is closely related to human well-being. The implicit tension between performance and satisfaction finds its origin in the inter-war period when the economic world was obsessed with boosting production, which prioritizes the performance of systems at the expense of human well-being (Schumpeter, 1976).

The notion behind this imbalance is viewing a human as *Homo Economicus*, where the nature of humanity is reduced to a desire to maximize utility, regardless of personal needs and emotions (Femia, 2006). The notion usually requires normalizing human sizes, physical and cognitive capabilities, as well as organizational activities into ideal models, and then examining them by objective measures and statistical calculations. This notion was especially expressed by *behaviorism*, which has been penetrating many aspects of working system design, from internationalism architecture (Corbusier, 2014), to functionalism design (Barr et al., 1948), to ergonomics and human factors (Dul et al., 2012), lately to Human-Computer Interaction (Shneiderman et al., 2016) and Artificial Intelligence (Parkes & Wellman, 2015). Recently, more and more researchers question: “Are we, human beings, like this?” Thence they attempt to re-evaluate its machine-ethical value (Persson & Erlandsson, 2002). Reconsidering the utility-oriented image of humanity as the guideline and proposing a more appropriate notion of people is the cornerstone for any design aiming at human well-being. Researchers who challenge this notion propose alternatives, like *Homo Ludens* or *Aesthetics Pleasure* (Gaver, 2002; Hekkert, 2006). These images of humanity may be debatable, but stating the nature of humanity is of paramount importance to rebalancing performance and human well-being, especially in developing product-service systems.

Enhancing human well-being is a central goal for the professionals who develop PSSs (IEA, 2021). Human well-being indicates “the state of being happy, healthy, and prosperous” (Merriam-Webster, 2023). Experiences focus not only on meeting expectations, but also on valuable and/or pleasant experiential outcomes, like surprise, pride, or spirituality (Hassenzahl, 2010). Hence, they can benefit human well-being holistically. Design qualities like satisfaction, referring to a general state of positive experiences, shall be granted core values in developing PSSs.

1.2.2. User Experience (UX)

Human well-being can be influenced by experiences, which emerge from a unique intertwining of perception, action, motivation, emotion, and cognition, and because of the interplay of many different sub-systems in a human being (Overbeeke et al., 2002; Russell, 2003). *An experience* is 'an episode, a chunk of time' that people go through and will remember' (Hassenzahl & Tractinsky, 2006). When people are *experiencing*, they are making continuous commentary on their state of events, a 'constant stream of self-talk' as Forlizzi and Battarbee (2004) stated. Hence, experience comes from mediators, among which, technology made experiences to the broadest extent possible. Take the flight experience as an example: seats, sleeping blocks, lights, and shelters, are all carefully designed and combined to create a comfortable perception; the unique shapes of fuselage and section enable fuel-saving; a compact kitchen set to prepare the breakfast; software provides inflight entertainment and relaxation; radar system makes sure that the jet will keep its track. A product-service system is nevertheless important insofar as it allows for the episodes of experiences – it mediates and shapes experiences. These systems mainly differentiate from each other in creating qualitatively different experiences; some can be apt and joyful, while others can be improper and tedious, or even unsafe. In this sense, *User experience* is not much different from experience per se, referring to all affective episodes involved in human-system interaction (Desmet & Hekkert, 2007). Hence, the main concern of user experience is to create a smooth and intuitive interaction between humans and other elements of a system.

The value of experiences consists in understanding and focusing on what enhances human well-being - needs fulfillment, consequently motivating actions, and activities. Our life is filled with vivid, visual, and emotional accounts of good and bad experiences, where episodic memory authorizes autobiographical information about ourselves (Tulving, 1972). Hence, experience is of paramount value in forming who we are. Consuming positive experiences holds more power to boost happiness than any material possession (Boven & Gilovich, 2003).

Nowadays, virtual prototypes in testing or training support designers to understand users better. They help designers simulate potential interactions between human users and other system elements (Kent et al., 2021). Although two-dimensional virtual prototypes like CAD have higher fidelity in simulating design concepts than textual descriptions and sketches, designers and users still need to imagine and anticipate the whole episode of interacting with a product-service system that has not yet been produced (Moes & Horváth, 2016). This often causes miscommunication and misinterpretation of the design concepts. Moreover, the design community calls for a new possibility to test and verify the experience of human-system interaction. Current prototypes represent a fraction of the perception of an experience: it either be the feelings about the color and touch of materials, the scales in real size, or how the controls can be reached by hands or feet. Hence, integrating every facet, like explicit knowledge, tacit knowledge, and emotional responses, to envision a full experience is highly demanding mental work for designers (Polanyi, 2009). Extended Reality shows the potential as a key enabler to simulate various experiences beyond cost and technology constraints.

1.2.3. Extended Reality (XR)

Immersion is an omni-bearing experience, surrounding people with a digitally-generated 'world'. Within an immersive experience, when people believe that they are "being there" in a virtual place instead of seeing computer-generated images, the phenomenon - *Presence* appears(Witmer & Singer, 1998). The phenomena of *Presence* refer to three aspects: *Spatial presence*, *Social Presence*, and *Co-Presence*. *Spatial Presence* means the sense of being physically located in a virtual space other than their environment in the real world (IJsselsteijn & Riva, 2003). *Social Presence* indicates the feeling of being together and interacting with other virtual beings (Biocca et al., 2003). *Co-presence*, also known as *Holo-presence*, is the synthesis of spatial and social presence (Bulu, 2012). Consequently, immersion has been influencing psychological treatment, architecture design, professional training, education, gaming, and art creation since early 2000 (Ling et al., 2014).

This sense of immersion can be mediated by *Extended Reality* (XR), referring to a vivid, omnidirectional virtual environment either shutting out or blending with our physical reality (Cummings & Bailenson, 2015; Stephenson, 2000). *XR technologies*, also known as *immersive technologies*, is the parental term for different technological settings, among which display is a key attribute affecting the level of immersion (Bowman & McMahan, 2007). The relationship between immersion and technological settings has been studied for the last two decades, and the most well-known model is the Reality - Virtuality continuum (R-V continuum) by Milgram et al. (1995). The R-V continuum includes four groups - Virtual Reality (VR), Augmented Virtuality (AV), Augmented Reality (AR), and Tangible User Interface (TUI), bridging a completely digitally-generated world with the real world. As a mixture of the digital and physical worlds, XR technologies are endowed with great flexibility in crafting experiences.

Previously, implementing XR technologies in design was constrained by their technological immaturity, costliness, and low-quality interfaces, and at the same time is viewed as a future design enabler (Faisal, 2017). The advancement of high-end commercial XR systems after 2014, especially in visual resolution and embedded tracking sensors, brought better opportunities to explore XR as key enablers to shaping positive user experience for future designs of product-service systems (Stein, 2016). In this dissertation, the author thus needs to distinguish between the following key terms: '*Immersive Experiences*' - the psychological phenomena generated via XR technologies; '*XR experiences*' - the digital contents displayed on *XR hardware* (e.g., VR headsets) via *XR platforms* (software for developing/releasing XR experiences, e.g., Unity and SteamVR); an *XR system* refers to the technological setting of a particular XR experience including both hardware and software.

1.3. Extended Reality in Designing Product-Service Systems

1.3.1. Extended Reality in Design-Relevant Practices

XR experiences can stimulate a "WOW" effect in design stakeholders via their stunning visual-audio effects, and sometimes combining haptic effects. Users also need compelling narratives during interactions to gain valuable experiences. Hence, if designers need to use XR to conduct UX studies, each application needs to develop an XR experience based on its situation. Currently, computer scientists are busy offering technical solutions for better spatial presence, while video curators explore better storytelling ways to enhance social presence. Designers however need to put them together as a whole, so they are continuously looking for approaches to reach the desired level of co-presence. Using XR as a key enabler requires more understanding of the unique potentials and challenges that XR brings to the user experience, and developing a systematic approach to designing positive, valuable, and meaningful experiences via XR. To create an overview of why and how industries are applying XR currently, the author interviewed over 20 team leaders from different sectors (Table 1.31).

In these cases, XR experiences serve either as a training tool to replace or augment physical simulators or as a new type of living lab for deep insights into users. Sometimes, it also serves as a medium to bring remote experts to the spot for diagnosing, analyzing, or assisting. In other cases, XR experiences, particularly 3D digital twins, serve as a communication platform to promote mutual understanding in trans-disciplinary teams of product-services developers.

Table 1.3.1 The motivation for applying XRs from the interviewed industries
(for detailed information about the interviewed leaders please refer to the Appendix Table A.11)

Industry	Sub-section	Applications	XR experiences
Aviation	Training	Task proficiency	Task simulation in high-end VR headsets; Physical simulator plus AR headset
	User experience	Target group feedback	Environment simulation in cardboard VR
Automotive	Marketing	Novel experience/ Target group feedback	Multiple user interactions in VR with haptic feedback
	Research	Behavior observation/ Target group feedback	Rough physical mock-ups plus high-end VR headsets; Simulator/car plus high-end VR headsets
	Manufacturing	Remote diagnosis	Sharing local information via video see-through AR headsets
	Maintenance	Task proficiency	Task simulation in high-end VR headsets
Transportation	HCD	Target group feedback	Product simulation within a realistic context
	Planning	Behavior observation	Viewing holistic environments in cupboard VR; Simulator plus high-end VR headsets
Healthcare	Teaching	Anatomy understanding	Anatomy structure in Magic Mirror/HoloLens/ High-end VR headsets
	Training	Task proficiency	Interaction and environment simulation in high-end VR headsets and fine haptic feedback
	Plan	Better surgical plan	3D organ image in high-end VR headsets/ HoloLens
	Assistance	Remote assistance	Site sharing via handhold apps/HoloLens
Fabrication	Robotics	Remote analysis	Sharing digital twins with HoloLens/video see-through AR headsets
	Design	User co-creation	Rough physical prototypes plus video see-through AR headsets /projection

Table 1.3.1 Continued

Industry	Sub-section	Applications	XR experiences
	Maintenance	Task proficiency	Task simulation in high-end VR headsets
Architecture	Marketing	Target group feedback	Showing realistic environments to stakeholders in cupboard VR
	Design	Design review	Detailed modeling with high-end VR headsets
Design	User testing	Design evaluation	Interaction simulation in high-end VR headsets
	Design	Design communication	Sharing digital twins across teams of development

1.3.2. Extended Reality in User Experience Studies for Product-Service System

According to the Web of Science database, in the early 1990s, virtual reality (VR) first attracted the attention of the research circle. Researchers began with the human factors of the VR systems, and then they started to explore VR for human factor analysis and investigation in 1992 (Thomas & Stuart, 1992). In the last decade, publications covering both *XR* and *Ergonomics & Human Factors* (EHF) have grown gradually. For instance, the publications about XR in the context of product-service systems increased from 315 (2008) to 548 (2017).

Despite the interest in applying XR in design beginning in the mid-1990s (Smets & Stappers, 1995), the utilization of XR in design studies is a more recent tendency. A distribution shows the number of published design cases using XR during the last decade increased and started to accelerate after 2015 (Figure 1.31). The author speculates that the launch of commercial high-end XR headsets in 2014 largely fueled this growth, which lowered technological thresholds and heightened the flexibility to implement XR in design activities.

The low-cost XR technologies are continuously empowered by growing computational capacities over the last five years. The XR experience thus is increasingly enhanced by the advancing computational power and graphic quality equipped in the off-the-shelf XR headsets, including HTC Vive and Oculus Rift (Bergroth et al., 2018; Mallam et al., 2019). More and more XR headsets even try to provide a smooth switch between VR and AR experiences, e.g., Varjo XR headsets can display virtual objects seamlessly within a real location with high immersion. The rising interest in integrating XRs in design studies during the last five years, especially in user experiences, and its acceleration match a growing need for digitizing design processes (IDC, 2020a). Quantitative and hybrid measurements are focused in these XR cases, whose attention is on triangulating subjective and objective responses.

As shown above, design researchers are witnessing the growth of applying XR as a design tool to facilitate user experience studies. Many researchers acknowledge that XR shows great potential to facilitate the development of complex systems, including 1) design visualization, 2) provoking empathy among design teams, 3) human actions prediction via emotional stimulus, 4) remote cultural probes, 5) increasing user involvement, 6) prototyping and user testing, and 7) boosting co-creation among stakeholders (Keefe, 2009; H. J. Kim et al., 2018; Riva et al., 2007; Salzmann et al., 2009; Santos & Montagna, 2019; Slater et al., 2010; Thalen & van der Voort, 2012).

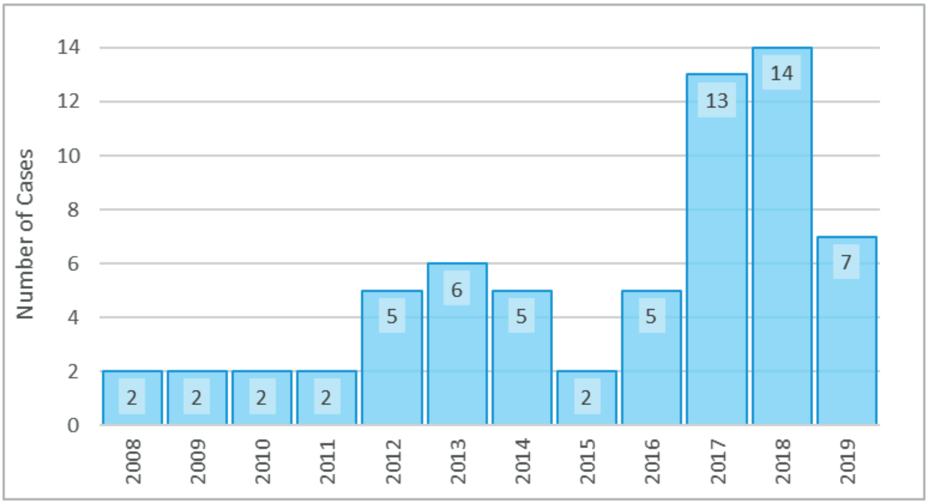


Figure 1.3.1 The yearly published design cases using XR to improve user experience. These cases are selected from peer-reviewed publications in four databases: Web of Science, Scopus, IEEE Xplore, and ACM. Three sets of search terms are Extended Reality, User Experience, and Human Factor & Ergonomics to collect the cases (for the detailed method please refer to section 3.1.3).

However, there are still several knowledge gaps when the design community discusses "whether XR is a valuable enabler currently for positive user experience design":

- It's rare to define the meanings of immersion and presence from the user's and designer's perspectives.
- An overview of XR technologies in line with design qualities and design processes is missing, so designers face difficulties in selecting suitable technologies.

- Designers need a framework to trustworthily transfer design-relevant daily experiences into an immersive experience via XR.
- The influence of the spatial presence, social presence, and co-presence phenomena on user experience is unclear.
- Design professionals lack references to assess the values and pitfalls of applying XR technologies in their practices.

1.4. The Aim and Research Questions

Thus, this dissertation aims to explore the use of XR for developing user experience in product-service systems. The author expects that XR will help designers improve design qualities in the sense of enhancing human well-being. This research also emphasizes the experiential approaches to effectively involve various design stakeholders in the co-creation of user experience.

1.4.1. Research Questions

To summarize the abovementioned knowledge gaps, the main research question of this dissertation is:

How can designers use extended reality to develop the user experience for product-service systems? The main research question is extended by the following sub-research questions (sRQs) about its relevance, methodology, and usefulness (Boess, 2009).

sRQ1: *What are the key factors of immersive experiences in product-service systems both from the user's and designer's perspectives?*

sRQ2: *What are the roles of state-of-the-art extended reality technologies in developing user experience for product-service systems?*

sRQ3: *How can designers efficiently ideate user experience via spatial presence in conceptualization?*

sRQ4: *How can designers effectively assess user experience via social presence across different user groups?*

sRQ5: *How can designers facilitate user experience via co-presence in remote collaboration?*

sRQ6: *What strategies do designers apply when introducing extended reality in product-service design practices?*

Considering the objective of this dissertation, the main research question is explorative instead of prescriptive. sRQ1 focuses on probing the nature of the experience via XR technologies, and then sRQ2 aims to depict the status quo of applying XR technologies in user experience studies. They establish the scope of this dissertation and, thus are descriptive and explorative.

This dissertation will also respond to the challenges in developing the user experience for product-service systems (Dul et al., 2012): 1) enhancing physical well-being under complex contexts; 2) enhancing cognitive well-being across various communities; 3) enhancing organizational well-being during remote risky collaborative work. The sRQ3 to sRQ5 select three aspects of the immersive experience: spatial presence, social presence, and co-presence, and observe their effects on the user experience resonating the effectiveness, efficiency, and satisfaction from the ISO9241. They hence attribute prescriptively to the main question. The sRQ6 then links the findings of previous studies with the empirical knowledge from design professionals and thus becomes descriptive and explorative concentrating on the context of design practices.

Therefore, this dissertation will conduct eight research cycles (RC) where XR serves as a key enabler in developing positive experiences that enhance the human well-being of product-service systems.

1.5. Theoretical Background and Research Methodology

sRQ1 and sRQ2 contribute to the *relevance* of this research. sRQ1 defines immersion both from the user's (RC1) and designer's (RC2) perspectives via a literature analysis. sRQ2 includes a scoping review of XR technologies in RC3 and a conceptual process in RC4. RC4 aggregates insight from the abovementioned theoretical studies, serving as a pivot point that transfers the relevance to the methodology.

sRQ3 to sRQ5 are related to the *methodology* to craft positive experiences in typical product-service systems, e.g., mobility, healthcare, and fabrication. sRQ3 is supported by RC5 and focuses on *spatial presence* phenomena and their effects on physical well-being. sRQ4 is supported by RC6 and focuses on *social presence* phenomena and their effects on cognitive well-being. sRQ5 is supported by RC7 and focuses on *co-presence* and its effects on organizational well-being.

sRQ6 is related to the *usefulness* of XR in shaping positive experiences in design practices, which is the main task of RC8.

1.5.1. *RC1 – The Immersive Cycle: Understanding Immersive Experiences through a User-Centered Approach*

An experience for a person is a chunk of time and space that one went through - with sights and sounds, feelings, thoughts, needs, and actions; they are closely knitted together, stored in memory, labeled, relived, and communicated to other people. In this episode, this person is in dialogues with her or his world through actions, at a particular time and place (Schmitt, 1999). Experiences hence may occur in an infinite number of variations in the real world, but they nevertheless share a common, defining core (Hassenzahl et al., 2013). One may understand experience explicitly as the result of a self-categorization process, as Russell states (2003); it means people read all elements and processes together and then compare them to past experiences and general knowledge of the world. Thus, the first work in this dissertation is to develop a model from the user's perspective to define key factors of immersive experiences, relating to sub-question1.

1.5.2. *RC2 – Mapping XR Platforms: Analyzing Immersive Experiences from a Designer's Perspective*

Pine and Gilmore (2011) suggested a matrix of experience to identify how people face an experience per their actions and their presence. Through this model, designers can understand the relations between the needs of "being immersive", "being engaged", "being interactive", and "being involved", which are mediated by an XR platform. Experiences are in line with typical HCD models but are different, as they hold the same goal to improve human well-being but via different approaches (McGrenere, 2000). Designers should understand experience as an emergent story, and extend their view to the fundamental needs/values of humans (Hassenzahl, 2010). The author hence tries to categorize XR platforms based on the experience matrix and then puts these platforms in line with an HCD process model. This work is also related to sub-question 1.

1.5.3. *RC3 – A Scoping Review of Extended Reality in User Experience (UX) Studies*

Technologies deliver experiences via their "functionality, content, presentation and interaction" (McCarthy & Wright, 2004), the same as XR technologies replicate real-life experiences in immersion. A prominent strength of XR technologies is their ability to simulate unlimited variations of experiences. These immersive sensations have an interesting balance between two primary drives of human beings: 'being curious' and 'being secure' (Berghman & Hekkert, 2017). For instance, 'jumping' into an unfamiliar place in virtuality is a source of novelty, and consequently, triggers curiosity; at the same time, people know what they've done there makes no harm to reality, thus they feel safe. Hence, XR might become an ideal enabler for exploring positive experiences of product-service systems, which tell what boosts human well-being. Published design studies provide a good resource to understand the relationship between XR technological settings and user experience investigated via XR. This dissertation hence demonstrated an attempt to systematically review user experience created via state-of-the-art XR technologies in product-service design cases. This is related to sub-question 2.

1.5.4. RC4 – A Concept of XR-facilitated Experience Design for Product-Service Systems

A design offers a novel way for humans to dialogue with their world, hence providing unique experiences for its users. John Gould and Clayton Lewis (1985) suggested that designers should observe and analyze users using simulations/prototypes in realistic activities. Hence, this dissertation integrates the insights from previous RCs to devise a concept of an XR-based process to develop positive experiences for product-service systems. It starts by analyzing positive experiences, extracting corresponding design qualities, and then addresses them to prototype user experience for a particular product-service system via XR technologies. Users and designers should co-construct design concepts via XR in "co-immersion", indicating experience communicating and empathizing via immersion. This conceptual process relates to sub-question 2 as well.

1.5.5. RC5 – Case Studies of Immersive Design for Physical Well-being

The first set of cases is to design comfort-relevant experiences for long-haul flights in developing a conceptual airplane. The design quality in these cases focuses on *Comfort* – the "discomfort-comfort" delta – which is the experience pattern related to the needs of physical striving and appreciation (Anjani et al., 2020), belonging to the security drive. Comfort highly influences the satisfaction of travel experiences.

Spatial presence is the phenomenon mainly determined by the technical settings of XR. The author is interested in how these settings, i.e., absorptive, and immersive display, as well as passive and active interaction, influence the perception of comfort, and consequently satisfaction.

Considering that experiences are highly situated, these studies created narratives to inspire past relevant experiences instead of demonstrating products in themselves (Hassenzahl et al., 2013). Relevant design elements will be displayed in simplified virtual environments. There might be an apparent gap between objective design elements and their subjective experiences. Thus, these cases help people to judge their experiences by comparing two versions of design elements or comparing them with relevant past experiences (Hornbæk & Law, 2007; Kahneman & Miller, 1986). These case studies refer to sub-question 3.

1.5.6. RC6 – Case Studies of Immersive Training for Cognitive Well-being

The second set of cases is to design competence-relevant experiences for mastering a minimally invasive surgery in a complex operational environment. Design quality *Competence* is the ability to 'exercise your skills to master challenges', which would mostly be stimulated by the drive of novelty (Desmet & Fokkinga, 2020). The feeling of 'being competent' is highly related to self-satisfaction with learning procedures, which motivates people to proceed with their learning activities (Deci & Ryan, 2000).

Social presence is a phenomenon strongly influenced by the narrative and social interactions within XR experiences. Design elements can make a scalable impact on the resultant dynamic of experiences, that is, they change over time not in materials but in the experiences, they provide. The author might argue that when trainees become more proficient, more likely that they would feel competent against challenges, in this case, distractions during surgical training. An experience itself is a cultural construct, hence the studies also check experiences of competence from different cultural backgrounds.

As experience is subjective, an experiential phenomenon is created and remains in people's heads who undergo it. Performance measures, like task errors, thus may not predict directly the experience of competence (Pucillo et al., 2016). Redelmeier and Kahneman (1996) demonstrated how objective qualities can be better translated to improve the subjective perception of an experience. Hence, these cases focus on subjective assessments related to experiences of competence, like mental task load, physical stresses, and perceived performance, instead of measuring performance objectively. These case studies refer to sub-question 4.

1.5.7. RC7 – Case Studies of Immersive Collaboration for Organizational Well-being

The third set of cases is to design relatedness-relevant experiences for remote co-design or co-work. The design quality in these cases is the experience of "being related" to solve a complicated problem with a team separated geographically. The experiences of remote teamwork are associated with the need for belongingness and competence, which are stimulated both by the security and novelty drive (Hassenzahl et al., 2015).

Co-presence is the phenomenon that combines spatial presence and social presence, meaning people feel that they are co-located in a virtual space. Collaboration has the best outcomes when team members believe that they are located together (Ens et al., 2019). Situation awareness is the indicator of how people feel about they are in a shared workspace. Hence, these studies will assess how XR interfaces affect the experiences of being related in remote teamwork. Like the previous case sets, these cases apply subjective measures for task load and intuitiveness to indicate the performance perceived by co-workers. The dynamic of experiences lies in the real-time and continuous interaction between remote and local co-workers. These case studies refer to sub-question 5.

1.5.8. RC8 – Extended Reality in Product-Service Design Practices

The lessons learned from the case studies will be analyzed to justify the conceptual process. However, the author still needs to know how design practices with immersive experiences are in line with this process. Thus, four co-creation studies are organized to explore the following questions, which are related to sub-question 6:

Co-creation 1: What knowledge do designers gain by piloting immersive experiences in their practices?

Co-creation 2: How can designers translate general needs to design concepts via an immersive design protocol?

Co-creation 3: Is an immersive experience suitable to prototype different design elements in product-service systems?

Co-creation 4: How do design stakeholders coordinate with each other in an immersive co-design space?

1.6. The Thesis Outline

This section outlines how the different parts of this PhD research are related, and how these are documented throughout this dissertation (see Figure 1.61).

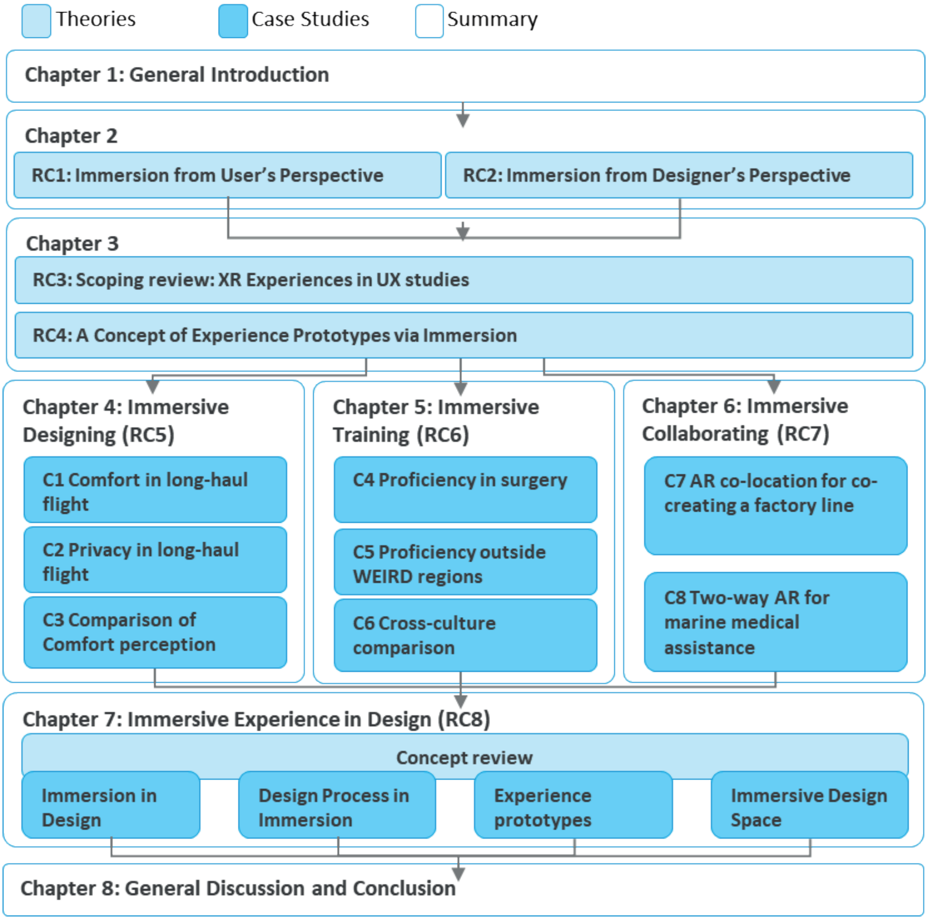


Figure 1.6.1 Visualization of the dissertation outline

Chapter 1 introduces three immersive experiences in current user experience studies as examples (1.1), and explains three relevant research topics of these experiences (1.2). It then reviews the applications of extended reality in designing product-service systems in practices and the literature (1.3) to propose the aim and research questions of this dissertation (1.4). Section 1.5 then explains the theoretical background and research methodology to explore these research questions.

Chapter 2 includes RC1 and RC2 to answer the research question about the essence of immersive experience from users' and designers' viewpoints. Section 2.1 proposes a user-centered model of immersive experience from literature and case analysis to explain how the perception of immersion appears. It then suggested a design guideline based on this model. Section 2.3 focuses on mapping currently available XR platforms concerning the categories of experiences, as well as the *Double-Diamond Model* - a model of HCD processes.

Chapter 3 first introduces RC3 to answer the research question about the technological mediator of immersive experiences to enhance human well-being, and then aggregates the insights from previous theoretical studies in RC4. It proposes a process to prototype experiences via XR to develop positive experiences for product-service systems. RC4 thus paves the way to develop user experience via XR in the following case studies.

Chapter 4 (RC5) starts with three case studies (C1-C3) to understand how to include extended reality at the early design stage, specifically in conceptualization. These studies focused on comfort-relevant experience in the context of a long-haul flight, which is mainly stimulated by the security drive. In addition, the studies also compared the influence of different viewpoints and ways of interaction on the perception of "being comfortable".

Chapter 5 (RC6) investigates how to involve extended reality across user groups and concentrates on competence-related experiences that are mostly stimulated by the novelty drive. The experiences of "being competent" are selected as they are broadly applied in the field of education and training, a heated domain of XR applications. This chapter contains three case studies (C4-C6) in the context of true-to-life surgical training where a successful surgery depends both on proficient psycho-motor skills and mature self-management of surgeons. In addition, these studies also observed the influences of proficiency, cultural backgrounds, and technology familiarity on the perception of competencies.

Chapter 6 (RC7) securitizes how to include extended reality in collaboration and the key is to mediate asymmetric coordination. This chapter covers two studies (C7-C8) in the context of remote co-work but applied in manufacturing or healthcare. The experiences about asymmetric coordination were selected in that they reflected the needs of "be-related" in a complicated work, which could be driven both by security and novelty. Given relatedness as a universal need, these studies focused on the influences of different interfaces, either immersive or non-immersive, on the perception of the situations and task loads.

Chapter 7 (RC8) first reviews the lessons learned from the case studies and then probes how design teams integrate immersive experiences into their practices. Hence, four co-creation studies are developed which are in line with the conceptual framework in Chapter 3. Section 7.2 aims to understand how designers craft immersive experiences within design projects. Section 7.3 targets how to enhance the design cognition of a design process via immersive experiences. Section 7.4 discusses how suitable XR technologies are used as mediators to prototype different designable elements. Section 7.5 is a pilot study to review the concept of immersive co-design space.

Chapter 8 reflects on each research question from an overarching perspective, and then generates three sets of recommendations for design stakeholders who are interested in integrating immersive experiences in their work. Finally, the limitations of this work were discussed and future research directions, particularly a concept of an immersive co-design community, 'Design Metaverse', were proposed.

CHAPTER 2

Understanding immersive experience from the user's and designer's perspectives

The immersive experiences generated by extended reality (XR) systems are the medium where designers can "touch" the world of the users and collect insights to develop product-service systems that meet users' needs and wishes. This chapter hence focuses on the research question "*What are the key factors of immersive experiences in product-service systems both from the user's and designer's perspectives?*"

Section 2.1 provides an overview of the most common terminologies from existing literature on the topic of "immersion" and "immersive experiences" and identifies connections between them. These terminologies are mapped out into a theoretical model that acknowledges the immersive perception of users as the core. Based on this model, a step-by-step checklist is developed, which is used in three immersive experiences to analyze and identify the key elements.

Section 2.2 shows an overview of the state-of-the-art commercially available XR platforms, the software from which designers can generate immersive experiences. This study analysed: (1) how these XR platforms match with different types of immersive experiences, and (2) at which stages of the Human-Centred Design processes each XR platform could be applied.

Section 2.1 is adapted from the publication:
Cesar Lucho Lingo, Meng Li, A.P.O.S. Vermeeren (2021). The Immersion Cycle: Understanding immersive experiences through a user-centred approach. *Proceedings of the Design Society*. 2021 August 16th-20th:3011-20, Gothenburg, Sweden.

Section 2.2 is adapted from the publication:
Meng Li, Daniel Houwing, Armagan Arbayrak, Mohammad Shidujaman, Daan van Eijk (2023). Mapping XR Platforms: Analysing Immersion from the Designer's Perspective. In M. Kurosu & A. Hashizume, *Human-Computer Interaction* HCII2023, Copenhagen.

2.1. The Immersive Cycle: Understanding Immersive Experiences Through a User-Centered Approach

2.1.1. Background

Our society is evolving continuously, and the advancement of technology fuels this trend. These societal-technological challenges reshape the processes of designing and developing products and services. Among these technologies, immersive technologies form one of the most prominent opportunities to transform the processes of designing. *Virtual Reality* (VR), *Augmented Reality* (AR), and *Mixed Reality* (MR) are well-known examples of immersive technologies, more precisely *Extended Reality* (XR), which "present a vivid virtual environment while shutting out physical reality" (Cummings & Bailenson, 2015). Since its first manifestation, the idea of using software and hardware to stimulate, enhance, and complement real-life environments has been widely studied and used by different researchers and practitioners across different fields. From the understanding of technology's role in the diverse types of immersive experiences in our contemporary life to the development of different ways of understanding immersive experiences (K. Kim et al., 2018; Pan et al., 2006). The combination of immersive technologies with activities in different fields, like video games and educational training, creates what is known as immersive experiences.

Presence, the core of immersive experiences, is defined as "the subjective experience of being in one place or environment, even when one is physically situated in another" (Witmer and Singer, 1998). On the other hand, the definition of "immersion" is either a synonym or a subcomponent of presence (McGloin et al., 2013; Witmer & Singer, 1998). Slater and Wilbur (1997) proposed a distinct difference between "presence" and "immersion": presence describes the psychological functions of humans while immersion depicts the quality of technological systems. Although these research, theories, and models were focused mainly on technological aspects of immersive experiences, a human-centered approach is missing; to be more precise, a user-centered perspective for understanding the general processes users undergo when they are parts of a virtual environment. Our model proposed in this section/study identifies the different concepts that different researchers (across time) have addressed as part of the immersive process, creates a framework where the user is at the core, and explores the possibility of how the different stakeholders can be facilitated to create immersive experiences.

In section 2.1.2, an overview of the similarities and differences between various immersive technologies and their contribution to immersive experiences is provided. In Section 2.1.3 immersion as a psychological phenomenon will be presented, and how it is being understood or used in the entertainment industry and educational training field. In Section 2.1.4, the immersion-relevant concepts will be organized into a cycle model by the user's presence. In section 2.1.5, a comparison will be made between the proposed model and the existing models and a checklist will be introduced. Section 2.1.6 explains how developers and designers could use the model and the checklist or guideline. Finally, section 2.1.7 presents an overview of future research for further development and validation.

2.1.2. Extended Reality Experiences – Similarities and Differences Across Time

XR experiences reflect the goal of triggering the feeling of immersion during an experience via immersive technologies. Over time, different researchers tried classifying these types of experiences based on the used technology. This classification was either based on; (1) how it was displayed or the type of peripheral devices it required (Psotka, 1995), or (2) how these technologies interact with their users and their surroundings (Azuma, 1997; Bowman & McMahan, 2007; Catalano, 2011; Milgram et al., 1995).

In recent times, the categorization introduces three types of XR experiences based on the level of digitization by Benford et al. (1998): Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR takes advantage of generating virtual environments around its users, typically by asking its users to use a head-mounted display device (HMD). The software and hardware's processing power affects the realism and the sensorial experience delivered through this XR experience type (Psotka, 1995). AR combines real-life environments with computer-generated perceptual elements, creating an "enhanced real-life environment" (Azuma, 1997). To achieve this, it is necessary to possess a device with the necessary technical features to display the generated virtual elements to the user. Currently, the most common devices for this are smartphones and tablets. By experimenting with the different types of perceptual and sensorial cues used to enhance AR's existing interaction, the concept of MR arises (Milgram et al., 1995). The relationships between computer-generated elements and real-life elements from the environments are intertwined and symbiotic. For example, while a real-life element can provide the idea of an object's weight or texture, computer-generated elements can visually overlap the real-life environment to complete the object's features in terms of colors and final shape. This immersive experience involves a more in-depth understanding of the relationships between real-life elements and computer-generated elements. Additionally, MR requires a similar device as AR. Furthermore, even though the technology and the types of experiences have been changing over time, the core goal has been always allowing XR experience users to feel immersed during the experience. This leads to the following question: How does immersion occur?

2.1.3. Understanding Immersion as A Phenomenon

Immersion is a phenomenon that has been studied for the last 30 years. During this time, different theories about how immersion occurs have been proposed. Two of the most prominent fields in which these are used today were analyzed: entertainment and educational training. The concepts that are found and are similar in the abovementioned fields will be presented.

In the entertainment field, video games are the most representative form of XR experiences. Thanks to virtual environments' immersive capabilities, the overall gaming experience is enhanced (Althoff et al., 2016; Catalano, 2011; Nacke & Lindley, 2008; Paavilainen et al., 2017; Tran Duy, 2017). In educational training, surgical skill training has benefited from immersive experiences. In both cases, immersive realities take advantage of sensorial stimuli during the simulated experience, which affects not only the user's objective-focus reasoning but also their emotions and moods (Ahmed et al., 2018; Azuma, 1997; Halabi & Halwani, 2018; Huber, Wunderling, et al., 2018; Li et al., 2020).

The just-mentioned situations relate to what different studies introduce as the "being there" effect, based on the described feeling of being part of something happening around the XR experiences' users. A starting point to achieve this experience relies on the *senses* (Bowman & McMahan, 2007; Ermi & Mäyrä, 2005; Psotka, 1995; Slater & Wilbur, 1997; D. Wang et al., 2019). Based on the idea of senses, different researchers established the ideas of *sensorial stimuli*, *sensorial immersion,* and *sensorial fidelity*. Sensorial stimuli comprise the effects of senses during an XR experience on its users (Bowman & McMahan, 2007; Psotka, 1995). *Sensorial immersion* combines the *sensorial stimuli* (give some examples) and connects them with the action, interactions, and dynamics between the XR experience's user and the simulated (or partially simulated) environments (Ermi & Mäyrä, 2005; D. Wang et al., 2019). *Sensorial fidelity* refers to the similarity between the sensorial stimuli from the real-world environment users perceived in the past and what they are experiencing in a simulated environment (Bowman & McMahan, 2007).

In general, the stimuli, interactions, actions, and dynamics during an experience are collected in different types of memories. The sensorial stimuli are connected to short-term memory, such as *sensorial memory* (Carlson, 2010), while the actions, interactions, and dynamics are connected to long-term memory, particularly *episodic memory* (Csikszentmihalyi, 2008). With these, XR experience users can recall and link specific actions, dynamics, or interactions they performed during an XR experience to corresponding experiences from real-world or other simulated environments via sensorial stimuli. This recalling and linking lead the user to be aware of their presence during the XR experience, similar to real-life environments (Slater, 2003). Moreover, as Slater and Wilbur (1997) stated, the idea of *presence* represents the subjective and psychological consequence of sensorial immersion and stimuli. In contrast, *immersion* represents what could happen in a system where the illusion of reality through sensorial stimuli can be achieved, becoming objective and quantifiable. This idea means that XR experience users are required to be aware of their presence by performing different actions, dynamics, and interactions alongside sensorial stimuli during the experience to create the idea of immersion.

The actions, dynamics, and interactions define what is known as the level of *involvement*, which affects the user's interest in the experience. This interest is also affected by *engagement*, defined by O'Brien and Toms (2008), as "a category of user experience characterized by attributes of challenge, positive affect, endurability, aesthetic and sensory appeal, attention, feedback, variety/novelty, interactivity, and perceived user control". The engagement of an experience is strongly connected to the *Flow Theory*, balancing the perceived level of challenges and the skills of a person in reaching the "flow state", which is "a holistic sensation that people feel when they act with total involvement" (Buchanan & Csikszentmihalyi, 1991; Csikszentmihalyi, 2000, 2008). The *Challenge* factor during an experience is also explored and presented by Ermi and Mäyrä (2005) and O'Brien and Toms (2008). According to Ermi and Mäyrä (2005), it is possible to achieve immersion by combining the environment with involvement and engagement through challenge-based activities, as is common in video games. The relationship between engagement, "flow state", and immersion is also addressed by Shin (2018).

In turn, the engagement and involvement factors are linked to *imagination* and *imaginative immersion* (Ermi & Mäyrä, 2005; D. Wang et al., 2019). Through the *matrix of experiences* proposed by Pine and Gilmore (1999), the relationship between imaginative immersion, engagement, and involvement can be understood. In this matrix, the *participation* and *connection* variables can determine how people will face an experience in terms of their actions (active or passive participation) and their presence (immersive or absorptive connection). The possible resultant combinations of these variables, also known as "natures of the experience" (e.g., escapist, esthetic), are not static but dynamic ones, depending on how these variables change across time.

As stated at the beginning of this part, the immersion-relevant concepts and theories from different studies are explored and an overview is created, as shown in Figure 2.1-1. Twelve key concepts refer to the phenomena of immersion. Each piece of literature shows the link between specific concepts in the group, which provides an opportunity to organize them into one model.

	Immersion	Sensorial Fidelity	Sensorial Immersion	Sensorial Stimuli	"Being there"	Challenge	Connection Participation	Involvement	Imagination/ Imaginative immersion	Presence	Interaction	Engagement
Bowman and McMahan (2007)	X	X		X	X							
Dangxiao et al. (2019)	X		X								X	
Ermi and Mäyrä (2005)	X		X			X			X			
O'Brien and Toms (2008)				X		X					X	X
Pine and Gillmore (1999)							X	X	X			
Psotka (1995)	X			X	X							
Shin (2017)	X				X					X		X
Slater and Wilbur (1997)	X				X			X		X		

Figure 2.1.1 Immersion-relevant models referred to by different studies

2.1.4. Arranging the Concepts: The Immersive Cycle (IC)

The researchers at this stage align the concepts identified above into a single process in understanding the key factors of immersion and what occurs with the user in an immersive environment. Based on the sensorial stimuli and the level of involvement (interactions, actions, and dynamics), it is possible to identify the nature of experience based on the participation and connection variables. The similarity of the user's previous experiences will confront the nature of the XR experience (fidelity). Simultaneously, the imaginative immersion complements the XR experience and the memory of past experiences (i.e., episodic memories). The XR experience's fidelity to the user's past experiences, the imaginative immersion, and the XR experience's nature combined will address the engagement factor during the experience. Thanks to the engagement factor during the XR experience, people will obtain a feeling of presence. By taking advantage of the engaging characteristics, the experience's developers and designers can establish situational challenges across the XR experience to reach the idea of immersion (as occurs in video games; Ermi and Mäyrä, 2005), which, is also called the "being there" effect on the user.

However, due to the changing nature of the experience which combines the different stimuli, actions, and interactions that users will be facing across an XR experience, the immersive process cannot be expressed as a single, linear process. During the XR experience, users will be confronting specific moments that could be either new for them, related to past experiences, or a specific fragment of them. In that regard, once users achieve the "being there" effect, the experience will be transformed into new memories. These new memories will be a part of either the user's sensorial memories or episodic memories.

Imagination appears as a central element in the immersive process. This element can be perceived as a general concept; however, it performs a critical role in the model. Imagination helps users make sense of what they are experiencing during an XR experience; it can enhance the originally proposed experience and transform it into a more in-depth experience. Also, imagination interacts with the information from the stimuli, the XR experience's level of involvement in conjunction with users' past experiences, helping them to understand what is happening during the experience. Moreover, if the experience possesses a cohesive narrative or story, the user's imagination can be guided, making sense of what users are experiencing.

Based on the different concepts that the researchers have found and by taking a human/user-centered perspective, the researchers developed the so-called *Immersive Cycle* model (IC), shown in Figure 2.12.

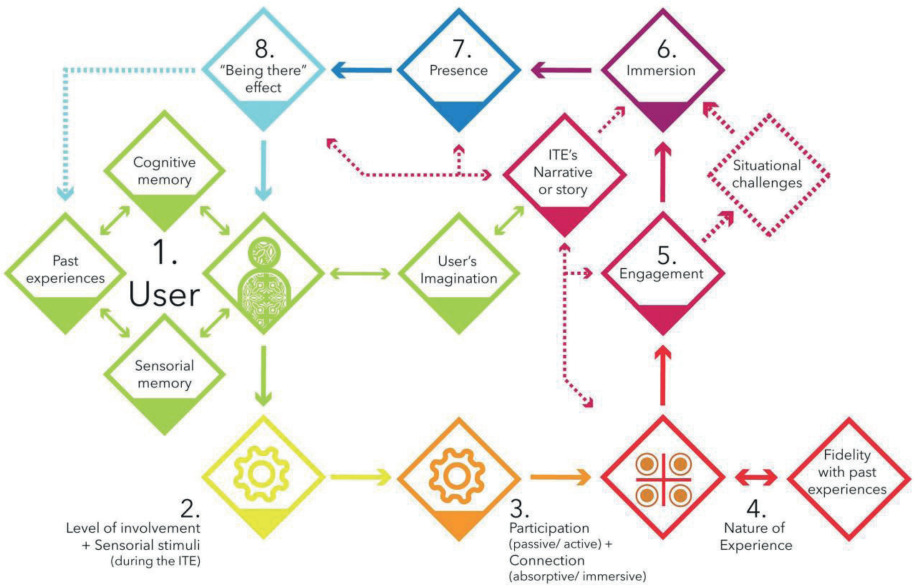


Figure 2.1.2 The Immersive Cycle Model

The IC model is a cyclical approach since the user becomes the starting point and the end of the immersion process, which contains eight steps:

Step 1 - Alongside the user, the concepts of the user's past experiences, sensorial memory, episodic memory, and imagination will also be present during the cycle.

Step 2 - The XR experience's sensorial stimuli and its level of involvement (proposed by the XR experience's developers) will shape the user experience. These elements are intertwined in the experience and will affect the user's imagination.

Step 3 - Via these elements, the nature of XR experiences can be defined by the developers and unconsciously (or consciously) assessed by XR experience's users based on its *connection* and *participation* features.

Step 4 - Users will confront the nature of the experience with their past experiences.

Step 5 - The experience's nature precedes the engagement. The engagement could benefit from situational challenges in conjunction with a proposed narrative or story through the XR experience.

Step 6 - The combination of these elements will lead to immersion.

Step 7 - The perception of presence follows the immersion.

Step 8 - The influence of presence and the XR experience's narrative or story will help the user reach the "being there" effect. Once the "being there" effect is reached, the XR experience will transition into new memories (sensorial and cognitive), returning to Step 1.

It is important to mention that the nature of experience (4), engagement (5), immersion (6), presence (7), and the "being there effect" (8) are affected by the user's imagination and vice versa. This situation happens due to the narrative or the story that goes across the experience. XR experience developers and designers must think of the narrative or story because it will guide the users across the XR experience (Brooks, 2003; Ermi & Mäyrä, 2005). Complementary, the elements in the IC do not appear only once during an XR experience; in reality, it happens at different times and speeds if the user is still exposed to the XR experience and how the narrative or story is proposed and unfolds.

2.1.5. The Immersive Cycle as A Checklist for Immersive Experiences from A User-Based Perspective

Currently, different models address immersion from various perspectives: for a specific type of experience like the *Gameplay Experience model* by Ermi and Mäyrä (2005); or as a technical approach, like the *Human-VE interaction loop* by Bowman and McMahan (2007); or the focus on aspects of immersion that occurs during user experiences, like the model proposed by (Shin, 2018). Although the IC collects its key concepts from these models, it distinguishes itself from them for different reasons.

Coming to the main differences between the IC model and these models, the researchers first notice that the IC focuses on general definitions for immersive experience transformed into new sensorial and cognitive memories, whereas the Gameplay Experience model focuses just on gaming (Ermi and Mäyrä, 2005). In addition, IC tackles concepts that inspired the immersive cycle's creation, like past experiences, senses, and challenges. Second, the IC focuses on what the user will experience through the immersion process. In contrast, the human-VE interaction loop focuses on software and hardware concepts that are part of the XR experience (Bowman and McMahan, 2007). Third, the IC model offers a cyclical approach that starts and ends with the user; thus, the model integrates *User Experience* with the *Quality of Experience* as a whole. Nevertheless, Shin's model (2018) presents a linear approach to immersion by dividing the concepts related to the phenomenon into two parts and then interconnecting them to reach *engagement*.

Based on the previous comparisons, the IC suggests an interesting opportunity for developers and designers of XR experience in terms of organizing and proposing an experience. For this matter, the researchers propose a step-by-step checklist that complements the IC (shown in Table 2.11).

Table 2.1.1 Immersive Cycle's checklist

Steps	[The Title of an XR experience]
1. User	-Which type of senses do we want to stimulate in the user? -What do people remember from past experiences that can be used for the XR experience? -How will the user's imagination be triggered by different elements and the narrative across the experience? -Who are the people who are going to become users of our XR experience?
2. Level of involvement + Sensorial stimuli	-What do we want to introduce in terms of interactions, dynamics, and actions during the experience? -What stimuli are we using alongside the interactions, dynamics, and actions during the experience?
3. Participation + Connection	-Do a user's actions affect the environment or other elements that are part of the experience? -Is the user going to spectate as an outsider (its presence is just symbolic) or as part of the experience?
4. Nature of experience + Fidelity with past experiences	-Based on the participation + connection answer. What is the nature of the experience? -Is this a nature-like experience that the user has already lived? How similar or different are they?
5. Engagement	-How engaging is the narrative or story that we want to propose during the experience? -Do we need to challenge the user with something to keep him/her engaged?
6. Immersion	-Are the previous elements cohesive with each other and do they make sense within the proposed narrative or story?
7. Presence	-Is the user reacting to what is experienced alongside the narrative? -In which sense is this reaction: Cognitive, physical, or sensorial?
8. "Being there" effect	-What are the elements that we expect the user to remember? Which specific actions or sensorial stimuli are in particular? -Is the "Being there effect" achieved by the cohesion of the previous elements that led to the immersion?
9. Miscellaneous (General)	-What do we want to achieve with our XR experience? -Is there a necessity for a detailed narrative or story across the experience?

With this checklist, the researchers want to reach two purposes: (1) to translate the visual cycle into a mapping tool for immersive experiences based on the process users undergo while experiencing an XR experience; (2) to serve as a checklist for early stages in the development of an XR experience. In contrast to existing questionnaires like those developed by Witmer and Singer (1998), the Immersive Cycle's checklist is oriented toward starting a conversation between users and designers rather than collecting concise or straightforward responses from users, giving the designers the necessary freedom for exploring and defining the ideas of an XR experience. Another purpose of the checklist is to initiate a dialogue between the developers and designers about what they need to consider about an immersive process. Additionally, there are questions at the end of the checklist focused on general aspects. It is expected one would use the IC as a flexible tool for the ideation and conceptualization of an XR experience rather than as a strict framework.

2.1.6. Case Studies: The Immersive Cycle as A Mapping Tool

To explore the value of IC as a mapping tool, different cases have been analyzed and the proposed immersive cycle checklist is applied to these case studies. The selected cases are shown in Figure 2.13, including:

(1) the gravity gloves experience in Half-Life Alyx, a VR video game developed by Valve Corporation, displayed via high-end VR headsets like Valve Index, HTC Vive, Oculus Rift, and MS Mixed Reality;

(2) a virtual prototype of a privacy protection seat in a future airplane cabin, developed by Delft University of Technology, displayed via HTC Vive;

(3) and the In-Car 6-DoF Mixed Reality for Rear-Seat and Co-Driver Entertainment by Haeling et al. (2018) in collaboration with Daimler AG, displayed in Oculus Rift.

Figure 2.1.3 The three cases: A) the Gravity gloves (source: theverge.com); B) the Privacy protection airplane seat; C) the In-car 6-DoF mixed Reality for Rear-Seat and Co-Driver Entertainment (source: IEEExplore.org).

In the three cases, users first achieve the "being there" effect by following the different steps in the immersion process. Multi-sensorial sensation, ordinary interactions, and immersive connection from stereoscopy produced the "wow" effect for first-time VR users. Finally, active, or passive engagement retains their attention. The integration of perceptual sensation into the narrative, as well as the virtual embodiment of users, needs further exploration to understand their compound effects in immersive experiences. The detailed analysis is shown in Table 2.12 The cases analyzed using the IC checklist.

Table 2.1.2 The cases analyzed using the IC checklist

Step	The Gravity Gloves of Half-Life Alyx
1. User	- Haptic, iconic, and echoic. - Reuse the experience from daily life to make as natural as possible interaction - Previous gaming experience (keyboard or controller)
2. Level of involvement + Sensorial stimuli	- The "ordinary" actions inside the game trigger an organic involvement between the player and the environment. - Simultaneous audio and visual feedback while the player's motion occurs in a game.
3. Participation + Connection	- The player's actions are the catalyst for the game's progression and experience (participation) - The player's presence is necessary for the game experience (immersive connection)
4. Nature of experience + Fidelity with past experience	- Active participation + immersive connection - This type of nature is similar to daily life experiences in most cases
5. Engagement	- Players are required to interact with the environment to progress with the narrative - The challenges are merged with the interaction with the environment
6. Immersion	Yes, the engagement factor occurs thanks to the narrative and interactions merged, reaching immersion.
7. Presence	- The user is reacting to the experience and the narrative. - The reaction is happening on three levels: cognitive, physical, and sensorial.
8. "Being there" effect	- Yes, the "being there" effect is achieved - The fact that players perform specific actions to achieve specific goals is the one that will be kept in the player's memory
9. Miscellaneous (General)	-Here it is shown what VR can reach if it's integrated into the narrative of a game experience.

The Privacy Protection Airplane Seat	Co-Driver Entertainment Experience
- Iconic and echoic - The users recalled their comfort-related experience of long-haul flights in real life - The virtual cabin brought the context of air travel and the animation of different functions shown as a miniature of long-haul flight in reality	- Iconic, echoic, haptic and smell - Reuse the sensations that are involved in traveling as a passenger in a car.
- The users used virtual hands to "pull down" the privacy shelter which is an "analog" to bring the user's involvement. - Simultaneous audio and visual stimuli started with the "analog" and played automatically	- The level of involvement is not so high in terms of the role the users have to perform during the experience (passenger). - The stimuli combine a different aspect of the real-life experience (the feeling of being inside a moving car) with the simulated environment (provided through the HMD)
- The user's action served as a switch of a set of automatic narratives (active participation) - The user's presence is never in the evaluation/ experience (immersive connection)	- The user's actions don't affect the experience (passive participation). - The user's presence is necessary for the experience (immersive connection)
- Semi-active participation + immersive connection - This type of nature is partially matching the daily life experience	- Passive participation + immersive connection - This experience isn't separate from the experience of being a passenger in a car.
- Users only need to interact with the "switch event" to progress with the narrative - No challenges are included in the environment	- The stimuli can be engaging, however, a narrative could enhance the entire experience's engagement - There are no challenges during this experience. However, subtle tasks through sightseeing could be added in favor of a narrative.
Yes, the full-scale prototype of both the cabin and the seats brings immersion.	The mixed reality (simulated and real-life stimuli) in this experience helps to reach the immersion feeling.
- The user concentrates on the functionalities needed to be evaluated. - The user goes around the seat and checks it from different angles, including from inside the shelter	- User's presence is occurring in the physical domain which affects slightly the user's cognitive processes.
- Yes, the "being there" effect is achieved. - The users viewed the shelter with a virtual body that felt even more realistic than from the outside.	- The "being there" effect is occurring thanks to the mixed reality taking advantage of the simulated inputs with the real-life inputs.
- Here it is shown that the embodiment of the users in VR brings a new dimension to the user-centered evaluation	- Here the possibility of taking advantage of real-life experiences to enhance the simulated experience is demonstrated.

To summarize, the next key features are important for an immersive experience:

- *Multi-sensorial memory*: at least three sensorial memories were concurrently activated, including iconic, echoic, and active or passive haptic.
- *"Ordinary"* actions as involvement triggers: The virtual environments replicated the principles of actions from daily life, such as "pull-down" the virtual shelter with virtual hands.
- *Immersive connection:* images from high-resolution VR headsets triggered a dominant sensation of stereoscopic vision, and isolated the distractions from physical environments.
- *Active or passive engagement:* either direct interaction (Alyx) or semi-automatic interaction (privacy seat) and simulated environmental stimuli, especially distractors (co-driver entertainment), could keep user attention throughout the experience.
- *Immersion:* interactive narrative, full-scale prototype prototypes, or mixed stimuli could serve as the key triggers for the immersion.
- *Presence:* physical, sensorial, and cognitive reactions or the resonance between them were observed alongside the narrative.

2.1.7. Conclusion and future work on the Immersive Cycle

The main advantage of this cyclical approach is that it takes the perspective of users. While traditional approaches relate to a developer's perspective, the IC model focuses on developing a step-by-step checklist to understand immersion from a user's perspective.

With the introduction of the cyclical model to describe the process of immersion in XR experiences, designers can perceive the importance of the user across the process. The user's role starts at the beginning of the immersion process, goes across the different steps that occur during an XR experience, and finishes with the user again, collecting new memories based on the experience that he/she went through. Additionally, by recognizing the steps involved in the cycle, designers can deep dive into the different characteristics of immersive experiences they are developing, as the researchers demonstrated with the previous case studies. Furthermore, in that sense, developers and designers can use the IC as a mapping tool across different XR experiences from a user perspective or as a conversation starter to ideate and conceptualize immersive experiences. The future applications of IC in ongoing products and service development need to focus on efficacy with developers and designers via various XR experiences.

It is important to emphasize that this model does not introduce new concepts about immersion but reorganizes existing ones in a single model. It addresses the user as the most important element during an immersive experience, as was shown when comparing the IC model with other models. The model can be used to analyze XR experiences as shown in the case studies and needs to be used by designers in the early stages of designing or redesigning an XR experience. In that sense, the proposed checklist that accompanies the visual approach (Figure 2.12) is the first version that will be developed based on further studies with developers and designers of XR experiences in chapter 7.

2.2. Mapping XR Platforms: Analyzing Immersion from the Designer's Perspective

2.2.1. Introduction

Understanding humans has been acknowledged as superior in creating better design solutions for product-service systems (Stappers et al., 2007). On one hand, designers use many methods and tools to understand human needs and requirements, particularly Human-Centered Design (HCD) methods (Van Boeijen et al., 2020). On the other hand, HCD methods often focus on specific design elements instead of the entire episode of the human-system interaction. Most of the HCD models thus articulate pragmatic and technology-focused design qualities, which can remove barriers to fulfilling human needs instead of targeting the positive experience itself. Experiential approaches are in line with but beyond typical HCD models (e.g., usability) as they generate positive experiences to contribute to human well-being. Extended Reality (XR) showed the potential to replicate or simulate the entire experience of product-service systems (Lingan et al., 2021), thus gaining attention from design communities. However, the fast-growing XR platforms and the diversity of immersive experiences that they can create are unknown by designers and therefore have limited implementations in practice. This study aims to explore: 1) the state-of-the-art XR platforms and the immersive experiences they can create, and 2) how XR platforms are applied in a human-centered design process.

2.2.2. Related Work

XR: a new opportunity to develop user experience in product-service systems

Extended Reality (XR) as the key technological setting to generate immersive experiences, is more and more applied in the domains of interior design, architecture, product development, simulation, training, and education. The first-person immersion generated by XR platforms could enhance key components in creative and intuitive processes, like emotional engagement and multisensory solicitation (Pietroni, 2019). Additionally, XR supports true-to-life simulations, which are as effective as corresponding experiences in the real world (Klahr et al., 2007). Studies have demonstrated the effectiveness of XR platforms for designing airport interiors

(Kefalidou et al., 2019), evaluating the ergonomics of machinery (Aromaa & Väänänen, 2016), as well as creative form-making in visual art (Keefe, 2009). Hence, a consensus in design communities is forming about the new opportunities XR platforms might bring, particularly for experience design (Kim et al., 2020). Exploring XR in experience-driven design has been accelerated by the uncertainties of global crises like COVID-19 during the last two years (IDC, 2020b).

The problems of designers introducing XR in design practices

Technological advancement enables XR platforms to craft experiences with high fidelity. Designers, however, are unfamiliar with these platforms and therefore do not use their full potential. Different studies revealed both benefits and limitations of XR platforms in product-service system design (Rieuf et al., 2017; Toma et al., 2012). Considering the different functionalities and creating pipelines of XR platforms, they may add value to some design stages and activities but might be incompetent for others in terms of time and cost. For example, Rieuf et al. investigated how XR augments the quality of design outcomes at the early design stages and found out that the XR experiences effectively enhance design qualities (Rieuf et al., 2017). Kim et al. (2020) showed the advantages of XR simulation to enhance the aesthetics and originality of the final design. When introducing XR during the development, it became however troublesome. For example, modeling is less intuitive and even more frustrating in VR than on the desktop (Toma et al., 2012). The researchers interviewed industry team leaders and showed that generative tasks (like modeling) seemed more difficult in XR than ideating tasks like brainstorming and sketching. Some design professionals who are keen to integrate XR into design practices felt frustrated, even if they used XR for sketching instead of modeling.

Without a clear overview, designers can hardly decide where and when it is necessary or beneficial to implement XR, resulting in skepticism and a low application rate (Armstrong, 2018). It thus needs to be researched for which design stage XR brings opportunities and for which design challenges XR is not yet ready. By observing the curiosity and the struggles of design teams when applying XR, the researchers find it necessary to analyze experiences from current XR platforms from the perspective of designers. The goal of this study is to realize an overview of XR platforms in terms of the categories of experiences and the HCD process, as well as recommendations for different designers. This study will investigate: (1) how XR platforms can be categorized according to their experiences in an experiential model, and (2) at which stages of HCD processes can different XR platforms be useful.

2.2.3. Studies

Study 1 – The categories of the state-of-the-art XR platforms based on immersive experiences

Method

Selecting XR Platforms

The website, *XRcollaboration.com*[1], is a well-known open dictionary to register the latest XR platforms, including development toolkits, digital galleries, or virtual campus/ conferences both from big companies and start-ups. The XR platforms enrolled in this platform were the main source of this study. These XR platforms are documented via a structured one-pager on the website. The researchers collected the documents of seventy-one systems listed in the dictionary up to January 2022, whereas two systems were excluded because they are merely concepts, or their XR-relevant functions were too limited, such as a hidden VR plugin. Nineteen XR platforms from the interviews with team leaders were added when they were not listed but were well-known in the design community. In total, eighty-eight systems are included in the analysis.

Defining Key Categories

To analyze the XR platforms concerning the categories of experiences, the first step is collecting their key attributes of them. At first, the one-pagers of each XR platform were reviewed and corresponding characteristics were collected in a spreadsheet following the six filters on the dictionary: max. collaborators and speculators, hardware support (i.e., XR headsets), collaboration types, OS platforms, features, and industry. The one-sentence description of each platform from the one-pagers is recorded as well. The researchers independently labeled each platform based on its description, collaboration types, and features. When the information of a platform from the dictionary is not sufficient to put a label, the researchers searched for external sources (e.g., video demos) from its official website. Then they compared the labels of the platforms together. If there was a disagreement about a label, the team reviewed the collected information about the platform to decide the label about it.

Labeling XR platforms requires an iterative process. For example, there can be a lot of similarities between a platform tagged as 'Conference Room' and another one tagged as 'Roam & Discover'. After the first round of labeling, the researchers put platforms with similar tags side-by-side and identified the differences: the platforms that have conference rooms but allow visitors to walk out and roam into a bigger world belong to the Roam & Discover, whereas the Conference Room is restricted to allowing a single meeting room. Thus, when the researchers checked the key attributes to label the categories, they kept in mind that if the category seems to be ambiguous, look at

1 https://xrcollaboration.com/directory/

similar categories. The final categories are labeled in such a way that they best describe the attributes of the category (shown in Figure 2.21).

In the end, nineteen categories with specific names and synopses were identified and the numbers of XR platforms in each category were calculated. Each category is coded with different colors for the statistical analysis.

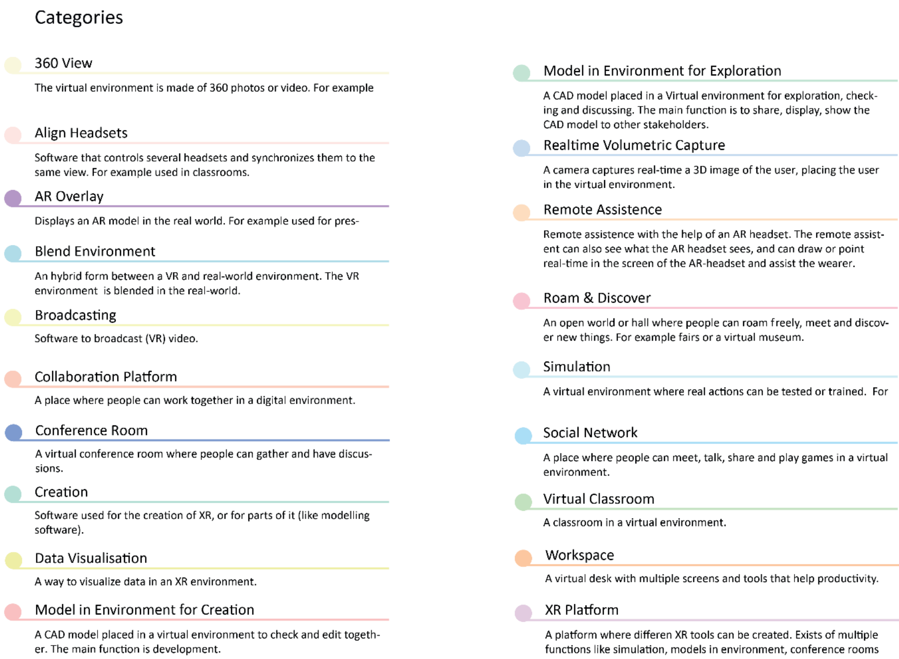


Figure 2.2.1 The key categories of XR platforms

Mapping XR platforms on the Experience Matrix

The researchers applied the *Experience Matrix* by Pine and Gilmore to show the types of experiences that can be created via these XR platforms (Pine & Gilmore, 2011). As a key step in the Immersion Cycle model, this well-known model (Figure 2.22) explains the dimensions to engage the receiver of an experience (Lingan et al., 2021). On the participation dimension (X-axis), the researchers chose supported hardware (e.g., stereoscopic headsets) and OS platforms (e.g., smartphones or Web XR) to analyze whether an XR platform provides an absorptive or immersive experience; on the connection dimension (Y-axis), the researchers selected collaboration types (e.g., co-working or lecture) and features (e.g., CAD images or 360 images) to analyze that an XR platform can support active or passive interactions. The XR platforms are mapped into the four quadrants regarding the 'participation' and 'connection' dimensions.

The quadrants indicate the types of experiences that can be crafted via different XR platforms, including *Entertainment*, *Educational*, *Esthetic*, and *Escapist*. The *Entertainment* quadrant indicates the *absorb-passive* realm where experiences "go into" receivers from a distance and receivers' actions do not influence the process, such as listening to a joke. The *Educational* quadrant represents the *absorb-active* aspect where receivers absorb events with active engagement of mind or body. The *Esthetic* quadrant implies the *immerse-passive* facet where individuals are immersed in an event or environment without any influences on it. The *Escapist* quadrant depicts the *immerse-active* sector where receivers are completely immersed as active participants. The researchers utilized a bubble chart (see Figure 2.24) to show the distribution of XR platforms across these quadrants. Each bubble represents a category, and the size is proportional to the number of XR platforms belonging to this category, where platforms within the category are scattered randomly.

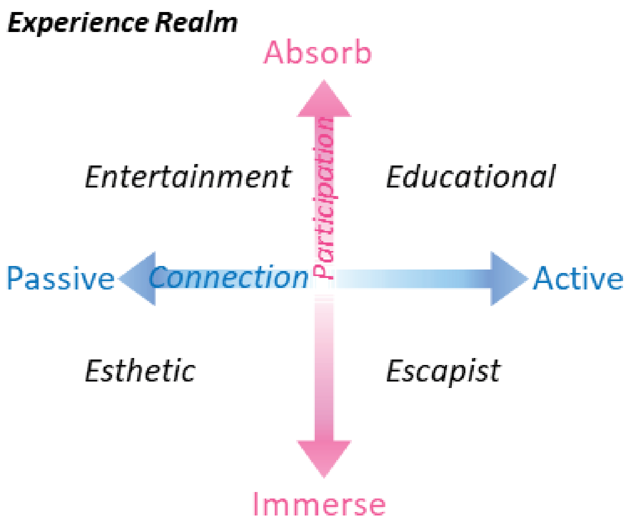


Figure 2.2.2 The Experience Matrix with the 'participation' dimension (from absorb to immerse) and the 'connection' dimension (from passive to active) (Inspired by Pine & Gilmore, 2011)

Results

The Categories of XR Experiences

In Study 1, nineteen categories of the eighty-eight XR platforms were identified (Figure 2.23). 'Creation', 'Simulation', 'MiE Exploration', and 'Remote Assistance' represent 46.6% of the key attributes, followed by the group containing 'Conference Room', 'Model in Environment for Creation', 'Data Visualization', 'Roam & Discover', and 'XR Platform'. These nine categories in total cover 82.9% of the key attributes in XR platforms.

Creation, the largest cluster, represents the functions to create content that can be used in XR. The *Simulation* group is about a virtual environment where one can integrate advanced interaction with a model. If the researchers mainly look at the models to evaluate and explore in a virtual environment, then the researchers get at the *Model in Environment for Exploration*. *Remote Assistance* seems like a popular way to use XR as well. The main goal is to help a remote expert in assisting a worker on location. For example, drawing in an AR application with motion tracking enables the drawing to remain on the object, and not move with the camera.

The *Conference Room* often provides a virtual space for co-working, meeting, and interpersonal interaction which can be accessed via multiple ends, such as XR goggles, tablets, or smartphones. The *MiE Creation* is an extension of *MiE Exploration* where objects can also be edited. The *Data Visualization* category allows teams to visualize, manipulate, and analyze data remotely and collectively. *Roam & Discover* is an open space where guests can roam freely, supporting collaboration, marketing, or showcases. The *XR Platform* is often a software development kit to create XR experiences focusing on specific fields, such as enterprise training, product visualization, or team collaboration.

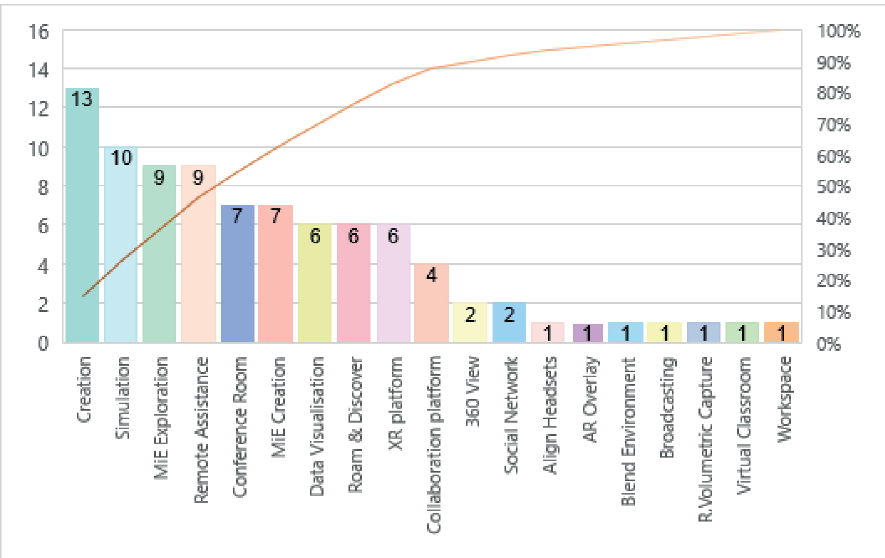


Figure 2.2.3 The distribution of the categories of XR platforms

A Map of XR Experiences

When looking at the analysis in Figure 2.24, what immediately stands out is the *escapist* quadrant is quite occupied. In this quadrant, the XR platform's experiences can immerse their receivers completely in virtual environments, where the receivers actively interact within these environments and memorize their visiting as 'places' instead of digital images.

In *simulating* scenarios that are complicated to build in the real world, user tests might be done faster, easier, cheaper, and even remotely, especially for large-scale products, like aircraft interiors (KLM, 2019), ergonomic research (Whitman et al., 2004), or urban planning (Schubert, 2017). Likewise, designing in XR can have benefits. Designer teams can work together globally and can test products with customers before major investments. *MiEE* is an interesting category for retail and design because the product can be seen in an intended environment, and it's even possible to turn, move, or scale objects. Yet these are precisely where the interesting possibilities for the future lie. In addition, *Remote Assistance* can be advantageous by sharing the first-person view and involving stakeholders in contexts, where they can choose between immersive and non-immersive platforms. It would be beneficial for mutual understanding both assigning the designer's view to users and vice versa.

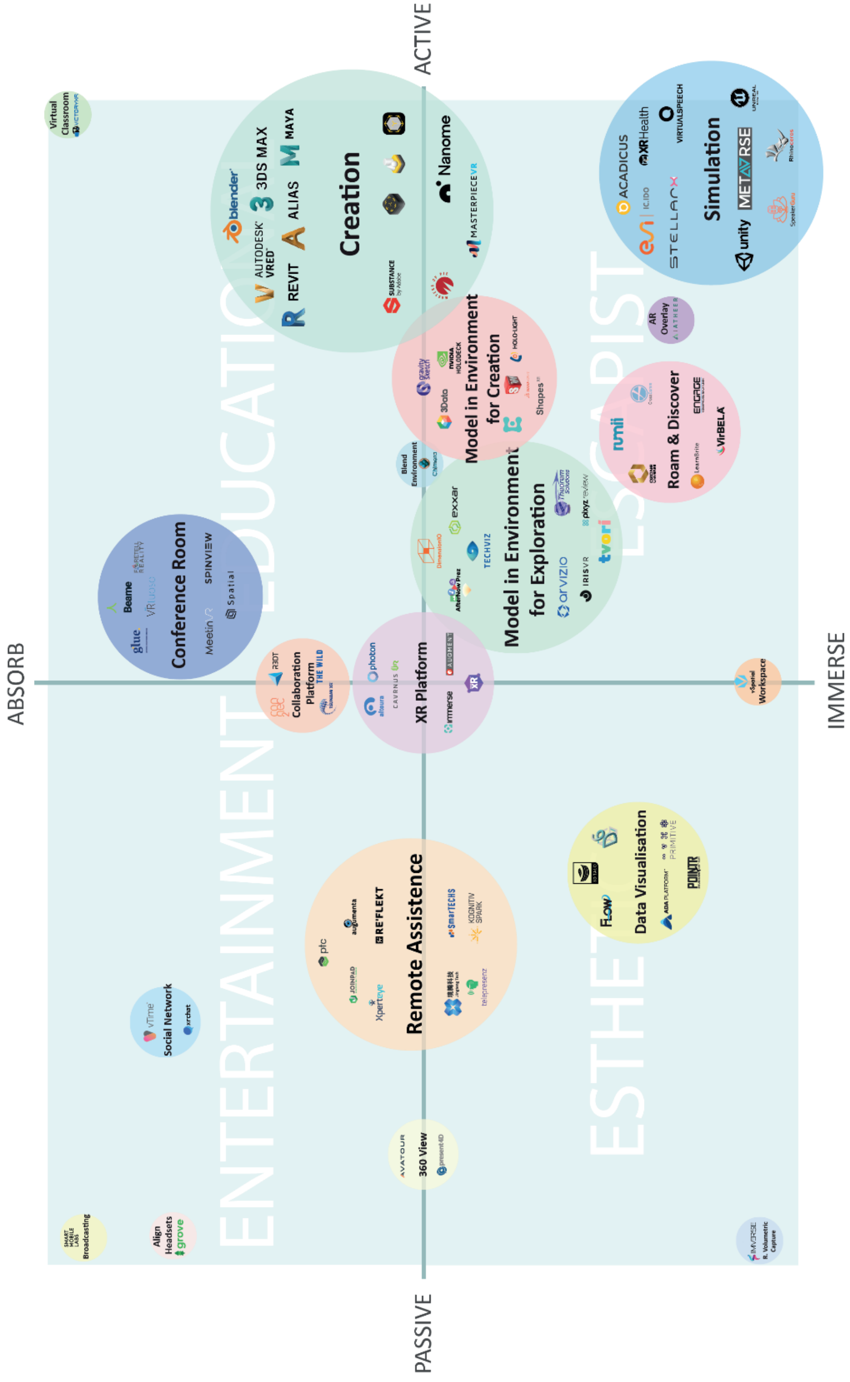


Figure 2.2.4 The XR experience map - XR platforms following the Experience Matrix

Study 2 – XR Platforms in HCD Processes

Methods

According to Miaskiewicz and Kozar's thought experiment (2011), the researchers created two personas of designers, a freelance designer and a corporate designer. The freelance designer has a limited budget for software licenses and develops XR experiences by himself/herself, while the corporate designer has more budget and can use commercial software and databases from the company. To clarify the differences between XR platform choices, a fictional design project is assigned to them, which requires creating an XR experience so that stakeholders can view a product in a particular context (see Figure 2.25).

Figure 2.2.5 The fictional kitchen design project in virtual reality

The researchers used a kitchen design as an example: CAD models simulated the requirements of a client, providing some parts in the kitchen, like a refrigerator and a stove. The cupboards need to be designed from scratch. It must be possible to interact with the drawers and kitchenware (like opening the fridge) in the VR demo. The researchers discuss the general barriers of XR platforms and their implementation strategies according to the designer's personas.

The choice of XR platforms is then analyzed according to the two personas. XR platforms from the previous study are analyzed to support HCD methods and tools in the fictional project. The XR platforms need to be assigned to the stages in the *Double-Diamond Model (DDM)*: *Discover*, *Define*, *Develop,* and *Deliver,* according to the tools and principles listed in Figure 2.26 (Design Council, 2007). If an XR platform is assigned to a certain stage, it means that it can support at least one or more design methods or tools at this stage. These XR platforms then are visualized on the *DDM*.

As need fulfillment is key to generating positive experiences, the researchers also analyzed the selected XR platforms to understand how they can support to understand users' needs and requirements (Hassenzahl, 2010). A hierarchical model of goals from the *Action Theory* by Carver (1990) is used in this survey. According to this theory, *be-goals* represent the universal needs and values of human beings, and they motivate actions and provide meaning to them; *do-goals* refer to the concrete outcomes that a user wants to attain in an action; *motor-goals* drive people to press a button or click an icon.

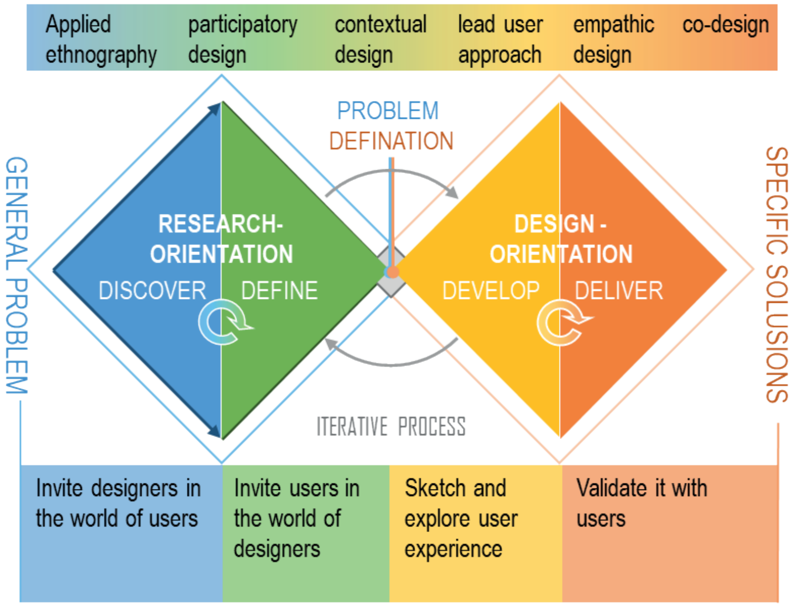


Figure 2.2.6 The DDM process with design principles and methods. On top of the double diamond are examples of HCD methods at each stage; at the bottom are the principles related to each stage. (Inspired by Design Council, 2007; Van Bijl-Brouwer & Dorst, 2017)

Results

The Barriers of XR Platforms and Their Implementation Strategies

A common problem faced by designers is the steep learning curve. In addition, the learning and developing hours can pile up when complex materials (e.g., mirrors) or interactions (e.g., interactive objects) are involved. Different types of designers developed diverse strategies to cope with it (Table 2.21).

Table 2.2.1 Strategies used by designer's personas when developing XR experiences

	Obtaining assets	Interacting assets	Texturing	Effects
Freelance designer	Purchasing models from *Sketchfab* or *Asset store*	Developing objectives using *Blender / Rhino*	Mapping textures with *Materialize* or *Substance*	Applying basic/ designated templates in *Unity* or *Unreal Engine*
Corporate designer	Company's database of models and imagery.	Autodesk toolkit including *Maya* (animation), *AutoCAD* (manufacturer), *Revit* (architecture), and *VRED* (automotive)	Autodesk material library shared by *Maya*, Revit, and *AutoCAD* or creating materials with *Mudbox*	Outsourcing to XR developers

For freelance designers, it is advantageous to use open-source software so that they save on license costs, and can invest in assets or training to save time. Freelance designers need to allocate learning hours alongside production hours to explore alternative pipelines, especially finding formats that can transfer assets between different platforms errorless. Changing purchased assets might cause errors as well. The corporate designer has more resources at his/her disposal, and there is already a stock database for images and models. They can concentrate on sophisticated design solutions. The corporate designer probably already has a high budget for an XR project. For complicated XR experiences, outsourcing is a time-efficient option. However, corporate designers have limited capacity to reuse the XR experiences afterward. Moreover, many 3D engines, like *Unreal Engine* or *Unity* are often not compatible with enterprise engineering software.

The situation is changing due to the increasing need for XR experiences. Many simulations have recently been included in open-source programs like *Rhinoceros*. Both freelance and corporate designers now can create relevant XR experiences to help clients clarify or promote their products when they can master alternative pipelines. For example, many XR platforms (e.g., *Unity*, *Unreal*, *Substances*, and *Autodesk*) offer asset stores where designers can purchase models or templates, which would save a lot of time on modeling and animating. This offers an option for freelancers, who would demand a budget from clients to purchase assets to save production hours. With the accumulated experience in developing XR experiences, the assets, i.e., models, materials, code, and environment, could be reused in different projects.

Different Ways for Choosing XR Platforms in an HCD Process
There are different ways of choosing XR platforms in the sense of time and budget. For example, freelance designers prefer open-source software such as *Blender*, which is free to use but very limited on technical support; whereas corporate designers are bound to enterprise software like *Autodesk* which a one-year subscription per package costs between two and three thousand Euros. These licenses usually are decided by the company and include different types of services from technical support to customized development. On the contrary, freelance designers have more flexibility in allocating learning and production hours, whereas for corporate designers, putting in extra hours to learn new tools requires an agreement at the organizational level. Moreover, XR developing skills serve as a new competence for freelancers as well.

The design tasks are different as well. The freelancers can easily do simple assignments, which are like the tutorial provided by each XR platform. As the complexity increases, such as multiple environments, interactive functionalities, or specific objects to be modeled, freelancers bear instant rises both in learning efforts and workloads. Precisely with these complex assignments, corporate designers benefit from licensed systems, like the Autodesk toolkit. It consists of a set of software that works in a smooth pipeline. For instance, exporting models to another program is effortless and simulations can be configured with 'one-click' functions. Hence, corporate designers can focus on more complex and detailed design tasks. Designers have different platforms at their disposal that can facilitate different design activities. The study listed selected XR platforms following the *DDM* (Figure 2.27).

The Discover stage: IC.IDO, for example, supports replacing physical prototypes with interactive and digital mock-ups with real-time physics simulations in a team of six members. It enables remote observation with teams of up to twenty collaborators as well as a maximum of forty spectators. The platforms from the *Conference Room* category, like *glue,* focusing on casual co-working and review, which mostly share 2D video, presentation, and desktop would be suitable for probe *be-goals* of users. The *Simulation* category with 360 videos and images, like the *IC.IDO* would help designers gain empathy under contexts. Other categories that help to understand be-goals are the *Data Visualization* and *XR platform*.

The Define stage: Spatial.io is an online gallery supporting self-defined rooms for shared reviews with forty collaborators. *R3DT* and *the Wild* emphasize remote collaboration that allows a twenty-person team to use CAD data for visual prototypes. *Holo-light* can create co-work AR space to inspect, manipulate, and share engineering designs. When a platform from the *Conference Room* or *Collaboration Platform* categories that share 3D assets or CAD images, like *the Wild*, it's suitable for defining a particular design problem and its relevant do-goals. The *MiE Creation* category (e.g., Holo-light) enabling visualizing, manipulating, and sharing CAD data immersively could support the survey on do-goals alike.

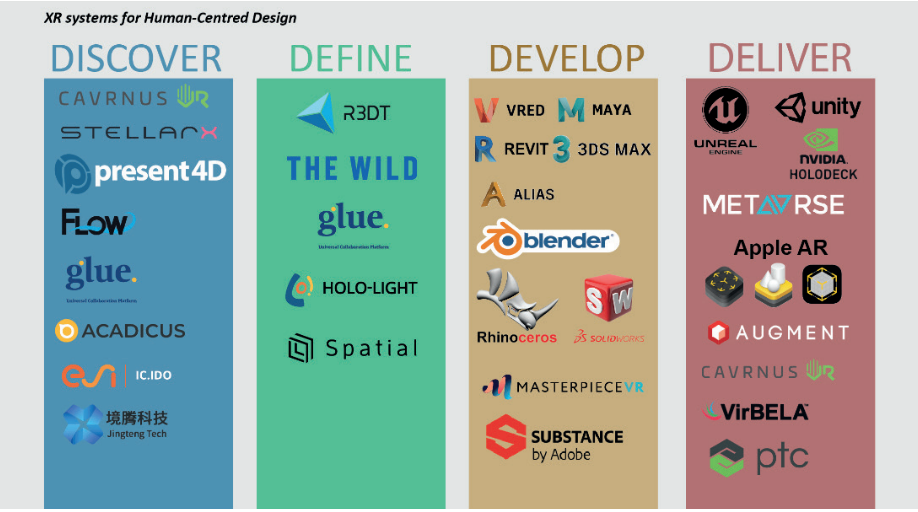


Figure 2.2.7 The typical XR platforms that are in line with the DDM

The Develop stage: The software, for modelling and prototyping, is *VRED*, *MAYA*, *ALIAS*, and *3DS Max*, or open-source software like *Blender* and *Rhinoceros*. *Substance* from Adobe focuses on 3D materials for photorealistic rendering. *SolidWorks* from Dassault Systems also put efforts into direct modeling in VR. The XR interfaces of SolidWorks and Rhinoceros can help designers check the ergonomic issues (like sizes, visibility, and reachability) with intuitions. When reviewing the early prototypes with stakeholders, designers can easily check the fulfilments of the *do-goals* and the *motor-goals* with a specific design.

The Deliver stage: XR experiences need to be released across different hardware, where the most common ones are headsets, iOS/Android smartphones, or web browsers. Additionally, advanced interactions and animations, like physics effects, are mainly made via 3D engines, like *Unreal Engine*, *Unity*, or *MetaVRse*. AR applications are popular ways to reach clients on smartphones or tablets, which are developed by *Apple AR* or *Augment*. The *HOLODECK* from NVIDIA targets a VR innovation platform to involve design teams and stakeholders. *Cavrnus* and PTC *Vuforia Chalk* can support both the *Discover* and *Deliver* stage. *VirBELA* is a web-browser-based virtual campus that provides online presentations, meetings, conferences, and customized events.

XR platforms at this stage need to deliver the essence of a specific experience to stakeholders, particularly end users. They thus shall review all levels of goals together. The platforms belonging to the *Simulation*, *Creation*, and *XR Platform* categories might fulfill this requirement.

2.2.4. Discussion

Study 1

The categories of XR platforms still focus on *Creation* and *Simulation*, among which *Unity* or *Unreal Engine* are the most-used tools to create advanced interactions and narratives in XR experiences. As already explained, in the future the *Simulation* category will be helpful to train employees in different cases or test the experiences of product-service systems. It's worth noticing that the categories supporting remote collaboration in different levels of immersion, such as *MiE Exploration*, *Remote Assistance*, and *Conference Room*, become popular as well. A possible speculation is their attributes might link the design activities with marketing activities, which seems to accelerate iteration loops in design processes.

In the XR experience map, the *immerse-active* quadrant is more occupied compared to the other three quadrants. A possible explanation is that being immersed in a virtual environment is seen as active as you need to navigate and grab objects. Immersing and spatializing experience not only helps to transfer design problems to solutions but also enriches the emotional component of designers' work (Rieuf et al., 2017). Compared to a real-life PowerPoint presentation, presenting in a virtual environment can be immersive to the receivers, but the presentation tools would be relatively absorptive compared to other XR platforms. Therefore, when it comes to immersion, the axis is relative to XR experiences as XR is generally seen as an immersive tool (Mbaabu, 2020). The absorptive experience is less represented by current platforms. Pine and Gilmore (2011) state: "*If the experience "goes into" guests, as when watching TV, then they are absorbing the experience (…)*". The absorption thus might as well invite high mental engagement which is very important in design communication. For instance, designers walk through an immersive environment while sharing their viewpoints with stakeholders on desktops or tablets to enhance mutual understanding.

Study 2

To create a positive, valuable, and meaningful experience in a product-service system, it is important to satisfy universal needs and values, like emotional connection, affection, and other experiential aspects (Hassenzahl & Tractinsky, 2006). Experience approaches thus show the possibility to solicit multisensory sensations, such as vision, audition, and touch. It might not only facilitate the assessment of pragmatic qualities, but also appraise the hedonic qualities, such as familiarity, pleasure, and communication (Schifferstein & Desmet, 2007). Moreover, sometimes there are different conditions where the real-time involvement of stakeholders can be challenging (Kim et al., 2020), like limited time, accessibility of contexts, and ethical considerations (Freina & Ott, 2015). There is thus a shift from the technology-focused perspective to experiential approaches, where the first-person perspective enables design professionals to collect subjective experiences as rich as possible for analysis (Rieuf et al., 2017; Xue & Desmet, 2019).

When it comes to implementing XR platforms in design, the first look is the costs. There's a trade-off between license expenses and asset purchases. For freelance designers, the expenses on licenses shall be as low as possible, while the budget for buying assets can be higher. To corporate designers, the situation is reversed because they already have enterprise dictionaries at their disposal. Design assignments leverage the license-asset balance as well. Thinking of a kitchen design as shown in Figure 2.25, freelancers can produce XR experiences with standardized kitchen models and 'one-click' XR functions at a very low cost. As customized requirements increase, corporate designers have more resources that allow them to collaborate with colleagues and create detailed solutions that are impossible for freelancers.

In terms of time, designers probably need longer to learn than to produce at the beginning. When simulating sophisticated interactions, the learning curve can go even steeper. Another barrier, in terms of time, is the threshold to embed XR into design processes, in that design teams need a smooth workflow that links XR platforms with current pipelines. The errors occurring now frequently on incompatible file formats consume a lot of development hours. Regarding using XR in user testing, there's a learning gap as well because designers need to train users to understand the navigation and controls at first. Therefore, using XR platforms without thinking about them is the key to increasing the application rate.

2.2.5. Conclusion on XR platforms

Extended Reality, as a growing trend in digital transformation, is still evolving but has shown great potential for global economic and technological growth (IDC, 2020a). Considering the rapid growth in computational power, especially in AI design (Chen et al., 2020) and graphic computing (Mims, 2020), it would be possible for everyone to create their own XR experiences soon. The next focus would be the improvements on interfaces of XR software and hardware, so it becomes intuitive both for ideating and developing tasks. More and more researchers put their efforts into the human factors of XR platforms, and many developments are expected in this area. It is therefore an interesting field to monitor in the coming years.

Several limitations in this work might pinpoint room for future studies: 1) Many simulation games or similar applications that serve as a good representative real-world experience are not included in this study. The analysis of how games can simulate corresponding experiences might be beneficial to designing relevant product-service experiences as well. 2) The categorization and map of XR platforms by their experiences was an attempt to analyze the XR technologies from the experiential perspective instead of providing a taxonomy. Hence, further studies are required to elaborate the protocol for this categorization. 3) Experience by nature is memorable, as well as unique and irreducible (McCarthy & Wright, 2004; Pine & Gilmore, 2011). Hence, XR simulations should not merely focus on photorealistic appearances but also on generating relevant narratives. 4) The participation and connection axes of the experience model could be correlated. More specific analyses on immersive factors are needed. 5) Design agencies or small teams, who are both limited on time and budgets, are missing in this analysis. Further studies will involve different roles of designers to understand their needs and expectations of XR platforms.

The ability to observe from the first-person perspective, such as looking inwards, looking outwards, backward into the past, and forward into the future, is as significant as the third-person view, like observing the user's eye movements, in understanding human needs and emotions (Xue & Desmet, 2019). XR platforms show the potential to integrate both in the future. Additionally, remote design is never as good as when people are together, but XR might offer a different solution. The researchers can be cautiously optimistic that when the interfaces of XR hardware and software become intuitive, designers will be empowered to create what's impossible to experience now.

2.3. Conclusions

This chapter explored the research question: "*What are the key factors of immersive experiences in product-service systems both from the user's and designer's perspectives?*"

Section 2.1 introduced the Immersion Cycle (IC), the model describes the immersive experience from the user's perspective. It starts with sensorial and cognitive memories of relevant experiences in the real world and ends with new memories from "virtual places" in virtual environments. By recognizing the steps involved in this cycle, the checklist would enable designers and developers to dive deeply into key characteristics of their XR experiences. Designers can use the IC as a mapping tool of immersion, or as a starting point to ideate or conceptualize a user-centered immersive experience.

The IC will serve as a key reference of this dissertation for the follow-up theoretical studies (see Ch3). Applying the IC in ongoing product-service system development in the follow-up studies will focus on the effectiveness of design teams using the checklist as the starting point (see Ch7).

Section 2.2 mapped various XR platforms according to immersive experiences in the sense of design assistance. *Creation* and *Simulation* are the most important categories of the XR platforms, where *creation* mainly involves 'absorptive-active' experiences and *simulation* relates to 'immersive-active' experiences. Sharing models in an immersive experience with design stakeholders (*MiE Exploration*) is the third important functionality. From the designer's perspective, the efficiency of design tools often takes priority in implementation. The popular XR developing platforms (e.g., Unity and Unreal Engine) are often open source with low initial investment (e.g., license costs) but bound to higher variable costs (e.g., digital assets purchasing). The XR platforms showed different focuses on each design stage, hence the threshold of implementing XR is the steep learning curve to merge them into current designing pipelines. The analysis of XR platforms for generating immersive experiences provides a new point of view on design processes and needs to be connected to the IC in the future work of this dissertation (see Ch3).

CHAPTER 3

Reviewing extended reality for developing user experience

Immersive experiences both from the user's and designer's perspectives were analyzed and their key factors were defined in Chapter 2. This chapter will explore how Extended Reality (XR) experiences – digital content created by XR technologies - can be applied to develop the user experience. On the one hand, from a practical viewpoint, designers showed great interest in the opportunities that XR technologies can offer in their practices but were skeptical due to the limited budgets and resources that can be allocated to implement XR experiences. On the other hand, from a general perspective, an overview of the state-of-the-art knowledge about applying XR experiences in user experience design is needed to bridge the gap between theories and applications. This chapter focuses on the research question "*What are the roles of state-of-the-art extended reality (XR) experiences in developing user experience for product-service systems?*"

To answer this question, Section 3.1 conducts a scoping review to outline the applications of XR technologies in the field of User Experience (UX), as well as their enablers and barriers. Sixty-five XR design cases were identified from four databases following a protocol of systematic review. The reviewed XR cases aimed at improving human well-being in physical, cognitive, and organizational domains. These cases then were categorized by three sets of taxonomies – types of XR technologies, UX-relevant design qualities and processes, and the factors of immersion - in these XR experiences.

Section 3.2 develops a concept of an XR-facilitated design process that integrates the theoretical works in Sections 2.1, 2.2, and 3.1. It aims at designing the user experience for product-service systems with insights from positive experiences in daily life. This process envisions the possibility of using XR to prototype experiences of a product-service system and will direct the case studies in the following chapters.

Section 3.1 is adapted from the publication under review in
Li, M., Albayrak, A., and van Eijk, D. A Scoping Review of Extended Reality in User Experience Studies, Frontiers in Virtual Reality, *Under review*.

3.1. A Scoping Review of Extended Reality in User Experience Studies

3.1.1. Introduction

User Experience (UX) refers to general positive experiences humans undergo when they interact with a product-service system (Desmet & Hekkert, 2007). Experience-driven design sets a goal to create positive, valuable, and meaningful experiences, which are worthwhile because they fulfill users' universal needs (Hassenzahl, 2010). The consumption of positive experiences contributes the most to human well-being. By applying human factors/ergonomics principles as well as usability knowledge and techniques, UX focuses on discovering design qualities that trigger usable, useful, and pleasant experiences during human-system interactions. To identify design qualities contributing to user experiences, Human-Centred Design (HCD) offers design processes and tools in product-service system development (ISO, 2019). The involvement of stakeholders in design processes, particularly intended users, is thus crucial. The challenge of HCD however is the limited time and costs of involving users within tight developing schedules stressed by global competition (van Kuijk et al., 2017). The evolution of technologies that can immerse humans in a virtual world shows potential to tackle this issue.

Extended reality (XR) in general refers to digital environments that can generate high-level immersion, including *virtual reality* (VR), *augmented reality* (AR), and *mixed reality* (MR). In the early 1990s, VR technologies were already used to study the complex interactions between humans and spacecraft and to increase the compatibility between them (Smets & Stappers, 1995). As defined in Chapter 1, *XR experiences* are equivalent to the Apps running on a smartphone via its OS. Pilot studies explored different XR experiences and found they could increase the efficiency of UX processes on one hand, and on the other hand, collect users' insights holistically and early (De Crescenzio et al., 2019; Peruzzini et al., 2017). Despite the interest and early attempts, the applications of XR to enhance user experiences are still in their infancy due to the demanding resources required for the implementations (Peruzzini, Grandi, et al., 2019). There are very few literature reviews regarding the relationship between immersion and user experiences. In the architectural domain, Kim et al. (2013) reviewed the applications of VR in building environments such as architecture and design, urban planning, and landscape. Another systematic review focused on the utilization of VR in participatory design in evaluating spatial layouts of automobiles (Tseng et al., 2017). Within the engineering design domain, Seth et al. (2011) surveyed the usage of VR in assembly planning and evaluation. Guo et al. (2020) analyzed the application of VR in maintenance throughout the product lifecycle where maintainability design was included. Li et al. (2017) checked the pros and cons of AR techniques and applications, as well as their suitability in engineering analysis and simulation. For design research, Coburn et al. (2017) reviewed cutting-edge VR hardware and how it affected design research. Giunta et al. (2018) mapped the types of AR technology to the stage of design processes and identified how it supported design activities. Ens et al. (2019) reviewed how collaboration was supported by MR over the last three decades, which included design works. Next to the literature findings, the researchers interviewed several design teams and discovered a lot of attention and interest in applying XR. However, there are both doubts and debates due to the speedy advancements of XR technologies and limited design-oriented analysis. The key problem is that a thorough understanding of the capacities of extended reality and their limitations in design practices is not yet clearly stated, especially from the perspective of enhanced user experience.

The researchers hence reviewed literature (a) to categorize XR technologies in terms of the domains in user experience; (b) to analyze how and when to apply XR to enhance user experiences; as well as (c) to identify the factors of immersion in UX studies. Considering linking immersion with user experiences, the first step is defining key taxonomies to illustrate the landscape of design-related XR experiences.

3.1.2. Taxonomies of Extended Reality for User Experiences

The researchers state the definitions of taxonomies to categorize XR experiences. The first part explains the technological dimensions. The second part defines the aspects of UX from design qualities to design processes. The third part focuses on the factors of the immersive sensation and their corresponding system features.

Extended Reality (XR): Technologies for Immersion

As shown in Figure 3.11, *Extended Reality* (XR) can be viewed as a bridge that connects the perceptual sensations from the real world (reality) with the ones via digitally-generated worlds (virtuality) (Milgram et al., 1995). There are various types of XR, such as *virtual reality* (VR), *augmented reality* (AR), and *mixed reality* (MR). *VR* can surround users in a digitally-generated world that completely replaces the physical one. *AR* usually integrates digital layers or objects into physical surroundings to create an “enhanced real-life environment” (Azuma, 1997). *MR* mainly stands for a hybrid sensation. For example, using real objects to provide the idea of weight or touch while applying computer-generated objects to add visual features in terms of shape, color, or texture (Lingan et al., 2021).

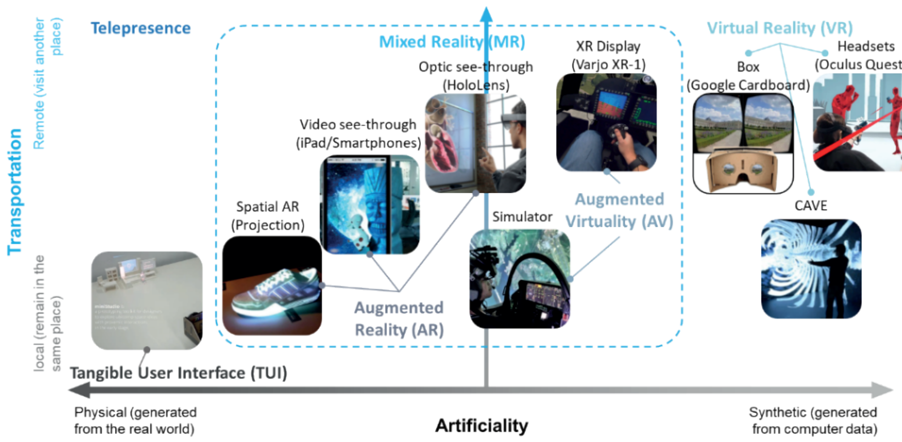


Figure 3.1.1 A technical roadmap of XR technologies in the R-V continuum with the classification dimensions of artificiality and transportation (Inspired by Milgram et al., 1995; Benford et al., 1998)

Among different types of XR technologies, displays play a critical role in creating a stereoscopic (i.e., three-dimensional visual) sensation. They can be categorized into four types with reducing immersion: *headset* (head-mounted 3D display), *CAVE* (large projection system with at least three digital walls), *projection-based* (e.g., power wall), and *others* (e.g., 2D displays such as smartphones, tablets, or simulators) (Bowman & McMahan, 2007). Their differences are not only influenced by their displays but also lie in the level of *artificiality* that represents to what extent the content is digitally generated (Benford et al., 1998).

User Experience: From Design Qualities to Design Processes

To define the domains of UX, the researchers used the most often cited categories - *physical*, *cognitive*, and *organizational* human-system interaction from ergonomics and human factors (IEA, 2021). The *physical* domain is mainly concerned with physical interaction between human and technological systems; the *cognitive* domain emphasizes the fitness of devices and tasks to match the mental capabilities of human beings; whereas the *organizational* domain regards the optimization of social-technical systems as important (Dul et al., 2012; Karwowski, 2005). These domains link to various design qualities to be investigated via matching design activities.

A design providing positive user experiences requires the *Effectiveness*, *Efficiency*, and *Satisfaction* of a product-service system that particular users operate under particular contexts to accomplish desired goals (ISO, 2020). Thus, they are considered fundamental design qualities in this review. *Effectiveness* assesses the "accuracy and completeness with which users achieve specified goals"; *Efficiency* evaluates the "resources including time, human effort, costs and materials used in relation to the results achieved"; and *Satisfaction* estimates the "extent to which the user's physical, cognitive and emotional responses that result from the use of a system, product or service meet the user's needs and expectations" (ISO, 2019).

HCD processes claim to connect "the world of users" with "the world of designers", where designers convert the fuzzy, ill-defined problem into design proposals that aim at boosting positive user experience (van der Bijl-Brouwer & Dorst, 2017). A typical HCD process – the *Double-Diamond Model (DDM)* - represents designers' divergent and convergent thinking in a design process shown in Section 2.2 (see Figure 2.2-6). At the *Discover* stage, designers widen their perspectives of a project with a broad range of ideas; during the *Define* phase, designers need to review insights to narrow them down to the main challenge; at the *Develop* stage, designers brainstorm concepts and test them; and in the *Deliver* phase, designers finalize the project and evaluate it (Design Council, 2021).

During the process, the mind of designers undergoes continuous and iterative loops to facilitate the "exploration-testing" evolution. It helps designers to deepen their understanding of design qualities and relevant elements. Moreover, Donald Norman (2013) stated that within this process critical tasks could support a 'designerly way of knowing' (Cross, 2018), including *observation*, *idea generation*, *prototype*, and *testing*. *Observation* means observing user behaviors under contexts of usage. *Generation* represents brainstorming and ideating potential solutions. *Prototype* means building quick mock-ups of potential solutions. *Testing* indicates activities for collecting feedback from a sample of users on potential solutions.

The Factors of Immersion

The key psychological sensation of XR experiences is the "being there" effect - feeling like being in a scene in a different world (Barfield et al., 1998; Lingan et al., 2021). Thus, the importance of "being there" is the extent to which a virtual environment can evoke reactions and emotions that are the same as in the real world (Schuemie et al., 2001). The notion of *presence* represents the phenomenal consequence of such sensorial stimuli, while a corresponding concept – *immersion*, represents what could happen in an XR system – the hardware and software settings of an XR experience (Slater and Wilbur, 1997). The XR system's objective features generate the above-mentioned sensorial phenomena. The coupling between presence and immersion means that users become aware of their presence by performing different actions, dynamically and interactively alongside sensorial stimuli within the experience deriving from XR systems (Bowman & McMahan, 2007). Considering the correlation between the objective aspects of XR experiences and their phenomenal presence, it's necessary to identify the factors that provoke immersive sensations via technological settings (Cummings & Bailenson, 2015).

Referring to the well-known model of presence by Witmer and Singer (1998) together with the *Immersion Cycle Model* by Lingan et al. (2021) in Section 2.1, the researchers thus identify the taxonomies of immersion as *interaction*, *sensory*, *realism*, and *involvement* (Table 3.11). The researchers abstracted features of immersive technologies linking to these immersive factors via an iterative thematic approach (Kavanagh et al., 2017). For example, the capabilities of "movement perception" and "active navigation" mainly depend on the tracking technology (e.g., three or six-degree-of-freedom) of a system, thus can be viewed as a part of the interaction (Schuemie et al., 2001). To generalize the features, items were excluded when they largely depend on subjective perception and hardly connect to specific objective features, such as "environmental richness", "selective attention", and "separation anxiety/disorientation".

3.1.3. Method

This study applied the method of scoping review following the guidelines from Arksey and O'Malley (2005). The *scoping review* as defined by its nature is a process of mapping the existing literature or evidence to identify trends and aggregate research findings. Different from the systematic review, a scoping review has a broader target and synthesizes findings more qualitatively than quantitatively, hence does not require a rigor evaluation of individual study as the initial priority (Levac et al., 2010). In this study, the researchers adopted the scoping review instead of a systematic review in that our goal is to demonstrate a broad overview of XR-facilitated UX from the literature.

Inclusion criteria

The researchers selected four databases to yield a broad spectrum of literature: **Web of Science** and **Scopus** were used to provide an all-encompassing scientific search. **IEEE Xplore** and **ACM** were used for XR technology-oriented research. The researchers tracked the XR-related design published back to 1988 and decided to limit the publication from January 1, 2008, to November 30, 2018, in that a state-of-the-art overview is needed. The inclusion criteria were: 1) studies **written in English** and published in a **peer-reviewed journal** or **conference**; 2) studies that have a **design goal** to **improve human performance or well-being**; 3) studies that have at least **ONE XR experience**.

Table 3.1.1 The definitions of immersive factors and their corresponding features of XR systems

Factors	Definition	System Features	References
Interaction/ Control	represents the amount and responsiveness of control of a virtual environment that contains immediate consequences of the user's actions, predictable events and activities, natural or well-practiced modes of control, and modifiable objects.	- active navigation/ walk-through - 3D control, - motion capture, - objects manipulation, - extra interaction (e.g., verbal commands)	(Held & Durlach, 1992) (Schuemie et al., 2001)
Sensory	shows the influences of different senses and their combination including the influencing sensory such as the dominant visual channel, multimodal presentation that increases the capability for experiencing presence, and the consistency of information across sensorial modalities.	- 3D-vision - involving two senses - combining three or more senses	(Witmer et al., 2005)
Realism	shows the fidelity of the virtual environment that involves the realism of scenes, the consistency between the real world and the virtual one, and their meaningfulness to a person.	- real-size objects, - texture rendering, - digital human /avatar - task interaction - environment simulation	(Witmer et al., 2005; Witmer & Singer, 1998)
Involvement	indicated the extent to which a system provides an exclusive, continuous experience that isolates users from the physical world. When interface quality interferes with the person, he/she becomes aware of these interfaces. Interface awareness is thus a part of distraction/involvement. The involvement can be triggered by challenge-based activities, like video games.	- isolated from the physical world - no interface awareness - challenges / emergencies	(Schuemie et al., 2001; Witmer et al., 2005) (Buchanan & Csikszentmihalyi, 1991) (Ermi & Mäyrä, 2005)

The current review excluded literature under the conditions of 1) studies that were conducted in the non-immersive environment, such as mobile, desktop, and web applications; 2) studies that had no aim to improve human performance or well-being; 3) studies that didn't include use cases involving human participants; 4) studies that merely focused on the design of the virtual environment itself.

Search Terms

The search terms (Table 3.12) related to three groups of concepts - Extended Reality (XR), Design (DE), and Ergonomics and Human Factors (HFE), were developed throughout an iterative process. At first, 62 sample publications (e.g., articles published in *Applied Ergonomics* and *CHI*) were selected through pilot searching and back-referenced via Google Scholar. Second, the search terms were iteratively tested with twelve combinations until most of the sample publications (especially key articles) could be identified in more than one database.

Table 3.1.2 Search Terms for the scoping review

Concepts: Combine with AND		
concept 1: XR	**concept 2: DE**	**concept 3: HFE**
"immersi*" "virtual reality" "augmented reality" "mixed reality" "virtual environment*"	"design" "product develop*" "product service*" "user experience" "UX" "UE" "user-centered design" "human-centered design" "co$design" "co$creation"	"ergonom*" "ergo design" "human factor"

Study Selection

The search disclosed 3780 records, from which 160 articles were selected as potentially relevant from the title, keywords, and abstract screening; from which 58 studies including 65 cases satisfied all the above-mentioned criteria (Figure 3.12). Considering how much impact the selected studies had, the researchers used Google Scholar to find the total citations to date and calculated its *Average Citation Count* (ACC), which is the "total citations" divided by "lifetime" (published year till now) as suggested by Dey et al. (2018). The ACC of the selected cases ranged from 0 to 37.0, with an average of 6.3. Based on this calculation, it indicated the overall selection had a good impact in the field despite several low-impact but highly relevant cases.

The aim of the review

This review aims to address the roles of state-of-the-art XR experiences in developing positive experiences for PSSs via the literature relevant both to UX studies and XR experiences. The following relationships need to be investigated:

1. The types of XR technologies that support different domains of UX
2. The contribution of XR experiences on different design qualities and processes.
3. The factors of immersion that the XR experiences applied.

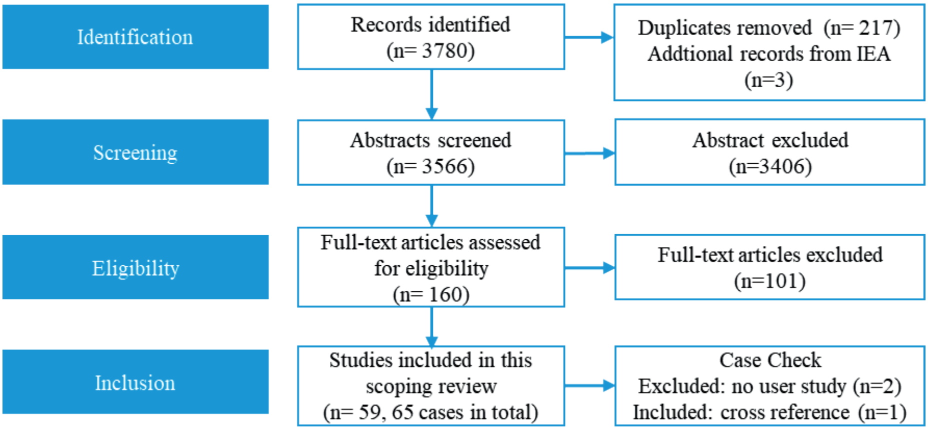


Figure 3.1.2 The workflow of the scoping review

Analysis methods

The sixty-five selected cases were categorized via the taxonomies described in section 3.1.2. For relationship 1, each case was labeled according to the taxonomies of XR technologies, whose categories are explained in Table 3.13:

Table 3.1.3 The taxonomies of XR technologies for categorizing XR experiences

Taxonomies	Categories	Reference
Reality-virtuality continuum	Virtual reality - the dominant digital world Mixed reality - the hybrid world Augmented reality - the enhanced real world	(Milgram et al., 1995)
Displays	headset, CAVE, projection, and others	(Bowman & McMahan, 2007)
Artificiality	mostly physical, hybrid, mostly virtual	(Benford et al., 1998)

For relationship 2, each XR case was labeled according to the UX taxonomies whose categories are discussed in Table 3.14. Several cases could involve two UX domains and others contributed to two design qualities. The researchers counted them separately and summarized them afterward.

Table 3.1.4 The taxonomies of UX for categorizing XR experiences

Taxonomies	Categories	Reference
UX Domains	Physical - the physical aspects of human-system interactions Cognitive - the mental compatibilities of human-system interaction Organizational - the optimization of social-technical systems	(IEA, 2021)
Design Qualities	Effectiveness - the accuracy and completeness of achieving users' goals Efficiency - the resources in relation to the achieved results Satisfaction - the fulfillment of needs and expectations from using a system	(ISO, 2019)
Design processes	Discover - Designers broaden their ideas about a design problem Define - Designers identify the key challenge of this design problem Develop - Designers propose and test concepts that aim to solve the problem Deliver - Designers finalize the solution and evaluate it with target users	(Design Council, 2007)
	Observation - to collect user data in the context of usage Generation - to form concepts of possible solutions Prototype – to build models for a conceptual solution Testing – to assess solutions based on user responses	(Norman, 2013)

For relationship 3, the system features of each case were identified according to the factors of immersion. Each feature counted for one point for the relevant factor, and the sum of all points indicates the level of immersion in this aspect. For example, on the "interaction" factor, an HTC Vive headset system contains "free walk-through" and "3D-control" features, thus belonging to 'level 2'. When no feature matched the criteria of a factor, the case counted as "0", such as a smartphone AR app has a 0-level-immersion on the *sensory* factor.

Table 3.1.5 The factors of immersion for categorizing XR experiences

Taxonomies	Categories	Features	Reference
Interaction	0-5	active navigating, object manipulation, free-hand motions, extra interactions	(Held & Durlach, 1992; Schuemie et al., 2001)
Sensory	0-3	3D-vision, sound feedback, haptic feedback, extra senses	(Witmer et al., 2005)
Realism	0-5	environment simulation, real-size objects, realistic rendering, avatars, task interactions	(Witmer et al., 2005; Witmer & Singer, 1998)
Involvement	0-3	Isolated from the real world, no awareness of interfaces, challenges/ emergencies	(Buchanan & Csikszentmihalyi, 1991; Ermi & Mäyrä, 2005)

3.1.4. Results

An Overview of UX Studies Applying XR Experiences

Overall, the researchers checked a total of 65 XR cases from 58 pieces of literature (the full list is available in the Appendix as Table A.21). There was an obvious increase in applying XR technologies after 2011, and it started to accelerate after the release of commercial high-end XR headsets in 2016. The cases covered nine application fields (Table 3.16) with the *Average Citation Count* ranging from 1 to 12. The focused fields are mobility, industry, manufacture, and safety with several applications in consumer products, medical, and buildings.

This review demonstrates a balance of publication venues between journals (32) and conferences (33) spanning widely across diverse fields, like Ergonomics and Human Factors, Human-Computer Interaction, Virtual Reality/Mixed Reality, Prototypes, and Product Development. The most common publication venues include *IEA* (6 cases), *Applied Ergonomics* (4 cases), and *Human Factors and Ergonomics in Manufacturing & Service Industries* (3 cases). Considering data collection, 39 cases only measured quantitative data, from performance measurements, and questionnaires, to physiological data. 19 cases included not only quantitative but also qualitative ones, such as observation, interview, or debriefing. Seven cases only involved qualitative methods containing audio recordings, notes, and design reviews. Regarding feedback types, 28 cases collected both subjective and objective ones, whereas 21 cases focused on objective feedback, and 16 cases only recorded subjective ones.

Categorizing these products or services according to human sizes, i.e., the *Modulor*, demonstrates how XR experiences were utilized regarding human-system scales (Corbusier, 2004). Figure 3.13 shows that 58 cases are larger than 113 centimeters, concentrated on “113” (European male standing elbow height) and “>226” (room size) (Molenbroek & Huysmans, 2021). No case shows at two sizes, “43” (the sitting popliteal height) and “183” (the stature). More participants took part in XR design cases on large-size product-service systems.

Table 3.1.6 An overview of the 65 reviewed cases

Application	Paper	Mean ACC	Publication		Data collection			Feedback types		
			Jour.	Conf.	Quant.	Qual.	Both	Subj.	Obj.	Both
Mobility	17	5	7	10	10	4	3	7	5	5
Control room and workstation	11	5	7	4	6	2	3	3	3	5
Manufacture	11	9	7	4	7	0	4	2	4	5
Safety	7	7	3	4	4	0	3	0	3	4
Home applicance and elelctrionics	5	2	2	3	2	0	3	2	0	3
Medical	5	3	2	3	4	1	0	1	2	2
Furniture	3	1	1	2	1	0	2	0	1	2
Building design	3	12	1	2	2	0	1	1	0	2
Other	3	11	2	1	3	0	0	0	3	0

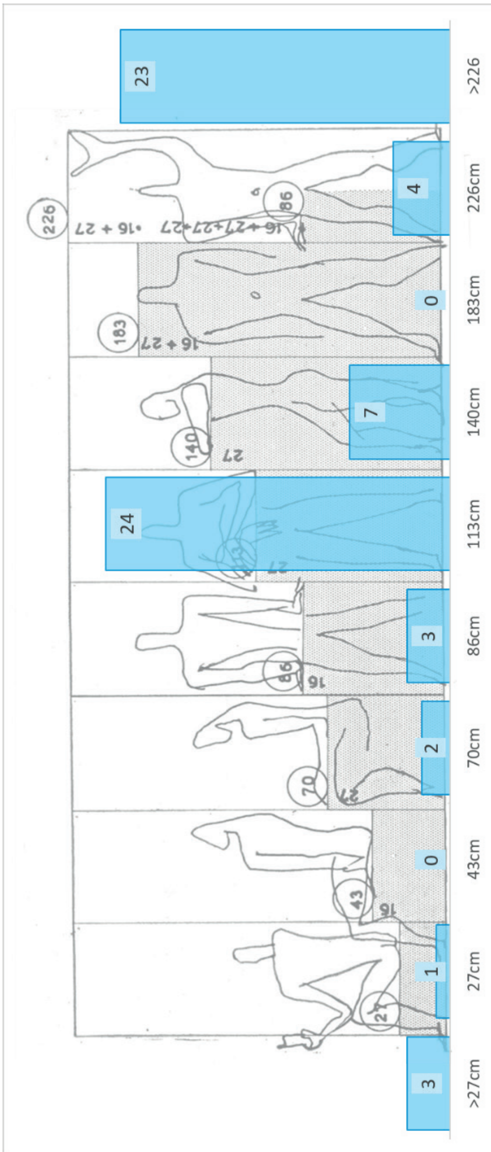


Figure 3.1.3 The reviewed XR experiences of product-service systems on different human scales

1. The types of XR technologies that support different domains of UX

After labeling the 65 cases with their types of XR technologies, the researchers mapped them in each domain of UX (Figure 3.14). *VR* systems have the highest number (39 cases), followed by *MR* systems (18 cases), while *AR* systems gain limited attention in the field of UX (7 cases). The *physical* domain counts for the highest XR applications (34 cases), with almost equal numbers of *VR* (16) and *MR* cases (13). The *cognitive* domain shares a similar number (32 cases), with the highest number of *VR* cases (21). The *organizational* domain is very limited (7 cases). 8 cases overlap different UX domains, including six '*physical-cognitive*' cases (5 *VR* and 1 *MR*), one '*cognitive-organizational*' case (*VR*), and one '*physical-organizational*' case (*VR*).

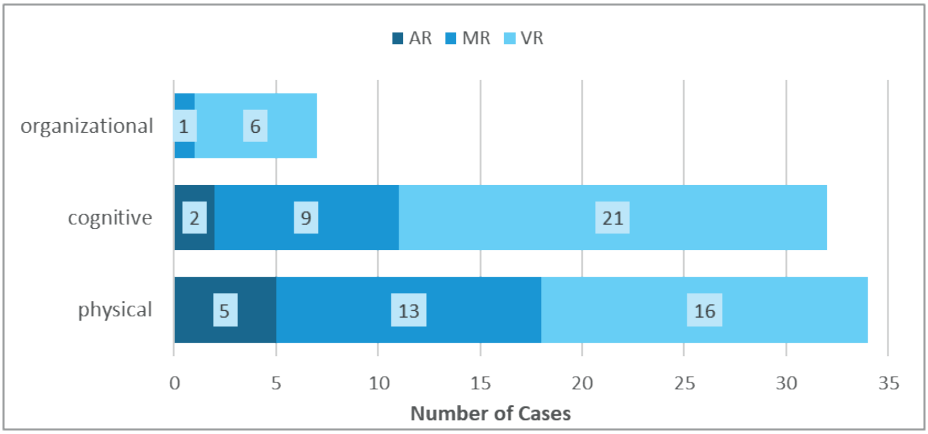


Figure 3.1.4 Different types of XR technologies in UX domains

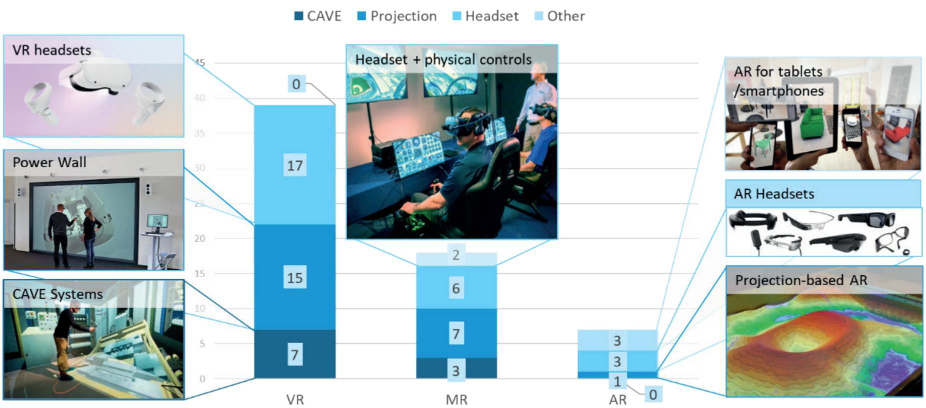


Figure 3.1.5 Different types of displays are used in the reviewed XR technologies

Figure 3.15 depicts the various displays deployed in the 65 cases, where the headset counts for the highest number (26 cases) across all XR types, and the projection had the second largest amount (23 cases). CAVE was the third with 10 cases only in the VR and MR types, while other displays (e.g., tablets, 3D workbench, driving simulator) obtained the lowest usage (7 cases) in MR and AR systems.

The *headset* had the highest number of commercially available solutions, among which mostly are *HTC* (6 cases) or *Oculus* (8 cases). The other XR headsets applied various displays, like self-developed ones (3 cases), *5DT headset*[1] (2 cases), *HoloLens* (1 case), Sony headset (1 case), *ARvision*[2] (1 case), or *eMagin*[3] (1 case). The *projection* displays usually were customized platforms combined with projectors (6 cases), wall displays (2 cases), or simulators with 3D glasses (1 case). The *CAVE* displays are room-scale multi-wall systems with three sides (1 case), four sides (3 cases), or six sides (2 cases), sometimes providing 4K images (1 case). Several commercial *CAVE* solutions were *PREVERCOS* and *HoloVis*[4]. *Projection* and *CAVE* displays often use stereoscopic glasses, 3D controllers (e.g., Wii controller or gamepad), or real-scale simulators to enhance the presence. *Other* displays contain tablets (2 cases) and self-developed platforms (3 cases).

XR displays often combine virtual or physical artifacts to create a realistic sensation. The artificiality levels indicate to what extent an XR system merged with physical surroundings or objects (Figure 3.16).

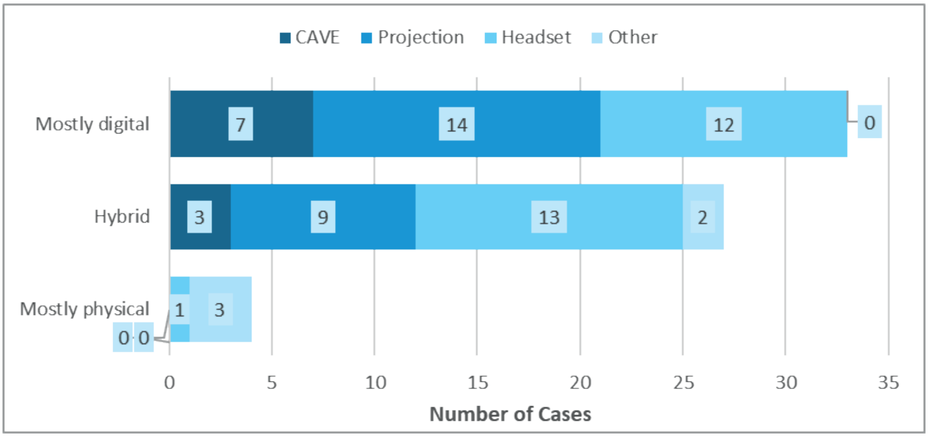


Figure 3.1.6 Different types of XR displays are associated with different levels of artificiality

[1] https://www.vrealities.com/?variations=5dt-hmd-800-26-3d
[2] https://www.inition.co.uk/extraordinary-technology/head-mounted-displays/
[3] https://productz.com/en/emagin-z800-3dvisor/p/lLqW
[4] https://www.holovis.com/products

A "mostly digital" system has its information almost entirely from the digital world, which counts for the highest number (33 cases). These systems are often safety-critical, technically complicated, or costly in the real world. For example, collecting users' behavioral and subjective responses under simulated emergency conditions (Bergroth et al., 2018) or in autonomous human-machine interaction (Koppenborg et al., 2017). They often applied *projection*-based (14 cases), *headset*-based (12 cases), or *CAVE*-based (7 cases) *VR*.

The "hybrid" systems are a blend of the physical world and digital artifacts. The "hybrid" systems have 27 cases, including *headsets* with haptics (13 cases), *projection* with physical prototypes (9 cases), *CAVE* with seats or cabin simulators (3 cases), and *others* (2 cases). For example, sketching 2D or 3D images on a physical plane or objects (Arora et al., 2018); or complementing visual-auditory sensation with the haptics from physical objects like seat-bucks, full simulators, real vehicles, parts, or haptic devices (Goedicke et al., 2018; Kim et al., 2016; Langlois et al., 2016).

The "mostly physical" systems (4 cases) had their information largely derived from the physical world with digital augmentations on top of it. Examples are adding virtual products to a real environment to check their ergonomics and comfort (Forbes et al., 2018), testing virtual prototypes in contexts with 3D controllers (Caruso & Re, 2010), or with haptic feedback (Demirel & Duffy, 2017).

2. The contribution of XR experiences on different design qualities and processes

Figure 3.17 shows an overview of XR experiences in the domains of UX linking to design qualities and processes. In the *physical* domain (37 cases), most cases (27 cases) contribute to *effectiveness*, followed by 7 cases to *efficiency*, and 4 cases to *satisfaction*. The *cognitive* domain (36 cases) was similar, with 20 cases for *effectiveness*, 13 cases for *efficiency*, and 3 cases for *satisfaction*. The organizational domain (8 cases) had 4 cases for *efficiency*, 2 cases for *effectiveness*, and 1 case for *satisfaction*.

Considering the overlaps across UX domains, the cases linked to two domains were marked in a dark background. On *effectiveness* (48 cases), four cases covered the 'physical-cognitive' domain. On *efficiency* (24 cases), four cases belonged to the 'physical-cognitive' (2 cases), 'physical-organizational' (1 case), and 'cognitive-organizational' domains (1 case) respectively. On *satisfaction* (8 cases), a case is in the 'physical-cognitive' domain. For instance, Peruzzini et al. (2019) compare a desktop application with a digital human and an MR system to design a large part manufacturing system. It covered both *physical* and *cognitive* domains for improving *effectiveness*.

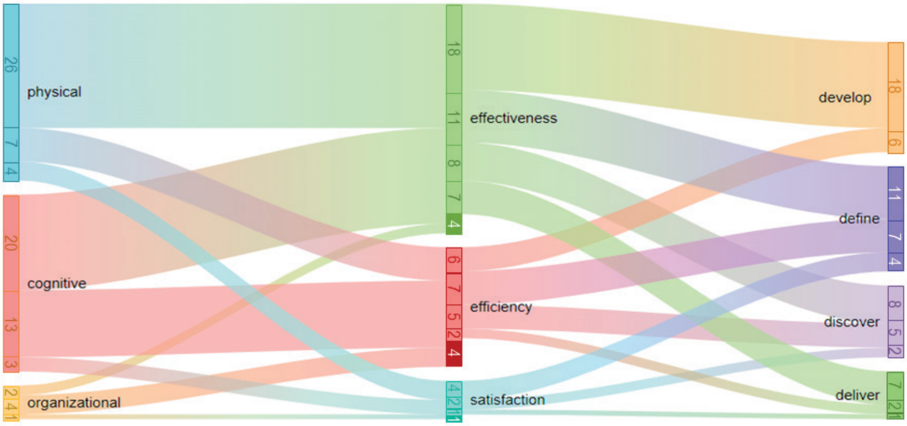


Figure 3.1.7 The XR experiences applied to physical, cognitive, and organizational domains that supported different design qualities across design processes. For instance, 26 cases from the physical domain, 20 cases from the cognitive domain, and 2 cases from the organizational domain contributed to effectiveness. Among them, 18 cases were studied at the develop stage

The cases connect design qualities with design processes as well. *Effectiveness* (44 cases) was studied throughout the design processes - *develop* (18 cases), *define* (11 cases), *discover* (8 cases), and *deliver* (7 cases). *Efficiency* (20 cases) covered the design process similarly, with 7 cases in *define*, 6 cases in *develop*, 5 cases in *discover*, and 2 cases in *deliver*. *Satisfaction* (7 cases) only were examined in *define* (4 cases), *discover* (2 cases), and *deliver* (1 case) stages. Six cases contributed to two qualities, including four cases for 'effectiveness - satisfaction' and two cases for 'efficiency - satisfaction'. For instance, Favi et al. (2018) applied a projection-based VR system to customize the ship bridge configuration. This study examined the efficiency and satisfaction of the workstation.

Figure 3.18 demonstrates how various design activities were involved in these design processes. XR experiences facilitated mostly conceiving activities, such as *prototype* (22 cases) and *generation* (14 cases), particularly at the developing stage (19 cases). The explorative activities like *observation* (13 cases) decreased gradually throughout the design processes, focusing on the discovery stage (7 cases). XR-facilitated evaluations - *testing* (18 cases) distributed almost evenly across the last three stages.

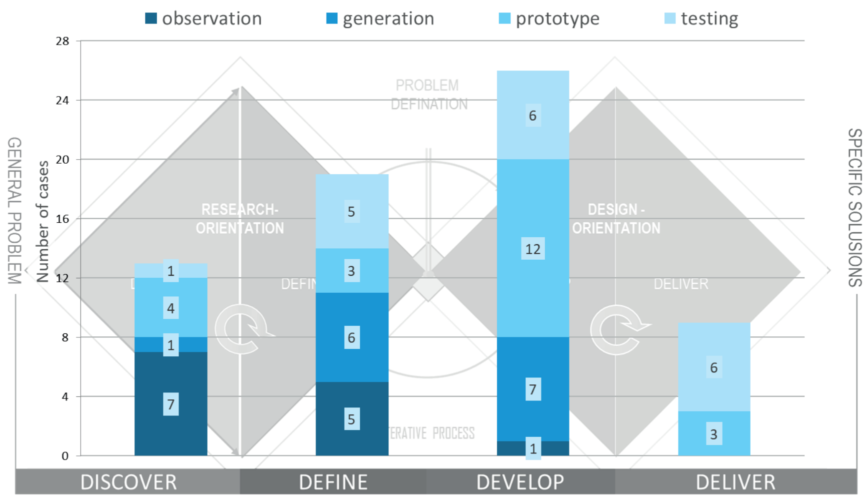


Figure 3.1.8 Mapping XR experiences according to the design process with UX activities

To summarize, *effectiveness* employed the highest amount of XR experiences, while *satisfaction* was least studied. The *define* and *develop* stages involved XR experiences at the most, focusing on the *prototype* and *generating* activities. However, no cases at the *develop* stage focused on *satisfaction*.

3. The factors of immersion that the XR experiences applied

Figure 3.19 provides an outline for four groups of immersive factors deployed in the XR-facilitated UX studies. The higher the level is on one factor; the higher immersion is created by an XR system on this aspect. For *interaction*, 93.8% of cases vary between the medium levels (*interaction* 1 to 3). As for *sensory*, 78.5% of cases cover level 1 and level 2. Regarding *realism*, 84.6% of cases span between high levels (*realism* 3 to 5). Considering *involvement*, 78.5% are between middle levels (*involvement* 1 and 2).

There is a summary of the system features applied in each level of the factors (n of cases):

Interaction:

0 (1) - using the passive walk-through (Di Gironimo et al., 2012).
1 (17) – ‘active navigation’, ‘free walk-through’, or ‘object manipulation’.
2 (24) – ‘free walk-through’ plus ‘objects manipulation/motion capture’, or ‘objects manipulation’ plus ‘behavior tracking/motion capture’.
3 (20) – ‘3D-control’ plus ‘extra interaction’ (e.g., eye-tracking, or virtual tools).
4 (2) – ‘motion capture’ and ‘extra sensor’ (e.g., full-body tracking or pulse sensor).

Sensory:

0 (2) – '2D-vision'

1 (24) – '3D-vision' (22) or '2D vision plus haptics '(2).

2 (27) – '3D-vision' plus 'sound' (9), '3D-vision' plus 'touch' (17), '2D vision' plus 'touch' and 'motion' (1).

3 (11) – '3D-vision' plus 'sound' and 'touch' (8), or '3D-vision' plus another 'haptics' (2, e.g., static force or vibration), or '3D-vision' plus 'physical objects' and 'motion tracking' (Lee et al., 2010).

Realism

1 (5) – 'real-size objects' (4), or 'task simulation' (1).

2 (13) - 'real-size objects' plus 'texture rendering' (9) or 'task simulation' (3), or 'task simulation' plus 'digital humans' (1).

3 (19) – combining three features, 'real-size objects' (16), 'task simulation' (13), 'texture rendering/true texture' (11), 'digital humans' (7), and 'environment simulation' (5).

4 (20) - They had four features except for 'digital human' (15), 'task simulation' (2), 'texture rendering' (2), or 'environment simulation' (1).

5 (6) – They carried all five realism features. The 'digital humans' had various representations, e.g., body parts like virtual hands and/or feet (Reinschluessel et al., 2017), or avatars of teams (Oberhauser and Dreyer, 2017).

Involvement

0 (2) - no physical world isolation, no challenges, and no awareness of interfaces.

1 (30) – 'invisible interfaces' (26), 'isolation' (3), or 'challenges' (1).

2 (21) – 'invisible interfaces' plus 'challenges' (13), or 'invisible interfaces' plus 'isolation' (8).

3 (11). - They combined all three involvement features.

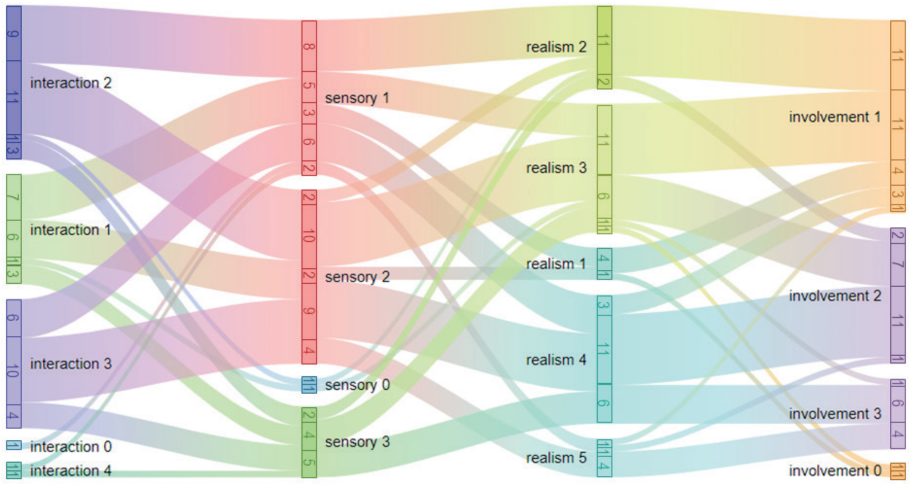
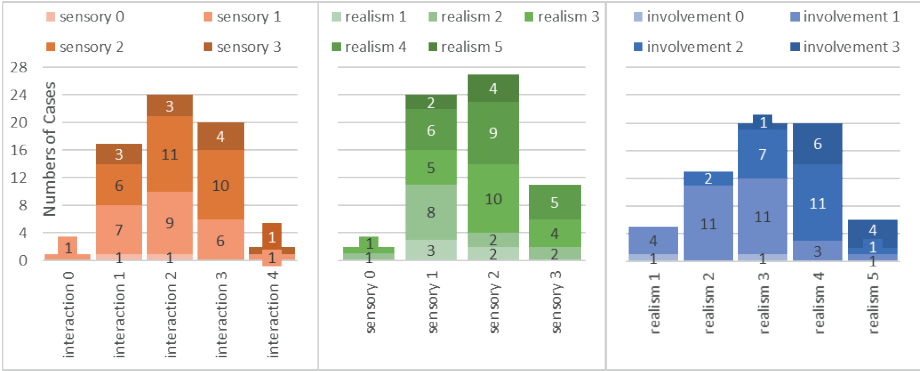


Figure 3.1.9 The factors of immersion applied in the reviewed XR experiences. For instance, 9 cases had level 2 interaction, and 8 of them applied to level 1 sensory; then they used level 2 realism and level 1 involvement

The challenges deployed in the cases include emergencies (9), extra workloads (6), environmental distractors (6), and teamwork (3). The simulated emergencies included collapse/collision, hazards, defects, alarms, fire, near misses, malfunctions, or ambush (Almeida et al., 2016; Gregoriades et al., 2015). The high workload tasks mean object detection, dual tasks, complex visuals, or difficult interactions (Koppenborg et al., 2017; Nickel & Lungfiel, 2018). The virtual distractors contain environmental noises, on-road events, products/robots' behaviors, and non-immersive actors (Deb et al., 2017; Weistroffer et al., 2013). The XR systems supporting teamwork often involve user-designer interactions with/without collaborations (Li et al., 2018).

When examining the interactive effects between the factors, as in Figure 3.110, the numbers of the XR cases demonstrate a trend of near-normal distributions. Low levels of *Interaction* (2 and 3) with medium levels of *sensory* (1 and 2) represent 55.4% of the cases. High levels of *sensory* (2 and 3) at high levels of *realism* (3 to 5) comprise 49.2% of the cases. High levels of *realism* (3 to 5) with high levels of *involvement* (2 and 3) cover 73.8% of the cases.



a) interaction vs. sensory b) sensory vs. realism c) realism vs. involvement

Figure 3.1.10 The interactive effects between the four factors of immersion

In brief, most XR cases employed medium levels of immersion in each factor except for *realism*. The common features of *interaction* are 'active navigation' or 'free walk-through' plus 'object manipulation' or 'motion capture'. '3D-vision' is the dominant *sensory* factor and is often augmented by 'sound' or 'touch'. The *involvement* focused on the 'invisible interfaces' feature.

3.1.5. Enablers and Barriers of Extended Reality

The benefits and pitfalls of introducing XR experiences are the key questions asked by designers. The researchers hence present the enablers and barriers in the reviewed cases from the aspects of *system features*, *design elements*, and *design activity*. Table 3.17 shows examples of these enablers and barriers (see Table A.31 in the Appendix for the full version).

3

Table 3.1.7 The examples of common enablers and barriers of extended reality in UX studies

Aspects	Enablers (n of cases)	Barriers (n of cases)
Physical Domain		
System feature	+ Graphic quality, e.g., rich visual information (3) + Multimodal modules, e.g., auditory-haptic feedback, visual-force feedback (2)	- Haptic fidelity, e.g., limited fidelity, missing touch, missing occlusion (5) - Visual fidelity, e.g., limited field-of-view, delays of video streaming, distortion of visualization (3)
Design element	+ Realistic biomechanical and behavioral data, e.g., upper limb postures, human movements, push-pull-related ergonomics (5) + Visibility, reachability, accessibility (3)	- Discomfort, simulation sicknesses, accuracy, effort, mental workload, presence (5) - Shape distortion (2)
Design activity	+ Effort-time saving, such as real-time analysis, rapid edit/switch prototypes, easy to program and flexible, easy customizing (6) + Emotional involvement, e.g., feelings, subjective fidelity, enjoyment in design, confidence in judgment (6) + Embodiment for judgments, performing in contexts, imagining usages, spatial references, and the natural motion of avatars (3)	- Imprecise estimation, e.g., different joint angles, unnatural motion, dependence on body sizes, and impossible to evaluate the shape (6). - Prototyping barriers, e.g., hard in sketching large objects, time of 3D modeling, hard in creating free-form objects, not fully adapted to the development context, raised costs (5) - Testing barriers, e.g., influences from physical surroundings, product scales (2)
Cognitive Domain		
System feature	+ Free walk-through (5) + Flexibility and robustness, e.g., flexible levels of usability and complexity, open-source coding (4) + New data collection, e.g., head, hands, eyes, and lips tracking (3)	- Visual fidelity, e.g., the field-of-view and resolution, latency (4) - Hand controllers, e.g., ergonomics (4) - Restricted movements (3)
Design element	+ Spatial perception, e.g., interaction considering physical relationships, understanding real scales (with digital humans), spatial-geometric arrangement, estimating distances, holistic spatial configuration (7) + Ecological validity (4) + Cognitive workload (3)	- Simulation sickness symptoms, e.g., difficulty concentrating, “full of head”, eye strain, focusing difficulty, nausea, blurred vision, and general discomfort (9) - Physical stress, e.g., the effort in navigating (5) - Negative effects on performance (2)

Table 3.1.7 Continued

Aspects	Enablers (n of cases)	Barriers (n of cases)
Design activity	+ Precise and efficient experimental control, e.g., manipulating complexity and intensity of the stimulus, dynamic simulation at low costs, post-hoc simulation, high reproducibility, natural responses from low fidelity, and many trials in a short time (10) + Safe and unlimited simulation, e.g., safety-critical environments, hazardous tasks, accidents, fire or smoke, and logistic issues (10) + Personalization, e.g., customization in contexts, support decision-making, on-demand simulation, good learning outcomes, good mobility, and accessibility (7)	- System usability, e.g., multimodal interfaces, its influences on outcomes, slow to perform, mentally demanding (7) - Reliability of behaviors and judgment, e.g., differences in key behaviors, detailed interaction, trajectories, and low perceived stresses (4) - Realism, e.g., mismatching experience, limited psychological fidelity (3)
Organizational Domain		
System feature	+ Spontaneous modifications (1)	- Tracking latency (2) - Rigid actions (2) - True-to-life simulation of work tasks (1)
Design element	+ Anxiety and task loads (2) + Human-machine collaboration, e.g., human-robot co-production, human-machine function allocations (2)	
Design activity	+ Realistic conditions, e.g., interaction and collaboration (3) + Cost efficiency, e.g., time-saving, being cost-effective and efficient without impeding productivity (2) + acilitating experience design, e.g., first-person viewpoint, project personal experience in the contexts (2)	- Lacking tools to enable consistent remote interaction between design stakeholders, e.g., views of users (3) - Low learnability, e.g., unfamiliar with the environment and the tasks (3) - Different emotions of users (2)
Linked domain		
System feature	+ Multi-modal interfaces, e.g., introducing haptics, and physical parts (2) + Sensor-tracking, e.g., motion-tracking, eye-tracking (1) + Natural, intuitive, and comfortable interaction (1)	- Visual fidelity, e.g., no photorealistic rendering (1) - Haptic fidelity, e.g., unrealistic feedback (1) - Single-person setup (1)

Table 3.1.7 Continued

Aspects	Enablers (n of cases)	Barriers (n of cases)
Design element	+ Task duration and motion strategies (1) + Posture, e.g., RULA, Borg, and APACT (1) + Dimension validation (1)	- Simulation sickness, e.g., different exposure times to different postures and conditions (2) - Missing specific motion strategies (1)
Design activity	+ Vast analyses, e.g., posture, visibility, reachability, occlusion, mental, and emotional, more detailed data than in the real world (2) + Good accuracy and reliability, e.g., similarity in subjective measurements (2) + Production efficiency, e.g., reusing artifacts, better comparisons between concepts, creating different alternatives, reducing design iterations (2)	- High costs of implementing, such as hardware (motion capture), licensed software (digital human), development time, and training, as well as the high effort and the shortage of personnel (3) - Missing co-location, e.g., no remote participation (1) - Insufficient familiarization (1)

XR experiences in general stimulate similar postural, cognitive, emotional, and collaborative responses as in corresponding realistic scenes. This characteristic enables them to study users' intuitive behaviors under safe, unlimited, and affordable conditions.

3.1.6. Discussion

The idea of using a virtual environment to simulate inaccessible situations was initiated in the early 1990s (Smets & Stappers, 1995). However, technologies for generating digital environments were at their infantry. Extended Reality (XR) – an immersive virtual world that could interact with the physical world - becomes the center of the world's attention (Shaw, 2021). Its acceleration matches the growing needs of global digitalization (IDC, 2020a).

The top three application fields of XR experiences are mobility, control room/ workstation, as well as manufacture, as a systematic review of AR usability also reflected (Dey et al., 2018). This study observed a rise in employing XR on UX after 2012, which was also witnessed by another review on MR collaboration (Ens et al., 2019). Quantitative and hybrid measurements are focused on these XR experiences, whose attention is on triangulating subjective and objective feedback. The XR experiences are usually combined with ergonomic tools for better design quality, including RULA, NASA-TLX, or psychological scales, as confirmed by Di Gironimo et al. (2006). The following sections discuss how XR experiences contribute to designing positive experiences for PSSs.

The XR technologies for user experience

The advancements in XR technologies are mainly concentrated on headset-based systems. The high-end commercial packages lower the threshold of introducing immersive experiences to explore human-system interaction (Bergroth et al., 2018; Deb et al., 2017). The other hardware options are custom-developed platforms, combining projectors, large- or multi-wall screens, stereoscopic glasses, 3D controllers (e.g., Wii controller or gamepad), or simplified full-scale simulators. Implementing such systems usually involves the competencies of configuring both hardware and software, like processing models into compatible formats, programming interaction/ visualization, and debugging the system (Peruzzini et al., 2018). These skills currently are not included in education or training curriculums for designers. Hence, large-scale XR technologies, such as projection or CAVE, mainly flourish in aviation, manufacturing, automobile, military, or research institutions where abundant intellectual and financial resources are available.

Except for the fully digital systems as the mainstream, more and more XR experiences choose to enhance their sensorial sensation by creating a mixture of physical and virtual artifacts. The combinations vary from blocks, haptic devices, physical controls or buttons, and self-developed mock-ups, to real parts, products, or simulators. This trend indicates designers' attempts to create a true-to-life experience that is relevant to users. This review found that immersive experiences introduced proprioception that substantially benefits designing large-scale PSSs. The researchers thus estimate that systems on these scales (e.g., elbow height) often refer to "spatiality" within human-system interaction. The "spatiality" is attributed to experiences of or relating to space which enhanced judgments via the sense of embodiment (the feeling of having a body inside the virtual world). Additionally, XR technologies allow involving a larger user sample with time and cost efficiency than traditional UX methods, particularly for large-scale PSSs (Delangle et al., 2017; Forbes et al., 2018).

XR experiences for user experience

In the UX domains, *physical* and *cognitive* aspects are the areas where most XR cases were applied. Due to the complexity of simulating collaborative actions (Cowgill et al., 2013), the researchers believe that applications in the organizational domain will increase when multi-player technology becomes affordable. Considering design qualities, *effectiveness* gains the most attention. This phenomenon indicates that most utilizations of XR experiences are explorative instead of design practices. Unlike our anticipation, *satisfaction* seemed to be out of the focus in current publications, especially during the *develop* and *deliver* stages. They usually serve as the "touchpoints" of the end-users. This indicates that the technological limitations of XR experiences still surpass the benefits, hence designers were concerned that these glitches would affect users' judgment of products (Paes & Irizarry, 2018).

From the perspective of design processes, the researchers found that the *define* and *develop* stages reached high numbers, mostly involving *prototyping,* and *generating* activities. They are the stages that bridge the user's world with designers by sketching and prototyping user experiences (Cross, 2001). Most XR cases were around the 'problem definition' point, "whereby designers explore two conceptual spaces, a 'problem space' and a 'solution space'" (Ball & Christensen, 2019). The findings resonate with the notion that designing revolves around the conjectures of solutions driven by "abductive reasoning" – for the best possible solutions (Ball & Christensen, 2019). As the researchers have seen in these publications, designers appraise the competencies of XR experiences by easily diverging design alternatives broader and then converging them efficiently regarding real user feedback. To some extent, designers even viewed XR experiences beyond real environments in that they enable the precise observation of users' natural interaction under good control of variables, real-time multi-modality data collection, post-hoc simulation, and reusing assets with costs efficiency (Peruzzini et al., 2018). XR experiences show the potential to boost creativity by setting free the ability to externalize designers' mental simulation/imagery without pondering the costs of prototyping (Ball & Christensen, 2019; Cross, 2001).

The factors of immersion to facilitate user experience

As observed in this review, the medium levels of immersion are enough for UX studies except for the realism factor. There are key features to generate an immersive experience for UX: free navigation and object handling for *interaction*, 3D visions plus another sensorial feedback for *sensory*, invisible interfaces plus challenges for *involvement*. To enhance *realism*, XR experiences need to encompass the following features: real-size objects, task simulation, texture rendering, environment simulation, and digital humans. The challenge simulations involve emergencies, high task loads, distractors, and teamwork. Nevertheless, the perception of immersion is not only influenced by the objective features of technologies but also determined by user characteristics that are rarely mentioned in the reviewed studies (Lessiter et al., 2001). Future work should investigate how user characteristics will contribute to or hinder immersion.

Future XR experiences for user experience

The XR experiences provide safe conditions to trigger human responses with cost and time efficiency in good control of variables. From the designer's perspective, this enables them to study users' natural behaviors under any conditions that are too dangerous or expensive to carry out. The first and foremost concern of introducing XR experiences in design practices is the human factors of the systems, including simulation sickness, discomfort and high effort in usage, and even negative effects on performances. Despite their natural interactions, XR technologies are still unfamiliar to most users and stakeholders, and this requires new design protocols with well-arranged training sessions.

Virtual environments are confounding factors themselves, the trustworthiness of XR experiences thus is of significance for UX studies compared to corresponding experiences in real life (Bordegoni et al., 2013). For example, validating XR experiences by comparing them with real environment behaviors, ethnography or the same tasks in the real world is important work (Duarte et al., 2014; Werner et al., 2018). Increasing size consistency with physical surroundings, higher fidelity in motion, and haptic feedback are mentioned in different studies as well (Caruso et al., 2011; Lawson et al., 2015). Forbes et al. (2018) emphasized the need to identify the product categories or features that are suitable to be simulated by different XR systems. Hence, the improvements in system features are about sensorial fidelities, such as improving the field-of-view and visual resolution, introducing the sense of touch, force, and weight, as well as adding users' avatars (Bernard et al., 2019; Friemert et al., 2018). For instance, using high-quality initial CAD files is a way to reach photorealistic visual quality (Lee et al., 2010). Semi-immersive systems like handhold AR shall provide multiple perspectives to compensate for the flattened experience (Kim et al., 2016).

Considering supporting design processes, the improvements focused on streamlining the pipeline of working with XR experiences. For observation, improvements are needed to streamline workflows of data collection and analysis, control experiments robustly and easily, and track behavior with low costs (Cowgill et al., 2013). XR systems need to add environmental alarms and real-time measurements (e.g., eye-gaze or self-report). To define concepts, studies proposed automating motion pattern detection as well (Lawson et al., 2016). For ideation, free manipulation of working space and correction of freeform 3D objectives is important (Arora et al., 2018). For delivery, Standardizing the numerical chain to straightforwardly import CAD models into XR assets is mentioned alike (Pontonnier et al., 2014). For customization, researchers suggested including diverse scenarios and conditions, technologies, and suppliers (Favi et al., 2018). Arroyave-Tobon and Osorio-Gomez (2017) added different percentiles of the population. For remote co-design, synchronization of different viewpoints is critical to involve the stakeholders (Li et al., 2018). To ensure a smooth design pipeline, XR systems should involve multi-disciplinary design teams, e.g., including ergonomists (Nguyen et al., 2017). Future advances in these systems should increase user control over the automation simulation as well.

Limitations and future work

Though the study strove to depict a state-of-the-art outlook as the researchers selected 58 publications and reviewed 65 cases, they can identify several limitations and validity concerns. The first involves the time scope of the publication. Though several studies published in early 2019 are included, it remains possible that the research works since 2019 contain venues and papers that should have been included. Second, the researchers individually reviewed sample papers and then iteratively discussed our results to reach a consensus about the taxonomies and criteria. The categorization might also be influenced by our empirical understanding of XR terminologies and technologies. Third, the domains of UX are not only specialized in the physical, cognitive, and organizational domains but also expand to social and emotional needs, as well as affective experience. Finally, although the researchers cross-referenced a study during the last selection stage, several relevant studies from references may still be missing.

3.1.7. Conclusion on the review

The roles of XR experiences in UX studies are two-fold: bridging the user's world with the designer's world, and accelerating the exploration of design alternatives with cost-efficiency and flexibility. The XR experiences show a potential to promote creativity by freeing designers' thinking to externalize their mental simulation of experiences. The emerging commercial XR technologies, embedding multi-tracking technologies (like Pico Neo3 pro eye), create an easy gateway to implement XR experiences in design practices. XR headset is embedding more tracking techniques, such as head-, hands-, and even eye-tracking or face-tracking, which collect richer user data that might be missed in real-world studies due to expenses or feasibility (Apple, 2023; Oculus, 2020; VARJO, 2021). Creating a hybrid experience with both virtual and physical objects might take advantage of multi-modality sensation for a high-level immersion at a low budget. Product-service systems that involve spatial experience or physical interactions seem to gain the most benefits from utilizing XR experiences.

The key enablers are triggering realistic responses in a safe and cost-efficient manner connecting different UX domains, along with good control of variables. Inside immersive experiences, users are emotionally involved with high engagement. The possibility to automate design protocols by reusing objects or coding stimuli empowers designers to run studies with a vast number of variables. XR experiences show the potential of being more personalized, distributed, and on-demand. Future systems that enable seamless data collection and faster feedback loops support design processes better.

Though glittering technological advances and heated discussions on XR experiences are opening new horizons for UX, the socio-technological concerns of implementing them are worth paying more attention to (Peruzzini, Pellicciari, et al., 2019). These concerns include but are not limited to comfort and human factors of the hardware, the steep learning curve of XR platforms, the creation pipeline from sketching to interacting, validating XR experiences with real-world scenarios, and so forth (Favi et al., 2018).

As increasing interests in XR experiences appear in the field of UX, the researchers urged further efforts to develop frameworks and protocols to translate experiences in the real world into XR experiences, which facilitates the development of positive experiences for product-service systems, and ultimately human well-being. The contributions of this work enclose:

- The state-of-the-art XR technologies and their key features for each UX domain.
- An overview that demonstrates how XR experiences contributed to design qualities and processes.

- The factors of immersion and the corresponding system features the XR experiences applied.
- The enablers and barriers in current XR experience that facilitate designing for UX.

3.2. A Concept of XR-facilitated Experience Design for Product-Service Systems

The goal of this section is to link the user's and designer's perspectives of immersive experiences and to develop a process that uses XR technologies to create positive experiences for product-service systems. To design positive experiences, we shall understand positivity in our daily experiences. From a philosophical perspective, experience involves senses, perceptions, and fundamental needs, at the same time being unique and dynamic in particular contexts (Hassenzahl, 2010). The consumption of experiences brings more happiness than material possessions. The experiences of product-service systems, as a part of our overall experience, show the story that a design tells about its users, purpose, and context (Desmet & Hekkert, 2007). The better the story is, the better a design provides worthiness to the world (Carroll et al., 1992). Thus, experience prototyping is a well-acknowledged design method that simulates and analyses true-to-life experiences in developing products and services (Buchenau & Suri, 2000).

As mentioned in previous studies, XR showed the potential as a medium to simulate the whole experience of a product-service system. This concept hence tries to propose a way to prototype experiences for product-service systems via XR (Figure 3.21).

The concept represents a procedure that combines two parallel cycles: the inner cycle shows a process in which users immerse in an XR experience that represents relevant experiences of a product-service system (Lingan et al., 2021); the outer cycle represents a process in which designers generalize the positiveness from daily experiences and convert them into positive experiences for product-service systems (Hassenzahl et al., 2013). XR technologies serve as the meditator to simulate material elements and system interactions of intended XR experiences that gradually integrate the two cycles. The following sections explain the rationales of this approach.

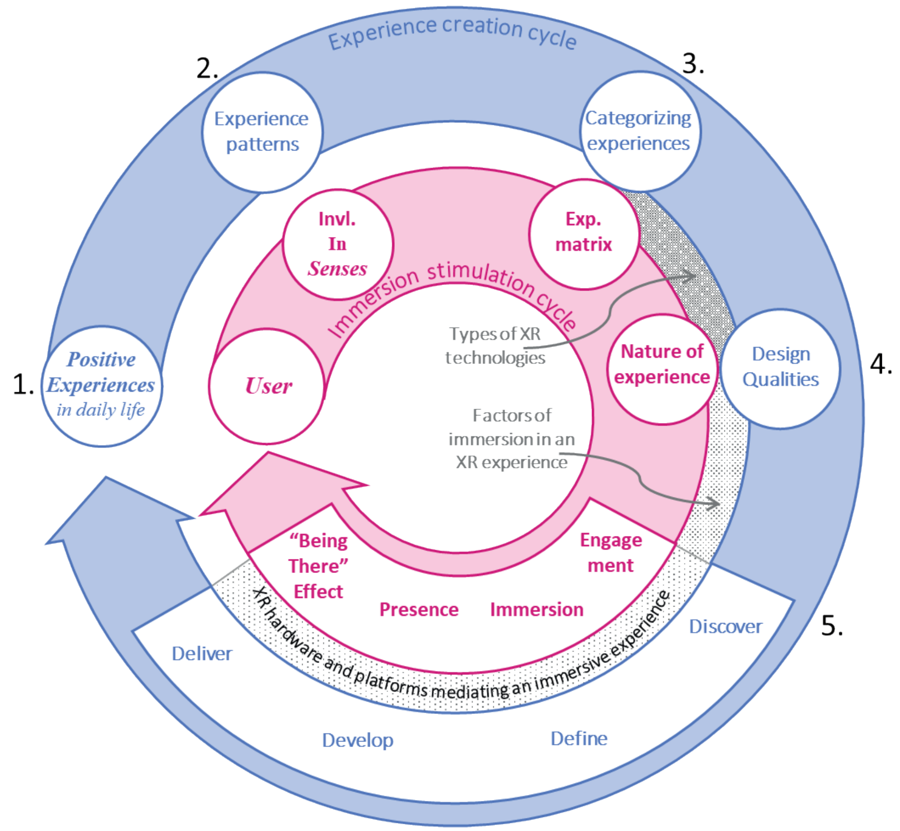


Figure 3.21 A concept for prototyping experiences of product-service systems via XR technologies to enhance UX.

3.2.1. The Inner Cycle – Immersion Stimulation Cycle

In the inner cycle, users become immersed and feel that they are "being in there" within a particular product-service system instead of viewing a computer-generated image. This process is the *Immersion Cycle* described in Section 2.1 with minor changes. The researchers link it with the findings from the previous review (Section 3.1).

Step 1 – *User*: The inner circle starts with defining target users for an immersive experience. This step sets a reference to the initial stage of the *experience creation cycle* (ECC) where the designer will collect relevant positive experiences from daily life for these users. Note that the main participants in the reviewed XR cases were students or professionals in industrialized economies.

Step 2 – *Involvement* in ***Senses***: This step focuses on the user's activities and the involved senses in selected positive experiences; it provides 'building blocks' to the second step of the outer cycle – *experience pattern*. In the previous review, user activities in XR cases mostly are professional operations, like cockpit tasks, safety behaviors, large part production, and workstations. These activities mainly involve stereo vision and sometimes combine with sound or haptic feedback.

Step 3 – *Experience Matrix*: This step checks the selected experience under the *Experience Matrix* to match it with a particular type of XR technology. This step resonates with the third step in ECC which categorizes the experience by general needs and the types of human-system interaction. In the reviewed XR cases, most selected experiences are highly immersive and include active exploration (drive-through, walk-through, or navigation) within an environment.

Step 4 – *Nature of Experiences*: Based on checking the selected experience, this step determines the nature of the intended XR experience. It connects to the fourth step in ECC in which the design quality to be simulated with XR is decided. This step will influence the factors of immersion in the intended XR experience. The XR experiences reviewed generally related to creating a similar virtual environment. Hence, they mainly belong to the active–immersive quadrant and can be generated via VR technologies. XR platforms in the *simulation* category (Section 2.2) can be a proper match for this purpose.

Step 5 – From ***Engagement*** to ***"Being there" Effect***: The intended XR experience proposes a narrative in conjunction with interactions or challenges that engage the users. It combines the above-named aspects and may deepen immersion. The users perceive presence via sensorial stimuli generated by the hardware and platform of the XR experience. The narrative together with presence helps users to reach the "being there" effect. This step parallels the design process step in ECC where design elements will be explored via various design activities. In the reviewed XR cases, the challenges usually are emergencies, high workload, distractors, and teamwork.

3.2.2. The Outer Cycle – Experience Creation Cycle

In the outer cycle, designers create positive experiences for the abovementioned users. Designing a positive experience of a product-service system can be compared to creating fiction, endowing essential elements to express - happiness, health, and prosperity – in different contexts.

Step 1 – Positive Experiences: The first step of the experience creation cycle is discovering the user's positive experiences in daily life. Designers can find wonderful examples of positive experiences in fiction, where universal themes represent the connections to understanding shared humanity under various contexts (Rice, 2005). For instance, the theme **hero's journey** appears in various spatiotemporal expressions - *'The Odyssey'* (ancient Greek, about 8the century B.C.), *'The Journey to the West'* (China, 16th century), *'The Lord of the Ring'* (the UK, 1937), and *'2001: A Space Odyssey'* (the US, 1968). In the reviewed XR cases, studies focused on promoting performances instead of creating positive experiences.

Step 2 – Experience Patterns: Designers then need to extract a general structure of activities – the "pattern", within the selected experience (Hassenzahl et al., 2013). For instance, *flow* is a pattern for self-motivated experiences with a tranquil mind. It contains the following 'ingredients': matching challenges with skills, setting a clear goal, and showing progress explicitly. They can be used in developing professional training that aims at promoting the intrinsic motivation of trainees. Moreover, each experience pattern usually links to a particular need, e.g., 'flow' reflects the need to "be competent". A pattern serves as a 'blueprint' to create a narrative of interactions in a product-service system. In current XR cases, researchers reproduced the users' activities directly from relevant operations and tasks instead of providing a narrative of interactions.

Step 3 – Categorizing experiences: In this step, designers link the selected experience and its pattern with fundamental needs that provide general ground for experiences. Hassenzahl and colleagues (2013) summarized six needs that are relevant to positive experiences: *Autonomy*, *Competence*, *Relatedness*, *Security*, *Popularity*, and *Stimulation*. Desmet and Fokkinga (2020) added seven other needs for positivity: *beauty*, *comfort*, *community*, *fitness*, *morality*, *purpose*, and *recognition*. Meanwhile, designers shall review positive experiences in terms of harmonic *human-system interaction* (HSI), and their types - *physical*, *cognitive*, and *organizational* are useful for categorizing the interactions of an experience (Dul et al., 2012). Most XR cases reviewed were relevant to the needs of *competence*, particularly in *physical* and *cognitive* HSI.

Step 4 – Design Qualities: This step translates the identified need into design qualities to be prototyped with XR technologies. In terms of positive experiences, there are two types of design qualities: 1) hedonic qualities that capture a system's perceivable ability to create positive outcomes through need fulfillment; and 2) pragmatic qualities that remove barriers in HSI to facilitate need fulfillment. For instance, *satisfaction* is related to the fulfillment of users' needs and their emotional responses towards a system, thus can be hedonic; whereas other qualities like *effectiveness* and *efficiency* focus on the objective countable outcomes of a system, hence are pragmatic. As observed from current XR cases, pragmatic qualities like effectiveness and efficiency were popular for designers, whereas hedonic qualities like satisfaction were out of focus.

Step 5 – Design Processes: Designers convert design qualities into design elements, including but not limited to shape, space/layouts, color, material, finishing, reachability, visibility, ease of use, or learnability (Bennes et al., 2012). These design elements need to be investigated via various design activities, generalized by Donald Norman (2013) including *observation*, *idea generation*, *prototype*, and *testing*. Designers conduct these design activities in a procedure organized by the *Double-Diamond Model*, namely the *Discover*, *Define*, *Develop,* and *Deliver* stages. Indeed, design elements should be co-constructed in a continuous dialogue between users and designers through design activities like *ideating* or *prototyping* happening in an immersive experience shared by them. However, as the review showed, the deliver stage had the lowest XR cases, which serves as the "touch point" between designers and users.

3.2.3. Technological Mediator – XR technologies

XR technologies shed light on how to holistically simulate the experience of a product-service system that contains various design elements. XR technologies play the roles of meditators, which support user-centered immersion - the *Immersion Stimulation Cycle*, and more importantly, the designer's way of thinking -the *Experience Creation Cycle*. To some extent, designers viewed XR experiences beyond a real environment in that they enable precise observations of users' natural behaviors under good control of design variables, real-time multi-modality data collection, post-hoc simulation, and reusing the assets with cost efficiency (Peruzzini et al., 2017). XR technologies progressively integrate the two cycles from Steps 3 to 5 as the mediator of immersive experiences.

Step 3 – Considering the types of XR technologies: As the tools of immersive experiences, the types of XR technologies can match the quadrants of the *Experience Matrix*. For example, augmented reality (AR) is generally more passive and absorbed than virtual reality (VR), whereas mixed reality is mainly immersive depending on the senses it involves. From the senses involved in the selected experience, designers can find specific XR technologies that involve similar senses, such as displays and haptic controls. Moreover, the categories of XR platforms (Section 2.2) provide a detailed reference of experiences they can easily generate.

Step 4 – Checking the factors of immersion in an immersive experience: After identifying the design quality of a product-service system and the nature of its experience, designers can determine the factors of immersion (i.e., interaction, sensory, realism, involvement) for the intended experience to be prototyped via selected XR technologies. These technologies need to be scrutinized for their potential to create or block the desired experience.

Step 5 – Mediating intended XR experience with hardware and software: Prototyping intended experience via XR involves converting these design qualities into an XR experience. Designers shall develop the factors of immersion in this XR experience to match the design quality of the intended product-service system. Moreover, developing enhanced narratives is crucial to prototyping experiences truthfully. In the end, designers use an XR platform, for instance, *Tvori*, to create 3D mock-ups as well as their storylines to immerse into the user's world. Meanwhile, users can navigate and interact with this immersive virtual environment via XR displays, such as the *HTC Vive* headset. While designing is mediated by XR, the relationship between designers and users is bi-directional.

3.2.4. Discussion and conclusion on the concept

The concept demonstrates the attempt to forge a process that translates daily positive experiences into corresponding digital content via XR to provide a better user experience of product-service systems.

According to the immersion stimulation cycle, XR experiences in UX studies simulated operational tasks that triggered the "being there" effect and similar behaviors among users. However, the influences of users' expertise and cultural background on their perception of XR experiences were less discussed. The focus of these cases was on the user's performance in operational tasks. Thus, most XR experiences in UX studies belong to one group -- the active–immersive quadrant. However, there are different natures of experiences, i.e., absorption and immersion, as well as passive and active interaction. They might influence the "being there" effect and consequently users' perception of design qualities. But it's less studied as well. These questions leave room for follow-up studies.

Regarding the experience creation cycle, XR experiences helped designers study competence-driven activities and improved performances. The positivity in human-system interaction was neglected. As Hassenzahl (2010) claims, under their appearances, positive experiences contain some "basic recipe", particularly via human-system interaction. If done well, from positive experiences in daily life, designers can create a fully-fledged, positive experience for future product-service systems. This shows the potential to narrow the gap between human well-being and the design of a particular system. Each experience is related to a particular need and has generic ways to fulfill it. Thus, recognizing its unique need is critical to replicate positive experiences truthfully. Despite that the need studied in current XR cases is competence, XR experiences showed the potential to study the needs that link different types of HSI. Satisfaction-related design qualities need to be investigated in the follow-up studies, particularly at the deliver stage.

XR technologies show the potential to bridge the user's and designer's cycles by externalizing imagery of product-service systems with time-cost efficiency (Ball & Christensen, 2019; Cross, 2001). The technological limitations in XR experiences are known; hence a critical concern is that these glitches shouldn't affect users' judgments of product-service systems when simulating an experience via XR.

This concept is merely based on the theoretical analysis and review, the further studies of this dissertation shall put effort into applying it in case studies and design practices.

3.3. Conclusions

This chapter explored the research question: "*What are the roles of state-of-the-art extended reality (XR) experiences in developing user experience for product-service systems?*"

Section 3.1 reviewed the state-of-the-art XR experiences that are applied in user experience studies. XR shows great potential to re-organize design processes and activities differently, as it enables the exploration of design proposals with high time-cost efficiency and flexibility. Designers and researchers prefer concise XR systems like VR/AR headsets as they lower the thresholds on required resources and knowledge of the implementation. However, the designer's attention to XR experiences still concentrates on pragmatic qualities like efficiency and effectiveness. Hence, assessing hedonic qualities like satisfaction via XR leaves a large room for future studies. The user experience of large-scale systems and physical interactions benefits the most via XR prototyping/simulation. The medium levels of the immersive factors are good enough to simulate experiences via XR except for the *realism* factor, which requires the highest level of immersion. The critical concern of applying XR experiences in UX is still the human factor and the learning curve in implementation. Utilizing XR as a design enabler despite its current limitations requires further studies on XR-based design processes/protocols.

Section 3.2 followed the above-mentioned work to integrate the user's and designer's perspectives of immersive experiences as an approach to developing positive experiences for product-service systems. This consequently suggested a process that translates real-world positive experiences into immersive experiences of product-service systems via XR technologies. It's crucial to identify the fundamental needs PSSs required to fulfill, and then translate them into corresponding design qualities for a system. Regarding the nature of an experience, designers shall both consider hedonic qualities and pragmatic qualities. Designers could use these qualities to develop XR experiences for product-service systems. In the end, users and designers could define the design elements to reach the desired experiences of such systems via co-immersion generated by XR technologies.

In the following case studies, the researchers will select specific needs and their corresponding design qualities, then develop XR experiences for product-service systems to understand how immersion will play a role in practice.

CHAPTER 4

Immersive Design for Physical Well-Being

The conceptual process in Chapter 3 required case studies in the physical, cognitive, and organizational domains of UX involving various design activities. XR was less applied at early design stages, this chapter thus investigates the usage of XR in concept designs. The research question is: "*How can designers effectively ideate user experience via spatial presence in conceptualization*?"

Comfort is a fundamental need contributing to physical well-being, and *Satisfaction* is the design quality closely related to comfort. In the context of mobility, comfort-relevant design elements refer to space, lighting, height, storage, and facilities, as well as privacy-related functionalities like shelter, visibility, and personalized lighting. These elements cover the physical-cognitive domain and need to be investigated in realistic contexts via spatial presence.

The first case study (4.1) focused on digitizing HCD methods (e.g., the Kano model) with VR prototypes for concept selection and verification with potential end-users. This study compares the comfort rates and gender preferences between narrative prototyping (e.g., online survey) and immersive prototyping (e.g., virtual reality).

The second case study (4.2) creates an interactive VR prototype to evaluate the comfort and satisfaction of a new concept of a privacy protection seat for long-haul flights. Forty participants assessed the new concept compared with the experience of the current design in a high level of immersion.

The last case study (4.3) investigates whether sharing the immersive viewpoint of a VR prototype with a desktop would generate a similar comfort perception. The subjective comfort rate and simulation sickness symptoms were compared between the VR review and the desktop review.

The case study in Section 4.1 is adapted from the publication
Meng Li, Doris Aschenbrenner, Xinhe Yao, Daan van Eijk, Peter Vink. (2021). Ergonomics 4.0: Human-Centred Design Procedure Using Virtual Reality Prototyping. HIS2021 November 17-19. San Diego, CA, US.

The case study in Section 4.2 is adapted from the publication
G. Torkashvanda, M. Li, P. Vink. Concept evaluation of a new aircraft passenger privacy bubble using virtual prototyping: A Human-Centred Design framework. WORK: A Journal of Prevention, Assessment & Rehabilitation, 2020 December.

The case study in Section 4.3 is adapted from the article
Meng Li, Xinhe Yao, Doris Aschenbrenner, Armagan Albayrak, Daan van Eijk, Peter Vink. (2021). Comfort in Long-Haul Travel from Immersion: Comparing Desktop and Headset Virtual Prototyping in Public Hygiene Space Design. CHI 2021 2VT workshop, 8th May.

4.1. Ergonomics 4.0: Human-Centered Procedure for Ergonomic Design Using Virtual Reality Prototyping

4.1.1. Introduction

Human-Centered Design and Comfort

Human-centeredness is a key quality of design, and the user's involvement at the early stage is of paramount importance in choosing the path that satisfies the user's needs well (van der Bijl-Brouwer & Dorst, 2017). In particular, comfort is one of the fundamental needs of human beings, which is described as "a feeling of relief or encouragement", "contented well-being" and "a satisfying or enjoyable experience" (Desmet & Fokkinga, 2020; Merriam-Webster, 2021). Despite the diverse perspectives on comfort-related experience, most studies agree that "comfort is a subjective experience" defined by personal nature, which plays an important role in boosting well-being (Mansfield et al., 2020; Vink et al., 2012). Hence, comfort is becoming increasingly significant for user satisfaction which ultimately judges the quality of products and services, especially long-haul travelling (Richards, 1980; Tan & Shen, 2010; Vink et al., 2012).

More and more companies and institutions view improving comfort as a new and necessary measurement to win customers, thus using many resources to develop comfort products and services (Cappetti et al., 2017; Mansfield et al., 2020). They face challenges in understanding how the (dis)comfort experience is formed while using them (Mansfield et al., 2020). On one hand, the traditional human-centered approaches, using physical prototypes or existing products to explore comfort-related design issues, have obvious drawbacks on time and cost efficiency, especially for large-scale systems like Flying-V; on the other hand, the digital prototypes showed difficulties in conducting comfort-related user assessments on a desktop PC application (Ahmed et al., 2018). Advanced ergonomic tools are needed to accelerate the procedures of comfort design.

Ergonomics 4.0

Industry 4.0, according to Lim, is a “complicated network of machines, physical contacts, virtual items, computing facilities, and storage, communication devices that interact with each other” and “exploit the enormous potential of new technologies” (Lim, 2017). In the envision of Industry 4.0, virtual copies of real objects - Digital Twins, and augmented visualization and operation - Technical Assistance, are the core of creating innovative products and services (Ceruti et al., 2019). Digitalization and augmented visualization of advanced ergonomic tools are defined as Ergonomics 4.0 in this study. Digitizing and simulating tremendously increased the integration of human factors during the early stages of design, as Digital Human Modelling (DHM) served as an aid for ergonomics over the last three decades (Scataglini & Paul, 2019).

DHM shows the advantages of providing a digital replica of various populations in postural comfort analysis (Tao et al., 2016). However, subjective comfort feedback still largely relied on consulting with end-users. Digital Twins (DT) of future products, immersing potential target users in virtual scenarios, play a central role in collecting user feedback on-site to ensure design quality in products and services development (Obbink, 2016). Virtual Reality (VR) brings a new opportunity to surround users with digital twins with cost and time advantages (Bowman & McMahan, 2007).

VR Prototyping of Design Elements

Human-centered design (HCD) is a learning process that invites users and designers into each other’s world to sketch and explore user experiences and validate with users (van der Bijl-Brouwer & Dorst, 2017). VR facilitates this learning process in three aspects:

1) Low-cost “trail-and-error” loops accelerate design processes and bring stakeholders closer. Liu et al. (2019) developed a virtual walkthrough of an architectural design with a third-person view for group reviews. Using VR for usability validation in workstation design helped bring the mindsets of users and designers together (Marc et al., 2007).

2) Immersion in VR triggers not only rational argumentation but also tacit insights (e.g., proprioception) during the human-system interaction. Mengoni et al. developed a protocol for analyzing the ergonomics of man-machine interaction in virtual environments (Mengoni et al., 2008). Panicker and Huysmans (2020) developed a VR application that allows designers to review the comfort of an airplane cabinet through the eyes of the overweight population (Panicker & Huysmans 2020). The study demonstrated that first-person immersion helps to understand both space experience and comfort.

3) VR shows the potential to become an integrated approach to ergonomic design. Aromaa and Väänänen discussed the suitability of virtual prototyping and found VR valued in both physical ergonomics (e.g., visibility, reach, and layout) and cognitive ergonomics (e.g., usability). To assess environmental and organizational aspects like lighting, time, and collaboration, multiple sensory modalities, and system model characteristics are required in VR prototyping (Aromaa & Väänänen, 2016).

The hardware and software constraints the usage of VR prototyping, including but not limited to simulation sicknesses, the field of view, visual resolution, latency, and weight of headsets. Thanks to the rapid development of VR technologies in the last five years, these limitations have become less and less influential. The integration of new technologies, such as inside-out head tracking, hand-tracking, and eye-tracking, shows new possibilities to merge subjective assessments with behavioral analysis (Castelan et al., 2021; Hillmann, 2019).

A follow-up question is: How can first-person immersion in VR be used to ensure comfort in a human-centered design process? It is the focus of this study. The following sub-questions will be examined:

1. Do different sexes perceive the comfort of various design elements differently?
2. Do the forms of prototyping (narrative vs. VR) change the comfort perception of design elements?
3. Does VR prototyping increase the perceived comfort of design elements in an HCD process?

4.1.2. Methods

In this study, the Kano model was used to map the design elements or functionalities into a general matrix according to comfort and satisfaction (Kano, 1984). The "comfort-discomfort" transition shows that comfort is driven by cognitive factors like well-being and plushness, while discomfort is related to physical factors like poor biomechanics and fatigue (Zhang et al., 2016). Comfort and satisfaction are both related to general experiences, e.g., space experience (Anjani et al., 2020; Park & Nagy, 2018). The "dissatisfied-satisfied" dichotomy of the Kano model mirrors the "discomfort-comfort" transition, thus the authors combined them. The advantage of the new model is differentiating the dissatisfied/uncomfortable elements from the satisfied/comfortable ones, which indicates the "hidden" needs and desires of users (Figure 4.11) (Sauerwein et al., 1996). The task of this study is to identify the key elements that improve the comfort of the hygiene experience for a future airplane, Flying-V. The design process was composed of three steps: narrative comfort analysis, VR comfort study, and VR experience study.

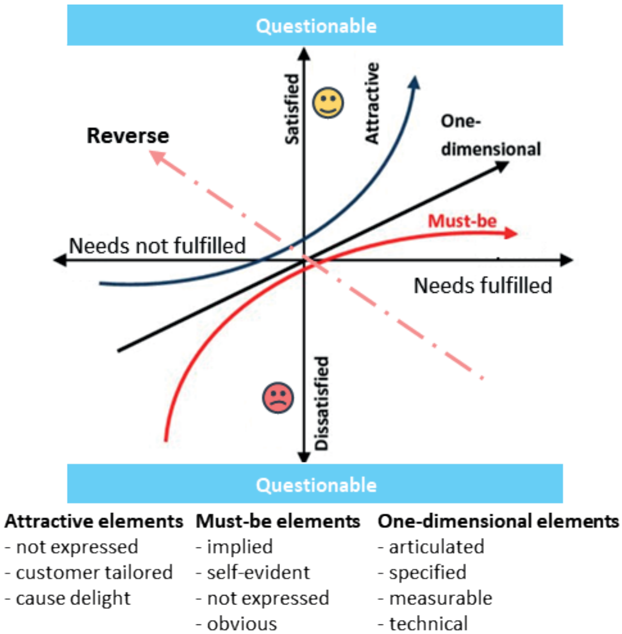


Figure 4.11 Kano Model, a tool to sort design elements into satisfying types: Must-be (M), One-dimensional (O), Attractive (A), Indifferent (I), user's satisfaction increases or be stable when they are fulfilled; and dissatisfying types: Questionable (Q) and Reverse (R), where user's satisfaction decreases or be uncertain when they are fulfilled (Tontini & Picolo, 2014).

Narrative Comfort Analysis

In this study, the authors followed the method proposed by Sauerwein et al. to conduct the narrative comfort analysis via an online survey (Sauerwein et al., 1996). First, co-creation sessions were held the collect factors related to the comfort of the hygiene experience on a long-haul flight (Yao & Vink, 2019). Second, a Kano questionnaire (7-point scale) was developed with ten design elements: *large standing space*, *sitting* *posture*, *storage places*, *large tap-basin height*, *warm light*, *facilities*, *easy door*, *open space*, *short waiting queue*, and *change room*. The questions were designed as the design elements were provided or not. The participants used 1 to indicate “very dissatisfied” and 7 as “very satisfied”. In the third step, fifty-eight female and forty-three male participants answered these twenty questions via a Google form (https://forms.gle/nUp5rNPHP8joQBRd6). Finally, the answers to two questions for each element were combined in an evaluation table, and then the design elements were categorized into six types (Sauerwein et al., 1996). The proportions of each design element on these types were mapped in a Kano evaluation table. In the end, the authors selected five design elements to undergo the follow-up VR comfort study.

VR Comfort Study

Five design elements directly related to the lavatory space were selected, including a sitting seat, tap-basin height, storage places, warm light, and facilities. Open space was removed as it has the highest reverse points. Large standing space, short waiting queue, and changing room were all attractive, hence needed to be fulfilled. Considering the limited simulation of haptic resistance in VR, the easy door was removed as well. A similar procedure to the first study was completed with ten VR prototypes developed with Maya and Unreal Engine 4.12 (Figure 4.12). The Kano questionnaire used “discomfort and dissatisfied” and “comfort and satisfied” instead of only “satisfied” and “dissatisfied”.

Twenty-eight students (including 12 males and 16 females) participated in the evaluation in the VR zone. Participants viewed the prototypes via an HTC Vive headset (1080×1200 per eye). A full-scale cupboard enclosure was built to generate a negative haptic of collision to enhance the immersion (D. Wang et al., 2019). After filling in the informed consent, the participants interacted with the VR prototypes shown in Figure 2. Every prototype was shown for 40 seconds to participants. A baseline prototype was demonstrated after each pair of prototypes, which included two taps, a wide front mirror, two full-length side mirrors, and child stairs considering the need for a large space and changing room. In the end, a semi-structured interview was conducted to collect qualitative design feedback.

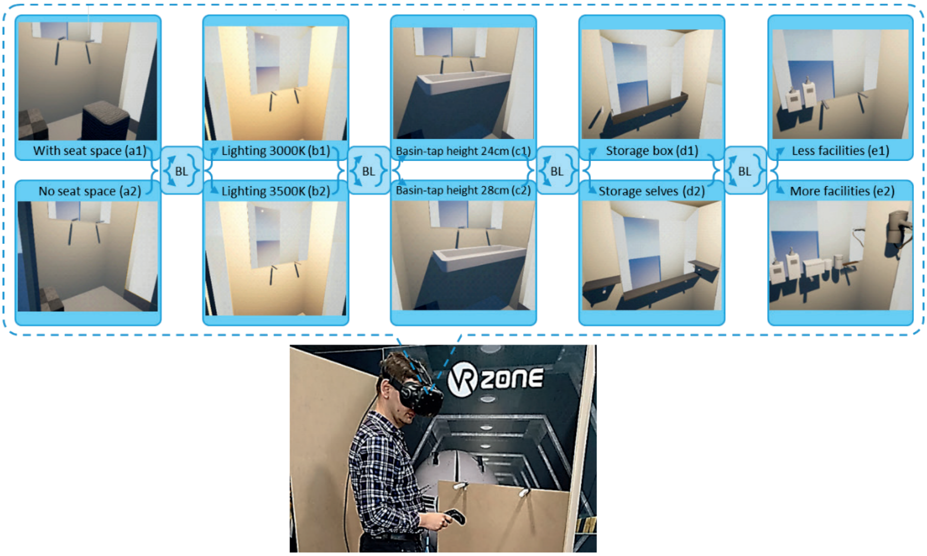


Figure 4.12 The setup of VR comfort evaluation: Participants interacted with ten VR prototypes from five design elements. Each prototype showed 40 seconds so they could navigate in and interact with it. A cardboard enclosure provided the passive haptic feedback. A baseline model was demonstrated between every pair of prototypes for 20 seconds. The participants rated the comfort of each prototype with a 7-point scale where "1" for discomfort and "7" for comfort.

VR Experience Study

The prototype was modified according to the comfort ratings and qualitative feedback. A comfort questionnaire, a realism questionnaire, and a Presence Questionnaire (PQ) were used in the final assessment of the simulated hygiene experience (Witmer et al., 2005). Both the comfort and realism questionnaires applied the seven-point Likert scale to indicate "discomfort/unrealistic" to "comfort/realistic" with one to seven on design elements.

Thirty-three university students and staff were invited to join the final evaluation. The usage context was letting them imagine that they were on a long-haul flight while seeking refreshments. The participants were asked to simulate their behavior when using this hygiene space. When finished, they filled in the questionnaires and reflected briefly on the VR experience.

Data Analysis

The data analysis used SPSS v.25 to calculate means and standard deviations, as well as the Chi-square test for independence when comparing the females versus males, and VR prototyping versus narrative prototyping. One sample t-test was used to compare the comfort scores of the final concept with the average comfort score from the first concepts.

4.1.1 *Results*

Narrative Comfort Analysis

Six elements were indifferent, meaning that the comfort perception was diverse among them (Table 4.11). Large standing spaces, storage places, short waiting queues, and changing rooms were attractive.

Table 4.11 The results of narrative comfort evaluation showing the types of ten design elements (A =”attractive”, I =”indifferent”)

Product requirements	Total (101)	Type	Female (58)	Type	Male (43)	Type
large standing space	63.4%	A	69.0%	A**	55.8%	A
sitting posture	66.3%	I	65.5%	I***	67.4%	I
storage places	72.3%	A	77.6%	A	65.1%	A
large tap-basin height	50.5%	I	48.3%	A/I	53.5%	I
warm light	68.3%	I	67.2%	I	69.8%	I
facilities	72.3%	I	65.5%	I	81.4%	I
easy door	50.5%	I	50.5%	I	53.5%	A
open space	73.3%	I	63.8%	I*	86.0%	I
short waiting queue	56.4%	A	58.6%	A	53.5%	A
changing room	69.3%	A	69.0%	A	69.8%	A

“*” indicates the significant level $p < 0.05$(Chi-square);
“**” indicates the significant level $p < 0.01$(Chi-square);
“***” indicates the significant level $p < 0.001$(Chi-square).

Large tap-basin height was either attractive or indifferent for females. Female and male participants have significantly different attitudes towards the large standing space and sitting posture. The attitudes toward sitting posture, large tap-basin height, warm light, facilities, easy door, and changing room were indifferent (from Figure 4.13 to Figure 4.17). Thus, they need further investigation during a follow-up detailed design.

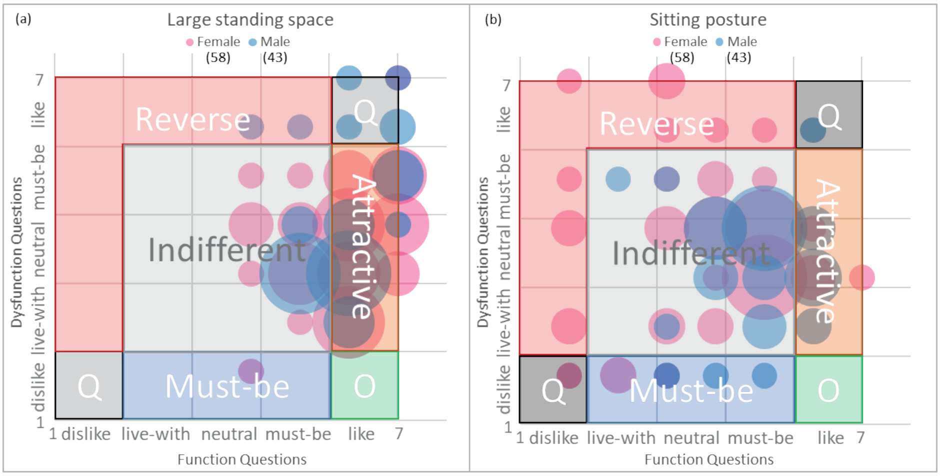


Figure 4.13 Kano evaluation table of large standing space (a) and sitting posture (b). Larger standing space was between attractive and indifferent which contributes to comfort while sitting posture was diverse among user groups.

The storage covered attractive, indifferent, one-dimensional, and must-be, thus its style needed a detailed design as well (Figure 4.14).

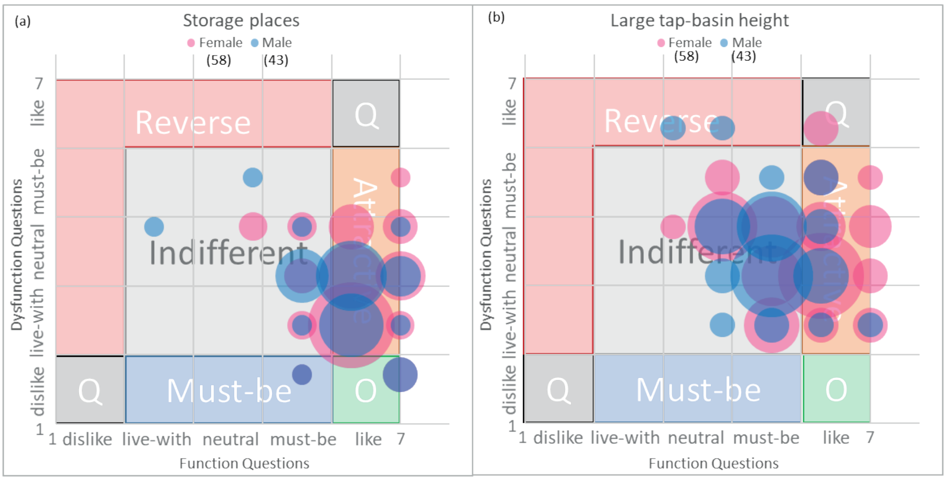


Figure 4.14 Kano evaluation table of storage space (a) and large tap-basin height (b). Males and females both like storage places, but a large tap-basin height seemed only attractive to a small group of people.

Warm light and facilities covered most types except for must-be and one-dimensional (Figure 4.15), like the storage places, large tap-basin height, and sitting posture.

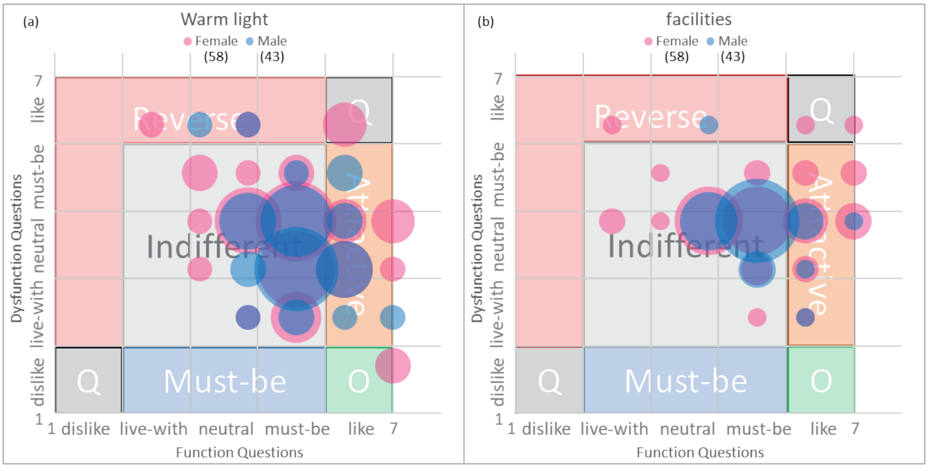


Figure 4.15 Kano evaluation table of warm light (a) and facilities(b). Warm lights and facilities didn't show clear influences on the comfort level.

Open space had the highest reverse score. A detailed design of the easy door was needed; however, virtual prototypes lack subtle resistance simulation (Figure 4.16).

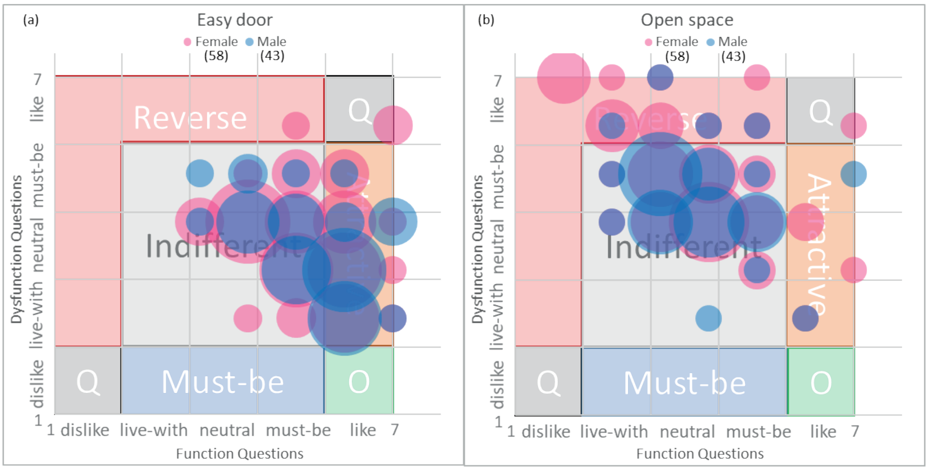


Figure 4.16 Kano evaluation table of the easy door (a) and open space (b). An easy door is attractive or indifferent but the open space decreases the comfort.

A short waiting queue (Figure 4.17) is attractive but outside of the hygiene space. The room of the airplane interior is very limited; thus, the detailed design should consider multi-purpose functionalities instead of providing an extra hygiene space. They should be removed from the VR evaluation.

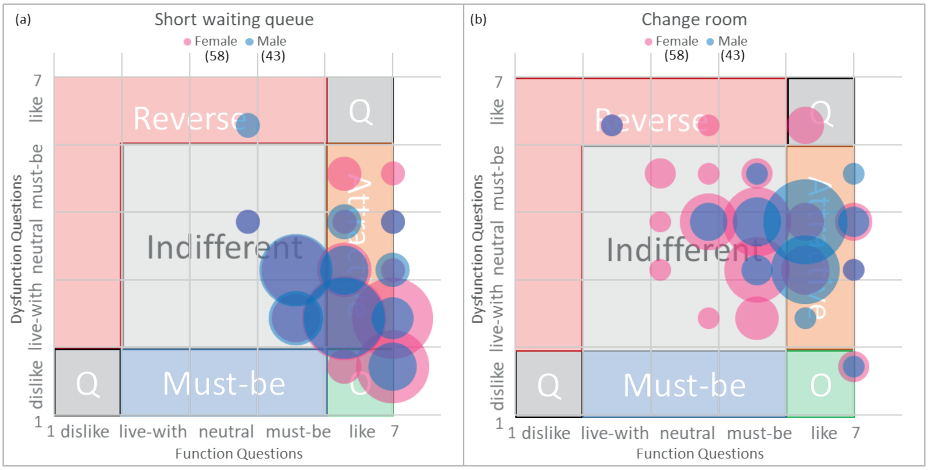


Figure 4.17 Kano evaluation table of short waiting queue (a) and change room (b). A short waiting queue is attractive and may continuously increase comfort as a one-dimensional element, particularly for females. Changing rooms for most participants is attractive, especially for males.

VR Comfort Study

Females perceived the comfort of each design element significantly differently than the males except for lighting (Table 4.12). The high-end facilities, i.e., hand soap, hand cream, cotton swabs, cotton pads, and a hairdryer, were attractive for both males and females, but females preferred it significantly higher than males. Large tap-basin height was reversed for around one-third of the females, and for males was mostly indifferent (41.7%). The storage shelves providing more storage places were attractive for more than 40% of the males, but most females (62.5%) made no difference.

Table 4.12 The table of results for VR comfort evaluation

Product requirements	Total (28)	Type	Female (16)	Type	Male (12)	Type
Sitting seat	53.6%	I	62.5%	I**	50.0%	R
Large tap-basin height	35.7%	I	31.3%	I/R***	41.7%	I
More storage places	53.6%	I	62.5%	I***	41.7%	A/I
Warm light	57.1%	I	56.3%	I	58.3%	I
More facilities	42.9%	A	50.0%	A**	33.3%	A

"**" indicates the significant level $p < 0.01$ (Chi-square).
"***" indicates the significant level $p < 0.001$(Chi-square).

The comfort perception changed significantly in VR prototyping than the narrative prototyping for all design elements and user groups except for the sitting seat in females (Table 4.13). Providing a sitting seat changed from indifferent to reverse for males, and the large tap-basin height transferred from attractive/indifferent to indifferent/reverse for females. The perception of storage places shifted a bit from attractive to indifferent.

Table 4.13 VR and narrative Kano results from the comparison

Product requirements	Total		Female		Male	
	VR	NA	VR	NA	VR	NA
Sitting seat	I***	I	I	I	R***	I
Large tap-basin height	I***	I	I/R***	A/I	I***	I
More storage places	I***	A	I***	A	A/I***	A
Warm light	I***	I	I***	I	I***	I
More facilities	A***	I	A***	I	A***	I

"***" indicates the significant level p <0.001 (Chi-square).

The attitude towards the sitting seat (Figure 4.18) shifted from indifferent, attractive, and must-be for the narrative to reverse and questionable in VR. Qualitative feedback indicated the seat might extend the duration of usage and reduce the limited space.

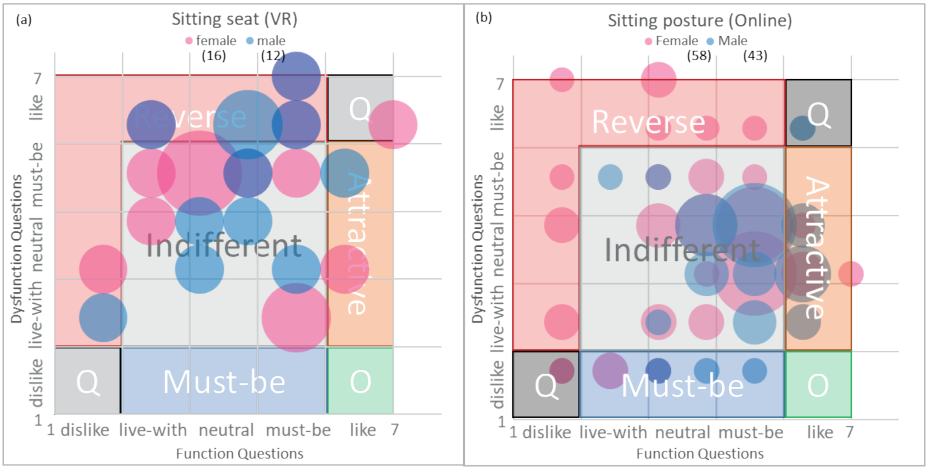


Figure 4.18 VR (a) and narrative (b) Kano evaluation table of the sitting seat. VR prototyping had a more diverse comfort rate than the narrative due to the narrow feeling of the space in VR.

The perception of large tap-basin height (Figure 4.19) shifted obviously from indifferent and attractive for the narrative survey towards questionable (positive) and reverse in VR, especially for the males. Qualitative feedback indicated the shorter height (24 cm) was enough comfortable and a larger height might cause more splash.

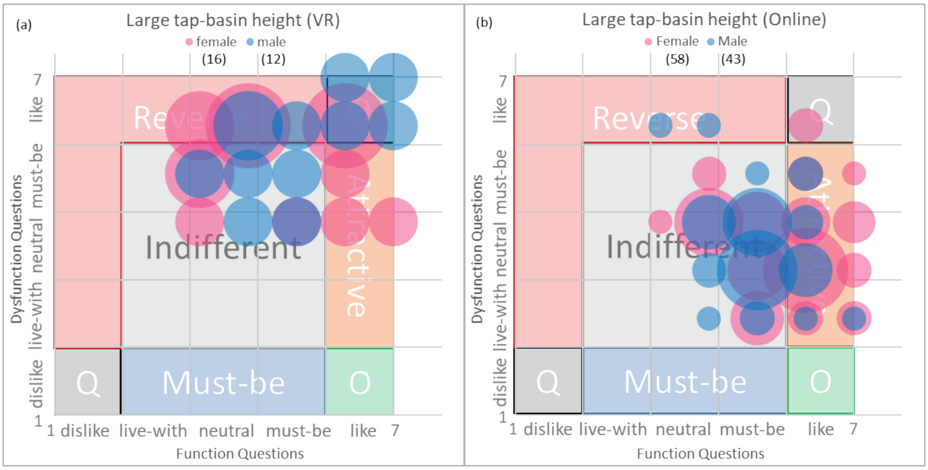


Figure 4.19 VR (a) and narrative (b) Kano evaluation table of large tap-basin height. Large tap-basin height associated with more splash thus became even reverse for a group of people in VR.

The storage preference (Figure 4.110) became more diverse in VR. Some preferred simpler storage like a box (reverse). Some females viewed more storage as a must-be both in VR and narrative.

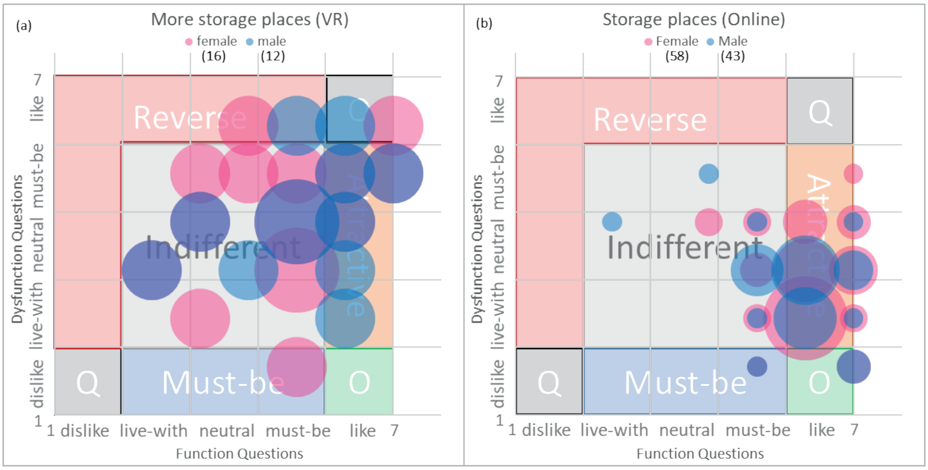


Figure 4.110 VR (a) and narrative (b) Kano evaluation table of more storage. Males liked more storage places but females' attitudes became more diverse in VR.

Participants commented that the shelves narrowed the perception of space and the edges were too sharp. A small rim was necessary considering turbulences. The questionable (positive) ratings increased obviously for warm light (Figure 4.111) in VR. Several participants prefer more neutral lighting (3000k) instead of warmer ones (3500K) in VR. Some participants said that they could notice the change in the lighting in VR but had no preference.

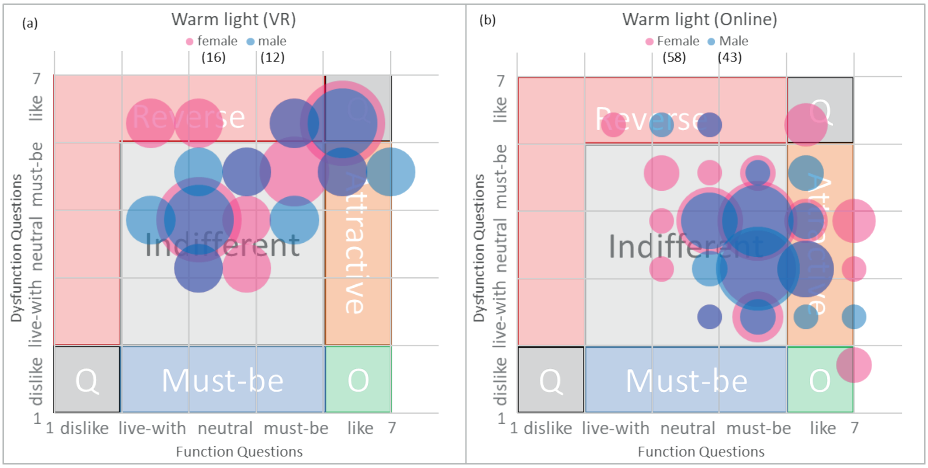


Figure 4.111 VR (a) and narrative (b) Kano evaluation table of warm light. The comfort rates on warm light moved towards reverse because of the yellowish tone of 3000K in VR.

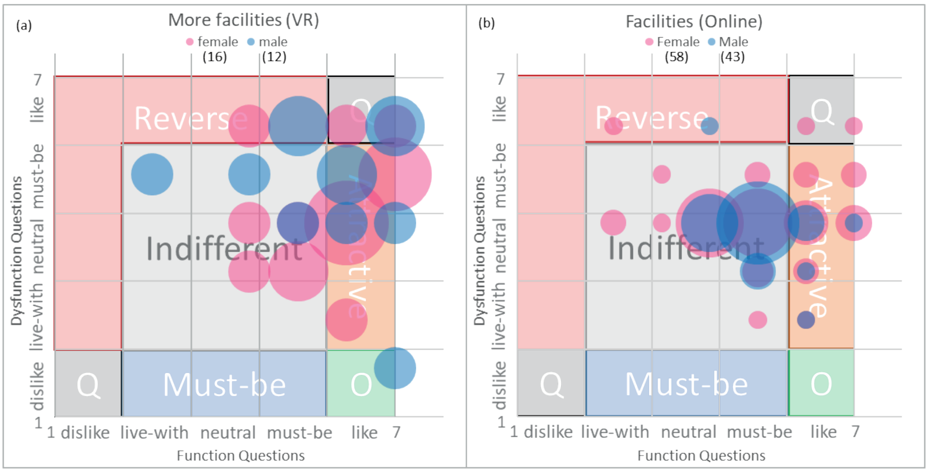


Figure 4.112 VR (a) and narrative (b) Kano evaluation table of more facilities. More facilities became more attractive for some females and males, but shared facilities caused higher concerns about hygiene for other groups.

More facilities became more attractive for the participants in VR, particularly for females (Figure 4.112). A larger group of males and females preferred fewer facilities like hand soap and hand cream than in the narrative survey. The qualitative feedback indicated more facilities looked more chaotic, hence not attractive in a narrow space like an inflight lavatory.

VR Experience Study

The final design (Figure 4.113) included a large basin with two induction taps, frontal long and right-hand short shelves with rims, a hook next to the short shelf, a hairdryer on the left-hand side, and child steps. Underneath the basin, there were paper towels and a dustbin. The researchers put the paper towels low considering the accessibility of children and avoiding dipping water back into sleeves which were participants' comments in the VR study. In the final evaluation, participants were asked to design an organizer for the facilities to make the environment more concise and cleaner. Handholds were also needed during turbulences.

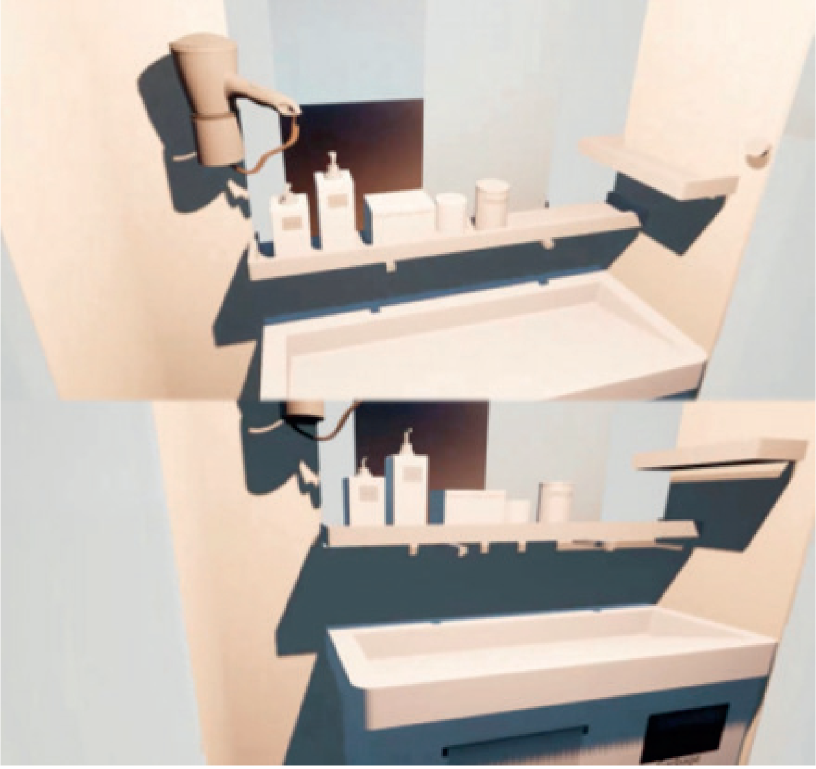


Figure 4.113 The final concept of the lavatory includes a 24cm basin, natural lighting, side and front shelves with rim and rounded corners, a hook, high-end facilities, paper towels, and a dustbin.

The general comfort was significantly higher than neutral (4). The design element "facilities" was the most comfortable factor (Figure 4.114). Participants considered the final VR prototype as realistic as well except for the use of water. The use of water was not realistic as the participants expected detailed interaction with the bottles and the taps. Though only showing virtual hands and a headset, the participants still felt confident enough to assess the use of mirrors.

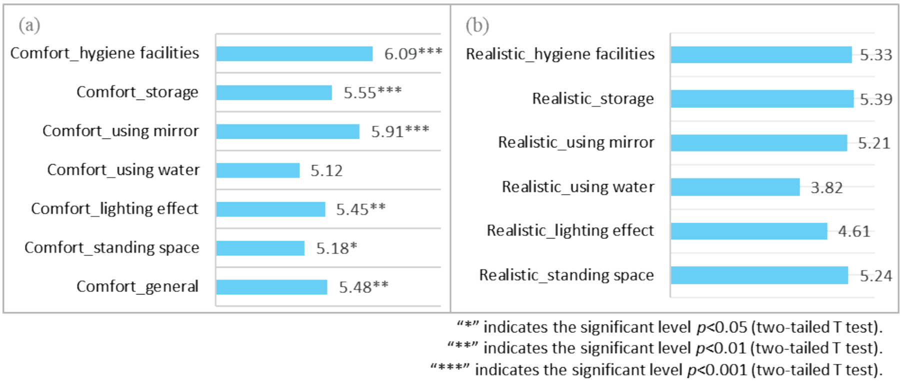


Figure 4.114 The comfort and realism perception of the final concept. The participants demonstrated significantly higher comfort than the average of the first group of prototypes (comfort mean = 4.70).

According to Witmer and Singer (2005), the perceived immersion between 90 and 100 is enough general the "being-there" effect in users, as shown in

Table 4.14 (Witmer et al., 2005). Most of the participants reported that they felt presented in a real lavatory and felt refreshed after the simulated tasks.

Table 4.14 The perceived immersion with the final VR prototype.

	Realism	Possible to Act	Quality of Interface	Possibility to Examine	Self-evaluation of Performance	Perceived Immersion
Total	36.67	18.15	15.03	15.39	11.79	97.03
Female	37.57	20.14	14.86	15.29	10.93	98.79
Male	36.00	16.68	15.16	15.47	12.42	95.74

4.1.3. Discussion and conclusion on the ergonomic design using VR prototyping

The lavatory or hygiene space is like a private island for long-haul travelers which lets them escape from the crowdedness and boredom of traveling (Tan & Shen, 2010). Therefore, enough space and cleanliness are the top priority for them. More storage or even more facilities became not attractive when they increased the narrow and chaotic feeling. An experience can be both comfortable and uncomfortable according to various cognitive and physical aspects. This insight is not only useful for the design of inflight lavatories but also for improving comfort during long-haul traveling.

The participants' judgments on the Kano table were significantly different when using immersive VR compared with the text narratives from the online questionnaire. Sütfeld et al. (2019) found that VR and text-based surveys didn't strongly influence the moral decision of drivers in autonomous cars (Sütfeld et al., 2019). Either the naturalism of the context, like text or realistic scenarios, or levels of immersion, like desktop versus VR, didn't change the driver's moral judgments except for the lane bias. This finding is in line with our speculation that VR affects strongly space-related judgment (associated with episodic memories) instead of moral (associated with semantic memory). Wang (2019) pointed out that the value of VR is to trigger imagination surrounded by target contexts, enabling designers and engineers to dig into the "hidden" and deeper needs and desires of target users (D. Wang et al., 2019).

In a narrow space, providing more storage changed the design from satisfied to dissatisfied, which is a new type of ***semi-circle*** in the Kano model (Figure 4-1-15). The participants reported that the passive haptic feedback reinforced their perception of the enclosure. It proved that user needs should be investigated in contexts of use, otherwise, conclusions might be misleading. Moreover, users' needs are way more complicated than we expected. The engagement of multiple senses in immersive VR might help users examine the visual cues (hand and headset) from multiple perspectives and enable proprioception (the sense of body movement) to facilitate their judgments. A similar interactive embodiment has been found valuable in analyzing and optimizing workplace design as well (Grajewski et al., 2013). Besides, the participants in VR gave their judgment based on observation instead of imagination, such as they disliked sharp edges or preferred standing in a narrow space. The immersive VR especially seems to enable users to check nuances in the design, when the human body-geometry relationship is of importance like in the hygiene space.

The design element "warm light" was the only one that kept indifferent for the narrative and VR studies: some questionnaire readers imagined that warm light would be more pleasant, while the warm light was indifferent or even unpleasant to the VR users. Light tracking is the most intriguing yet complex part of VR modeling and prototyping. Designated efforts are needed to simulate realistic lighting effects in a virtual environment. The insights from architecture design show simulating lighting effects in VR "support design stakeholders better perceive and optimize lighting condition to achieve higher satisfaction" (Natephra et al., 2017).

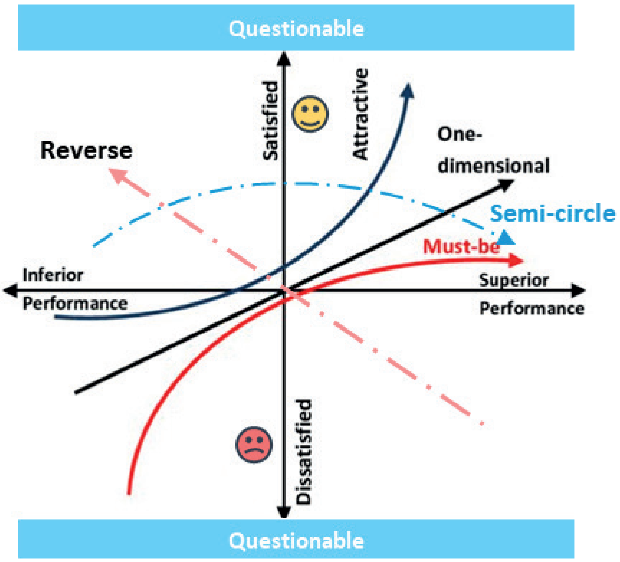


Figure 4.115. The new type is semi-circle in the Kano model.

There are the following limitations in this experiment which may open room for future studies. First, the findings were limited by the haptic and visual fidelity of the VR prototyping. The preference for an easy door was not studied due to the rough haptic simulation of the VR controllers (Aukstakalnis, 2016). Detailed interaction is needed when the design goes to the next level. However, the workload of developing interaction in VR soars when more details are involved. Second, the overall context of the cabin was missing, hence the studies on crowdedness and social distance were unavailable. A similar study from NS uses VR to demonstrate how the density of people influences seat preference (Nederlandse Spoorwegen, 2021). A user experience study to redesign ports of Dutch public transport demonstrated the value of VR for user evaluation in the context (Obbink, 2016). Hence, a fully virtual environment serves as a playground that allows design teams to explore problems that are impossible with other technologies. The third shortcoming is the small number of participants in VR studies. Though the qualitative reflection proved the changes in users' attitudes, the gap in sample size between the narrative survey and the VR studies is still large. Future studies should focus on how to conduct user studies via VR with massive participants like online questionnaires. Nevertheless, endowing every user with an immersive headset like a smartphone is still a far way to go.

Back to our research question: How can this first-person immersion be used in a product development process to ensure comfort? First-person immersion is of paramount importance to understanding space experience and context experience instead of moral judgment. Investigating the user's needs under specific contexts is the key to developing products and services satisfying target users.

The novelties of this study are as follows:

1) implementing the Kano model into a comfort study, and identifying a new type: *Semi-circle*;
2) VR and text-based evaluation were compared and showed the importance of conducting user research under the context of use;
3) identified the key elements, spaciousness, and cleanliness, of comfort design for a hygiene-relevant space for long-haul traveling.

Despite the technological barriers, such as the steep learning curve of VR programming and the availability of VR headsets, VR shows great potential as a designer's playground to liberate creativity and make impossibilities possible.

4.2. Concept Evaluation of A New Aircraft Passenger Privacy Bubble Using Virtual Prototyping: A Human-Centered Design Framework

4.2.1. Introduction

Human-centered design (HCD) is about regular testing and iterating user-informed product decisions to ensure that the desired functionality, comfort, and experience are reached. According to the principles of HCD ISO 9241-210 and participatory design of interactive systems, it is critical to involve end-users throughout design processes to evaluate interactive solutions (ISO, 2019; Kuhn & Muller, 1993).

Virtual Reality is a combination of different interface technologies that enable a user to intuitively interact with an immersive and dynamic computer-generated environment (Manetta & Blade, 1995). The application of various forms of VR prototyping has proven to be very useful in various stages of HCD (Wang, 2002). Especially, compared to the conventional prototyping methods, VR prototypes not only provide more efficiency in time and cost in product developing procedures but also facilitate participatory design, especially regarding aesthetic and ergonomics owning to its immersion (Lawson et al., 2016; Park et al., 2009; Wang, 2002). Therefore, its application is considered very helpful in delivering more human-centered solutions to the market (Aromaa & Väänänen, 2016).

In this study, the authors present the results of the concept evaluation of a new passenger seat in commercial aviation by taking advantage of virtual reality technology. The design requirements for the seat concept were extracted and synthesized from a previous study by Torkashvand et al. (2019) in which more than 100 passengers participated and clearly stated that passengers prefer to have privacy, which was affirmed also by the fact that the middle seat with two neighbors is least popular in aircraft interiors. To create more privacy a new seat concept PRIVA was developed.

The new seat concept PRIVA was based on the following demands consist of:

1. Enhancing passenger privacy
2. Maintaining/increasing situation awareness
3. Facilitate communication with other passengers/flight attendants
4. Including a more personalized IFE system
5. Being adjustable for comfort-related aspects (noise, temperature, etc.)

Also, the mentioned demands were directly or indirectly associated with some inflight activities such as 'resting and relaxing', 'sleeping', 'talking to neighbors', 'watching inflight IFE', 'interacting/communicating with flight attendants' as well as 'Adjusting lighting', 'adjusting IFE/LCD' and 'adjusting privacy'. These activities were earlier considered to be either important and/or not satisfactory by passengers (Torkashvand et al., 2019). The question is whether frequent flyers will see the advantages of using a VR prototype. Therefore, a VR model was made and evaluated by passengers.

4.2.2. Methodology

Modeling And Simulation

Initially, the model was developed in 3D using Rhinoceros software (Figure 4.21). This 3D model served as a visual representation of the concept for communicating the solution with other stakeholders and as a foundation for developing the VR prototype. Even though The researchers aimed to simulate the concept for subjective evaluations on the satisfaction and desirability of the features, to make it more realistic, The researchers used some realistic dimensions for the model. The researchers followed the standard height and depth for the seat design and angle (see Kokorikou et al. (2016), e.g., seat height of 16.1" and seat pan length of 16.7"). For the bubble height, the minimum standard dimension of the viewing distance of mobile LCD from the eyes and the maximum seated height of people was considered. Besides, the situation of the bubble, some short and tall seated dimensions were considered however the adjustability of that was inevitable concerning the design requirements.

A more advanced VR simulation of the PRIVA was developed through the gaming software "Unreal Engine"[1]. To add some realistic context, three rows of PRIVA seats

1 https://www.youtube.com/watch?v=T27IdT6EWdg

were then placed inside a virtual cabin under Flying-V interior design. The seats were arranged in a staggered configuration (Liu et al., 2021). Also, a dummy avatar was included in the mock-up to provide the participants with some estimation of PRIVA dimensions (Figure 4.22). Two interactions were programmed into the model to simulate some of the PRIVA features: opening and closing the PRIVA bubble. Animations associated with the effect of the above-mentioned inflight activities were demonstrated between these interactions. After the 3D space working prototype was developed, it was displayed with the HTC VIVE VR headset. The HTC Vive is a VR head-mounted display with 1080 × 1200 resolution per eye plus head-tracking. The tracking sensors of the headset allow users to move in a self-defined space up to 3.5 × 3.5m and use motion-tracked handheld controllers to interact with the environment.

Figure 4.21 PRIVA concept *original* 3D models.

Test setup

The experiment took place in Applied Labs at Delft University of Technology during the International Comfort Congress in August 2019. The track sensors were mounted on the top trusses to ensure a free-moving space as big as the virtual cabin. The auditory feedback was displayed when demonstrating IFE-related features. Besides, the VR headset was tethered to a graphic workstation to ensure smooth rendering of the virtual environment. The researchers were also granted access to the HTC Vive VR headset by the AR lab in TU Delft for this study.

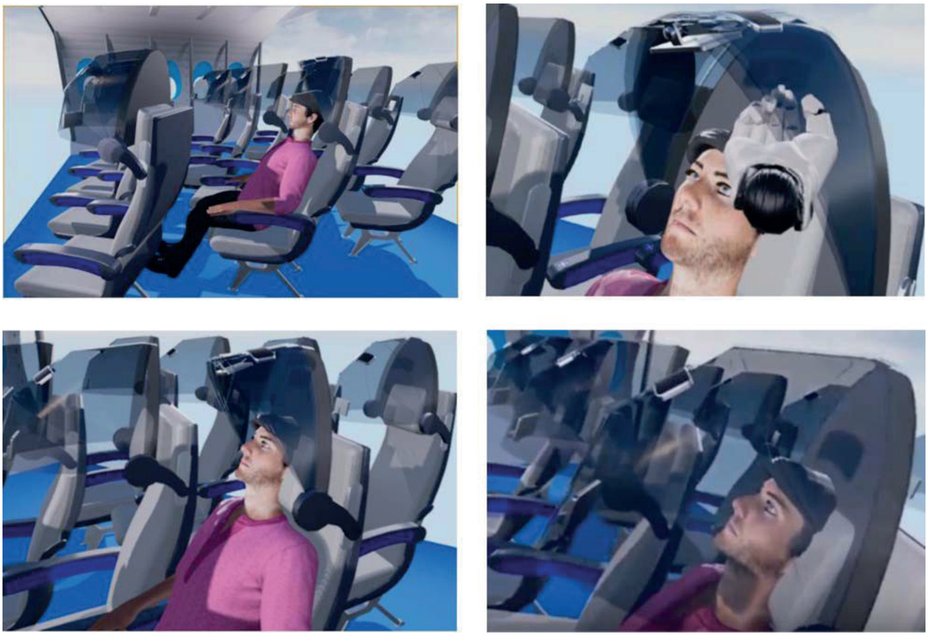


Figure 4.22 PRIVA concept simulation in VR

Survey design

A survey was developed with questions on how the new design was experienced. The survey started with a consent form to be agreed to by the participants. The survey included two sections:

The first sections included demographic questions such as age, gender, etc. It also asked the participants whether they often travel alone, or with a spouse, families, or a group of friends. The first section was adapted from the survey by Torkashvand et al. (2019). The three main segments - traveling alone, as couples, or in groups - were extracted from the same study to understand how each segment's perception differs regarding the current activities and satisfactions associated with them.

The second section was developed by the researchers, followed by some evaluative questions regarding participants' perceptions of each of the PRIVA features as well as the effectiveness of PRIVA (and its features) in ensuring more satisfaction with the mentioned inflight activities. The questions were generated on a Likert scale ranging from 1 = *not at all satisfactory* to 5 = *extremely satisfactory*. Also, the survey included other questions to evaluate passengers' evaluations of the PRIVA seat compared to the recall of passengers' overall experience with the current seats in the commercial aircraft. This part also included criteria such as satisfaction, comfort, appeal, privacy, and effectiveness.

Since qualitative data play an important role in featuring innovative solutions, this section also included two open-comment questions on what participants liked and disliked about PRIVA. Besides, to evaluate the effectiveness of VR prototyping in the communication of the features, The researchers included a question on the realistic level ranging from not at all realistic to very realistic.

Participants

The participants were invited and selected from the congress attendees. The reason was that the researchers intended to merely include the domain-expert participants in the field of comfort and applied ergonomics. The researchers also hoped to receive some expert feedback from the engineering and ergonomics experts regarding some technical attributes of the design to consider for improvements and next iterations.

Procedure

It took approximately 10 minutes for each participant to take part in the experiment. For each participant, the following high-level procedure was taken to the experiment:

- A welcoming and verbal explanation of the procedure and expectations
- Signing the consent form
- Demonstrating an introductory video on PRIVA features
- Cabin walkthrough wearing the VR headset Debriefing: The post-experiment survey and appreciation
- Debriefing: The post-experiment survey and appreciation

Welcoming and Verbal explanation of the procedure and expectations: Upon arrival and welcoming, a general overview of the objective of the study, the procedure of the experiment as well as a quick introduction of the PRIVA concept on a poster was verbally explained to participants. The researchers also explained to them the conceptual nature of PRIVA at this phase and encouraged them to ask if they had any questions before, during, or after the experiment.

Signing the consent form: Ethical documentation was issued by the Florida Institute of Technology months before the experiment. The participants were informed about the experiment and any risks and benefits associated with it. They were also asked whether they agreed to take part in the experiment. Besides, the form included information such as the confidentiality of the research as well as the contact information of the researcher. Upon request, a copy of the consent form was also handed to the participants for their records.

Demonstrating an introductory video on PRIVA features: To ensure that each participant gets a mutual understanding of all the features that PRIVA offers, as well as to prevent any later misunderstanding about the survey questions about the features, and to enhance the learnability of the features by the users during the VR experiment, the researchers planned to present the participants with a video that demonstrates these features one by one. The video included text labels to introduce the features.

Cabin walkthrough wearing the VR headset: After watching the demo video, the participants were directed to the lab setting where the VR equipment was set. The simulation was an interactive demo and required some training on how to use the controllers etc. Therefore, a short training was conducted before the simulation to guide the participants on how to walk through the scenario. In addition, a few interventions were also planned during the experiment, to assist the participants in completing the scenario (Figure 4.23).

Figure 4.23 A participant is being trained by the facilitator on using the VR.

- While running the simulation, the participants were supposed to find the seat with the dummy avatar.
- Standing next to the seat with the avatar on, they were then asked to use their hand controller to simulate the dragging of the PRIVA shelter down.
- At this step, the simulation played an automatic demonstration of all the seat features (Figure 4.24), during this automatic simulation phase, participants were supposed to only watch through the features within the immersive VR context.
- At the end of the VR experiment, the participants were asked to use their hand controllers to simulate the hand gesture for dragging the privacy shelter up. They were then assisted with taking off the VR headset.

Figure 4.24 A participant is experiencing the PRIVA using a VR headset.

Debriefing: The post-experiment survey and appreciation: After the experiments, the participants were directed to another part of the laboratory to complete the online survey (Figure 4.25). At this point, the experiment was finished; the researchers appreciated the participants for their contribution to the study.

Figure 4.25 A participant is taking the online survey after the experiment.

4.1.2 *Results and analysis*

In total 40 individuals (16 Females and 24 Males) participated in this experiment. There was an equal distribution of participants who traveled alone and those who traveled with their families. In addition, those who selected 'other' explained that they travel both alone and with family/friends. Most of the participants (95%) stated that they often travel in economy class.

The overall evaluation of participants regarding their perceived evaluation of PRIVA, when compared to the current aircraft seats, reveals that participants mostly perceive the new concept to be more comfortable, private, appealing, satisfactory, and effective (from Figure 4.26 to Figure 4.211). However, to comply with our original approach to assessing the experience based on activities, the researchers also analyzed participants' perceptions of PRIVA concerning the activities associated with that.

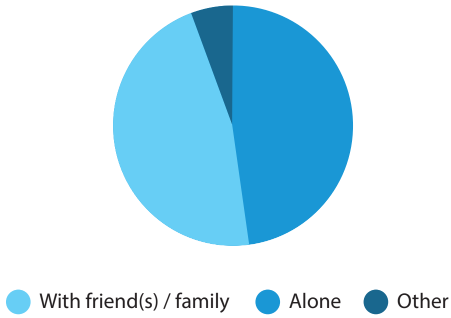


Figure 4.26 Distribution of traveler types.

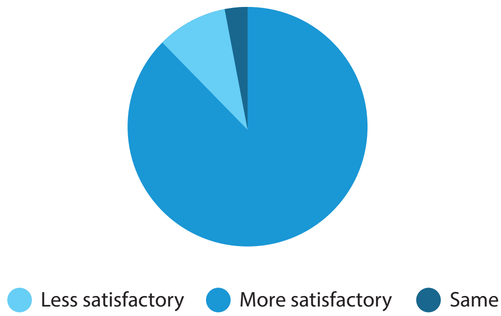


Figure 4.27 Perceived satisfaction compared to current seats.

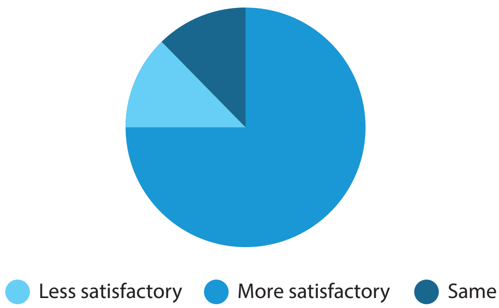


Figure 4.28 Perceived comfort compared to current seats.

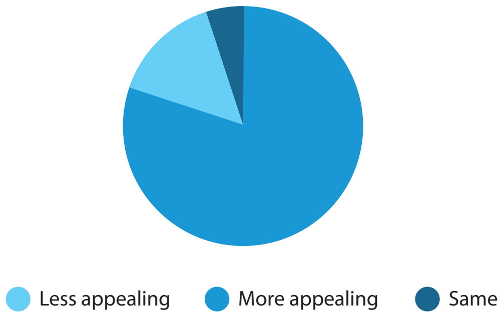


Figure 4.29 Perceived appeal compared to current seats.

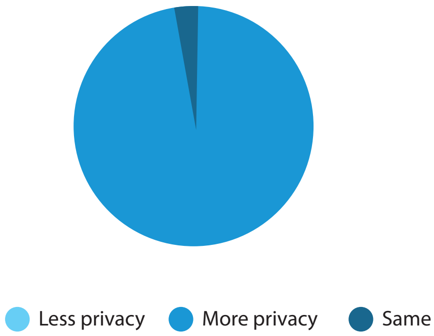


Figure 4.210 Perceived privacy compared to current seats.

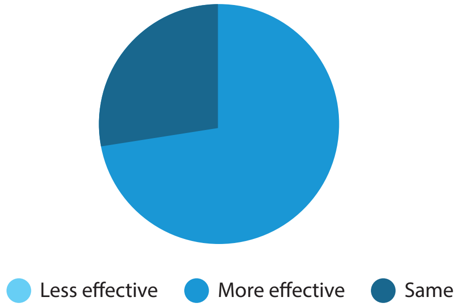


Figure 4.211. Perceived effectiveness compared to current seats.

Regarding the satisfaction of the new design while performing certain activities, adjusting privacy is the highest among all activities (Figure 4.212). Similarly, the next satisfactory activities include, adjusting lighting, resting/relaxing as well as sleeping. On the other hand, talking to neighbors was perceived as not satisfactory as the rest of the activities (Table 4.21).

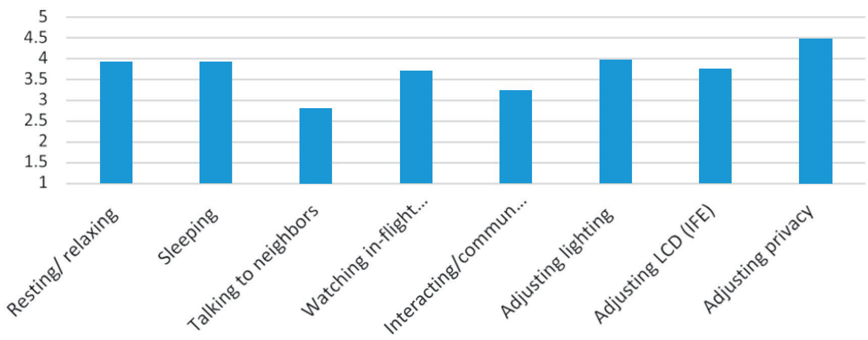


Figure 4.212 Satisfaction frequency by the activities in PRIVA.

Table 4.21 Distribution of responses on satisfaction by activities

Activities	Not at all satisfactory			Extremely satisfactory
	1	2	3	4	5
Resting/relaxing	0	8%	17.5%	60%	17.5%
Sleeping	0	5%	35%	25%	35%
Talking to neighbours	20%	20%	30%	20%	10%
Watching through IFE	0	12.5%	35%	22.5%	30%
Interacting/communicating with FA	0	17.5%	32.5%	40%	5%
Adjusting lighting	0	7.5%	20%	42.5%	30%
Adjusting LCD (IFE)	0	7.5%	32.5%	40%	20%
Adjusting Privacy	0	5%	25%	20%	65%

The average satisfaction with activities in group travelers is higher compared to individual ones (Figure 4.213). It was especially interesting as the researchers originally considered PRIVA to be targeted at individual travelers.

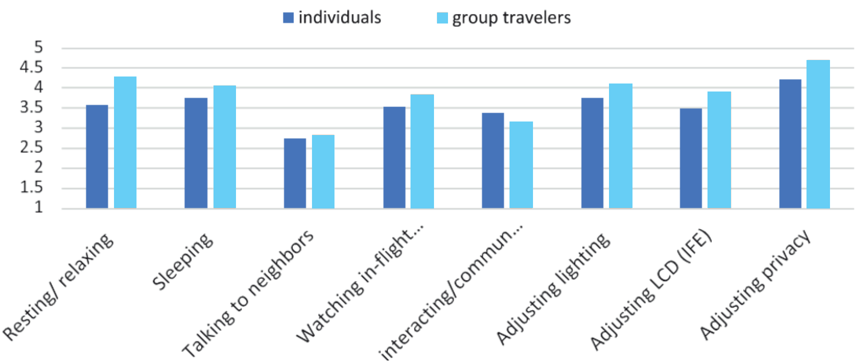


Figure 4.213 Satisfaction by activities among groups and individuals.

Regarding the realistic level of participants' perception of different features, the results show that the VR simulation was more effective in demonstrating the adjustable privacy feature (Figure 4.214).

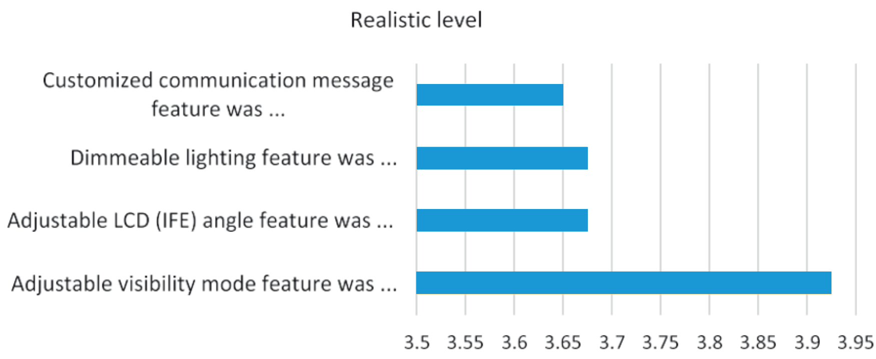


Figure 4.214 Realistic level evaluation of the PRIVA simulation.

4.2.3. Discussion

Regarding the question of whether frequent flyers will see the advantages of using a VR prototype, this study shows that many advantages were mentioned by the passengers.

According to Duarte et al. (2010), VR is a broad area that is defined in different ways in the literature. He mentions that VR consists of a sophisticated interface between people and computers. Virtual Environments (VEs) are made to be experienced by users. This means that there is a technological aspect and a human aspect. Steed (1993) indicates that VR consists of a computer-based system containing components like a head-mounted display (HMD), a tracking system, input devices, audio output, and a database, as the similar technical configuration in our case. The technological part registers multisensory stimuli on the human sense, which links to the human side (Bowman and McMahan, 2007). The passengers were placed into the virtual cabin and saw the new environment and by moving around freely they have the experience of being in or surrounded by an object or interior, achieving the "being there" effect (Bowman & McMahan, 2007). Duarte et al. (2010) mention that ". . . participants are placed into a virtual world or VE. The VE contains synthetic sensory information able to lead individuals to perceive an environmental context, and, if done well, perceive it as if it were not synthetic." The potential of VR prototypes lies in achieving "a high-fidelity simulation of an existing experience", which is not available due to safety, technology and cost restrictions (Buchenau & Suri, 2000). The advantage, in this case, is enhanced by precise space perception and intuitive interaction modalities, which use a stereoscopic HMD, and a motion-tracking system. Wang and Toma et al. present similar findings on VR-based modeling, assembly, and maintenance (Toma et al., 2012; Wang, 2002). It also had some mixed reality system features as the participants could sit on a physical chair aligned with the VR seat resonating with the tactile feedback. According to Burdea and Coiffet (2003), this is not VR in a strict sense.

Like in the study of Aromaa and Väänänen (2016), the results indicate that VR can be used to support human factors and ergonomics evaluation during the design. They also showed that it is important that a natural and interactive interface with the context in use supports the Human factors and ergonomics evaluation. They found it important that the participants were able to stand on the maintenance platform and see the feeder and other parts properly. In our case, the passengers were able to sit and experience the VR in its 'natural' environment. Adding noise would have probably made the evaluation better. Aromaa and Väänänen (2016) show that other sensory modalities, in addition to visual feedback, evaluate the environment better. This study supports the vision of Bruno and Muzzupappa (2010) that VR techniques are a valid alternative to traditional methods for product interface usability evaluation and that the interaction with the virtual interface does not invalidate the usability evaluation itself.

This research had limitations as all passengers were asked to imagine the new situation and comment on that. By mentioning it as a new situation it could already have a positive bias. However, the researchers also saw that passengers still mentioned that it would hinder communication with the neighbors. Another limitation is that the VR model was not stable and sometimes the researchers had to interfere to restart the system again, but in the end, all participants were able to experience the new interior.

The current study aimed at testing a new concept using VR technology. The approach taken in the application of VR in testing the desirability of the concept was effective in eliciting some insights from participants. The immersive interaction with the new concept also brought about a more realistic perception of the features as well.

The current study acknowledges that while PRIVA is not the only solution for privacy in passenger cabins, the researchers believe the added features make it more innovative than the previous privacy bubbles like Pangolin the helmet (see https://www.trendhunter.com/trends/alpha-helmet). In particular, the adjustability of privacy, the use of personal devices, as well as the communication feature are some unique aspects of this concept which were also validated by passengers in this experiment.

Regarding the outcomes, the application of VR technologies in the evaluation of the concept of desirability and perceptions of satisfaction and comfort seems to be effective. However, it is important to note that to move forward with further comfort and usability evaluations of the concept, VR or AR prototypes of different fidelity might be required as Lim et al. (2008) state that the suitability of virtual prototypes needs to be determined about the aspects of the product that the researchers aim to evaluate.

Some limitations also existed. The main concern of using a VR headset is simulation sickness as the researchers faced when inviting participants. Simulation sickness symptom may easily be triggered by dynamic scenarios and causes users to quit the evaluation (Ihemedu-Steinke et al., 2017), while few obvious discomforts were reported in a static environment as in this study. Besides, there is always a probability that participants become biased when being evaluated in immersed VR environments. This, however, could be overlooked due to the deeper qualitative open comments by participants on what they liked and disliked about PRIVA.

4.2.4. Conclusion on concept evaluation using virtual prototyping

The research finding validates that most participants perceived PRIVA as being more satisfactory, comfortable, effective, and appealing compared to their current experience with the economy class seats for long-haul flights. This is promising and certainly worthwhile to develop further. The study also validated the effective nature of VR prototyping in Human-Centred Design.

4.3. Comfort in Long-Haul Travel from Immersion: Comparing Desktop and Headset Virtual Prototyping in Public Hygiene Space Design

4.3.1. Introduction

The number of passengers in airplanes is expected to continue to grow at approximately 3.5% annually, which might result in 8.2 billion passengers by 2037 (IATA, 2018). However, the worldwide sustainability debate asks for new airplanes with fewer CO^2 emissions. The demand for comfortable airplanes that pay attention to the passenger's well-being is growing as well (Ahmadpour et al., 2014). Designing the innovative" Flying-V" needs to combine these two demands. It is a new concept airplane with a V-shape body, aiming to reduce fuel consumption by 20 % with current propulsion systems. This unique V-shape brings challenges for comfortable interior design, for example, the cross-section of the cabin is relatively flat compared with regular airplanes, and passengers will sit in the wings of the airplane. Both from a pre-study and the literature, it was found that hygiene-related in-flight activities are closely related to comfort (Vink & Hallbeck, 2012). The challenges of designing a hygienic space in long-haul public transport like airplanes and trains are its limited space, versatile functionalities, and personalized experience (Loth et al., 2014; Vink & Hallbeck, 2012).

To develop a comfortable and satisfying product, designers often make decisions on these issues by using various techniques, from paper prototyping to 3D printing models (Bordegoni et al., 2006; Mueller et al., 2014). On one hand, it is important to include target users to make decisions on a concept and to validate concept selection.

On the other hand, future products and systems like Flying-V do not exist yet, and the building of physical prototypes on a full scale would be costly and time-consuming. Especially in the early design phase, digital visualization was proven to be a useful tool to overcome these problems (Leif P Berg & Judy M Vance, 2017). The presentation of digital concepts provides a possibility to co-design not-yet-existing concepts with potential users. This can be done on a screen, but also in immersive VR. VR might theoretically be more beneficial as users could experience the interaction with their whole body better in a stereoscopic visualization. An immersive design review with a remote team can also be realized by projecting the VR environment on a 2D screen (Bennes et al., 2012).

This study aims to explore the use of virtual reality in prototyping for conceptual design review. The design goal is to improve the comfort and satisfaction of the future long-haul flight. The above-mentioned design challenges of developing a conceptual hygiene space in Flying-V will be used as an example. The researchers will compare the remote view on a desktop PC with the exploration of the concept within a VR prototype.

4.3.2. Related Works

VR prototyping in design

Virtual reality (VR) prototyping has the potential to represent attributes of design concepts more efficiently and effectively in that VR generates highly immersive environments via realistic rendering, stereo images, and sounds (Bordegoni et al., 2009; Phillips et al., 2010). Integrating this technology into the product development process promises major advantages, including reduction of developing time, saving cost, and improving the quality of design (Pontonnier et al., 2014). These advantages motivated extensive research and development in the academy and industry (Natephra et al., 2017). Currently, studies have investigated the usefulness of presenting design attributes in VR. Kim and Lee found that VR prototyping can replace physical prototypes in demonstrating color and material (Kim & Lee, 2011). Huang et al. (2012) indicated that combining form, color, and material in VR prototyping not only accelerates the iteration of user evaluation but also engages users in the design process. Bruno and Muzzupappa (2010) showed that VR prototyping is of value to communicating usability with end-users and creates a common language between users and designers across different cultural backgrounds. Bennes et al. (2012) also pointed out that VR is a valuable tool supporting decision-making in the concept design stage. The above-mentioned benefits of VR prototyping provide an opportunity to involve users in design decision-making at the early stages, especially in conceptual design.

Design review through VR prototyping

Reviewing a concept with potential users can provide relevant feedback as users perceive the features and functionalities of concepts when interacting with prototypes (Arastehfar et al., 2013). Kim et al. (2011) stated that the current competitive markets put higher demands on manufacturers that make faster development processes necessary and building fewer physical prototypes can reduce the development time. Also, users prefer products that can meet their functional requirements and affective needs. Prototyping in virtual reality is introduced as an alternative to regular prototyping with the advantage that it enables people to interact with and compare design alternatives without making any physical prototype (Kim et al., 2011).

The need for remote review in the design field is soaring due to the feasibility and costs of travel, communication, and integration, especially during the COVID-19 pandemic. Many design review studies showed that virtual environments can be displayed on a desktop as semi-immersive, on projection-based systems (e.g. CAVE systems and power walls), and in the headset as fully immersive (Bowman & McMahan, 2007). Kim et al. (2012) showed and also discussed in other studies, that different technological platforms may be appropriate for different scientific purposes. It has been reported that VR prototyping is more suitable to support the assessment of visibility, reach, and the use of tools than AR systems (Aromaa & Väänänen, 2016). The VR prototyping showed small differences in the physical product in evaluating manual tasks (Pontonnier et al., 2014). Users' rates of comfort and ergonomics of products can either rise or drop when viewing the products via printed images, CAD models, AR, and VR (Grajewski et al., 2013). A desktop VR can identify ergonomic factors affecting users' space perception and preference, yet the effect of VR headset prototyping on ergonomic evaluation is still unclear (Bokharaei & Nasar, 2016). Architectural design review using VR headsets not only enhanced spatial perception and improved design but also brought new perspectives on design processes and ways of thinking (Alatta & Freewan, 2017). VR has limitations on collective design reviews, including disorientation, blurring the overview, and higher physical effort (Li et al., 2003).

Comfort perception of virtual prototyping

A study of the comfort model showed that the perception of comfort is not only influenced by task, environment, and psychosocial factors but also depends on the physical and aesthetic features of products (Sauer & Sonderegger, 2009). The interaction between users and products results in the human body effect, which can be perceived by users and influenced by expectations (Lukosch, Lukosch, et al., 2015a). This perceived effect can be interpreted as comfort/discomfort. The subjective comfort rating is commonly used as a representation of the user's perception of comfort. For example, Forbes et al. (2018) found that different levels of immersion change the user's perception of fidelity, and then affect the user's judgment on the design concepts. When physical similarity, completeness of functions, and similarity of interaction rise, the fidelity of prototyping increases (Sauer & Sonderegger, 2009). Hence, a multi-sensory experience from VR prototyping could stimulate vivid imagination, so that it enables users to understand the true experience of design concepts.

As a pre-study, Yao et al. (2019) defined five design elements influencing the comfort of using an in-flight hygiene space via co-creation sessions. These design elements included sitting inside, lighting, tap-basin height, storage styles, and provided facilities. Preferences were diverse among male and female users. To identify the key elements of the comfort experience, different concepts derived from these elements needed to be assessed separately. Besides, this study was also interested in the differences between the comfort perception from a desktop and a VR headset.

Thus, the researchers propose the research question: Can immersive visualization and design influence the subjective comfort of a public hygiene space?

This research question is difficult to answer in general. The realism of lighting and head-based rendering are the main components of immersive virtual environments. The requirements for comfort assessment were realistic visual feedback of height and space, as well as testing real-life positions within the space (Panicker & Huysmans, 2020). The considerations for spatial judgment were full-scale modeling and neutral rendering with different light effects (Phillips et al., 2010). Self-embodiment in VR helps to explore how humans would interact with future products or spaces, especially in comfort (Panicker & Huysmans, 2020). Familiarity with VR technology is as important as realism in product evaluation (Söderman, 2005). Sharing the first-person view with remote reviewers is a common set-up in mixed reality facilitated collaborative tasks, in general, has low technology thresholds (Lukosch, Lukosch, et al., 2015a). However, the confounding effect on perception between the immersive, active experience and the absorptive, passive experience is rarely compared (Henry & Furmess, 1993).

Therefore, VR prototyping followed these specifications regarding comfort assessment: 1) basic texture rendering with variable lighting effects; 2) a virtual headset to show the height of the user; 3) a full-size view of the virtual prototype; 4) a virtual hand co-located with the user's hand using the controller; 5) automatically switching between design concepts; 6) deporting the immersive viewpoint on a desktop display.

4.3.3. Method

Immersion and interaction are critical for user experience (Pine & Gilmore, 1999). This study aims to understand the effects of immersion and design on the comfort perception of public space. A VR headset represents an immersive and actively interactive visualization, while a desktop display is absorptive and passively interactive (Henry & Furmess, 1993; Pine & Gilmore, 1999).

The researchers thus propose the following hypotheses in this study:

H1: The immersive display and the absorptive display will trigger different subjective comfort.

H2: Different concepts will change subjective comfort in general.

H3: Immersive display will trigger more symptoms of simulation sickness than absorptive display.

Participants

Twenty-eight university students and staff as potential users (16 females, 12 males) participated in this experiment in June 2019. Their age ranged from twenty to thirty. A within-subject research design was chosen to limit the personal differences in subjective comfort. During the experiment, participants made their assessment based on their first impression and associated imagination (Bordegoni & Ferrise, 2013).

Materials

Stimuli Two paired concepts of each design element were shown to participants one by one automatically (Table 4.31). They were randomized to reduce the learning effect.

Table 4.31 The ten concepts from the five design elements.

Design elements	Concept1	Concept2
Space	a1. with seat	a2. without seat
Light	b1. 3000K	b2. 3500K
Tap-basin height	c1. 24cm	c2. 24cm
Storage	d1. box	d2. shelves
Facilities	e1. basic (less)	e1. High-end (more)

A baseline (BL) of the prototype included three mirrors, two tapes, and a child staircase, 4000k lighting in a standard-size space of an airplane hygiene space (Figure 4.31).

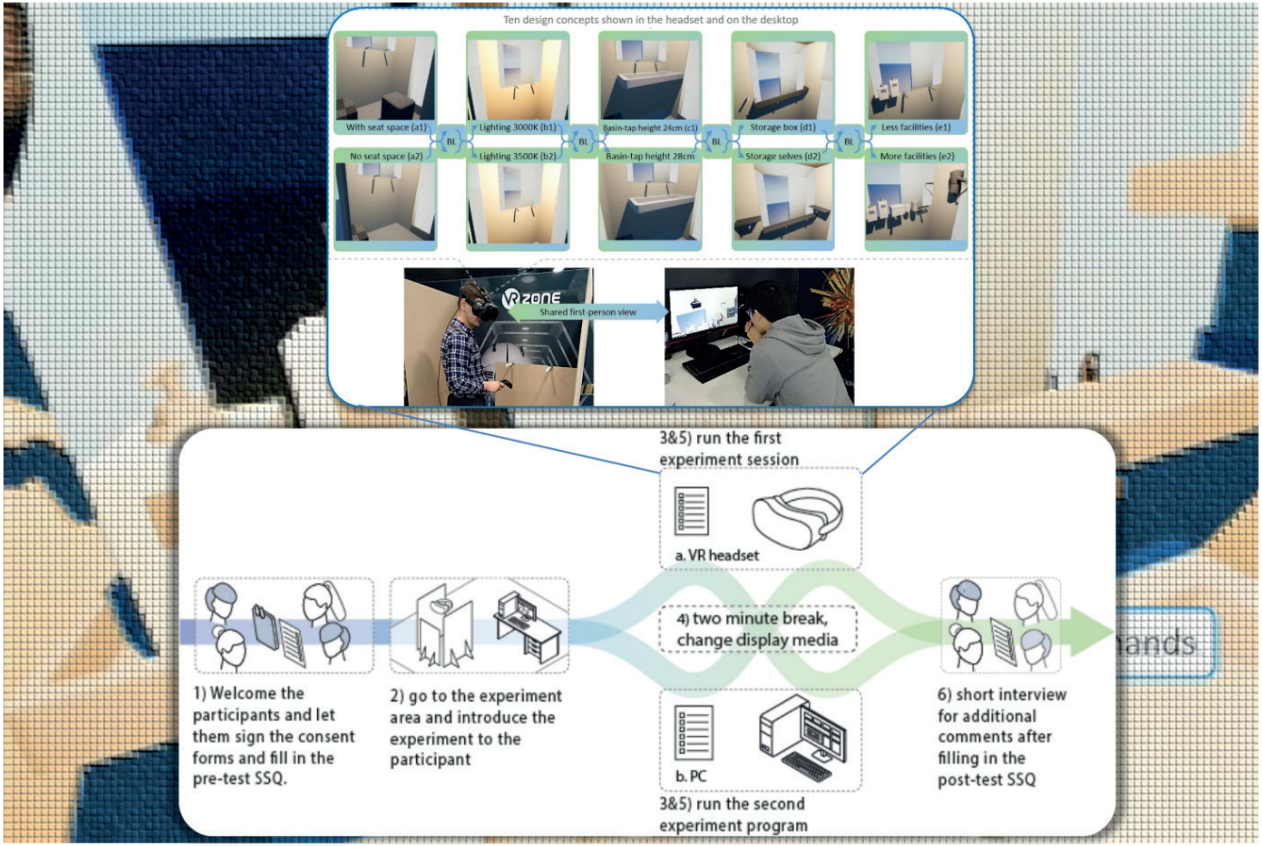


Figure 4.31 The procedure of the whole experiment. During step three and step five, the ten concepts of five design elements were shown in the headset and desktop respectively.

This baseline was shown to the participants every time before the next concept. The exposure duration of the baseline was 20 seconds while the exposure duration of each proposition was 40 seconds. This study shortened the baseline exposure to limit the duration of one test session to 8±0.5 minutes. According to literature and empirical experience, this kind of VR exposure had a low risk of causing simulation sickness symptoms (Liu et al., 2019). The researchers used Maya v.8 to create the concepts and programmed the interaction using Unreal Engine v. 4.21.

Apparatus The headset was an HTC Vive headset with a 1080 × 1200 resolution per eye. The visual information was combined with the haptic clues (Grajewski et al., 2013), such as 3D printed water taps and a full-scale enclosure made of cardboard to enhance the immersion and use two controllers to interact with the prototype. The desktop showed eye-level color views of the prototype on a 19-inch LCD screen with 1,280 × 800 resolution, and the desktop viewer watched the prototype through the eye of the headset viewer.

Questionnaire Pre- and Post-Simulation Sickness Questionnaire (SSQ) was used to measure the acceptance of users during the VR prototyping (Kennedy et al., 1993). The researchers asked participants to give their comfort rate using a 7-point scale when viewing these concepts (7 = very comfortable; 1 = very uncomfortable). A debriefing session was used to collect qualitative feedback on the immersive experience of the virtual prototypes, concept improvement, and simulation sickness symptoms.

Procedure
Two researchers first explained the goal and potential risks to each of the participants and informed consent was signed before the test. The participants then answered the pre-test SSQ. The test simulated a remote review where the participants were separated from the enclosure and played the roles of a headset viewer and a desktop viewer. When one participant was wearing the headset as an immersive viewer, at the same time the other participant had a first-person view of the immersive viewpoint as a remote viewer. Half of the participants started with the headset and the other half started on the desktop. Both participants had the same viewpoint on each design concept. Wearing a headset, participants could actively navigate while on the desktop the participants can only follow the route of the headset viewer. Figure 1 shows the workflow of this test.

The participants were randomly assigned either to a headset or a desktop. During the first round, the participants were asked to score their comfort level for each concept based on their first impression. To keep the participants engaged in the evolution, the research asked *“What’s your comfort level now?”* when each concept showed up (Csikszentmihalyi, 2008). Participants were required to indicate their comfort score silently with their hands throughout the procedure so that they would not influence the judgment of each other. The researchers then wrote down the ratings on a questionnaire. The researcher and participants practiced the hand gestures before the test to get an agreement.

After the first round, they were asked to complete the post-test SSQ. Participants then took two minutes to rest to recover from the possible effect of simulation sickness in the previous session. They switched their role and did the same evaluation again during the second round. When finishing the rating, the pair of participants had a debriefing with researchers where general comments were gathered.

Data analysis

The average preference (*m*) for each condition was calculated as well as the standard deviation via SPSS v.25. The comfort ratings on different elements were tested using the MANOVA ($p < 0.05$). The simulation sickness data was tested with the Wilcoxon signed-rank test due to non-normal distribution.

4.3.4. Results

The Effect of Display and Design on Comfort

H1: The immersive display and the absorptive display will trigger different subjective comfort.
Figure 4.32 shows the subjective comfort rates, which are significantly higher on the headset (*m*= 4.69) than on the desktop (*m*= 4.36). When looking at the specific design elements, the *basin heights* viewed in the headset (*m*= 5.11) were significantly higher than those on the desktop (*m*= 4.30). For the *space* (desktop *m*= 3.81; headset *m*= 4.25), *light* (desktop *m*= 4.45; headset *m*= 4.57), and *storage* (desktop *m*= 4.23; headset *m*= 4.46) elements, the headset showed a tendency for higher comfort perception. On *facilities* (desktop *m*= 5.00; headset *m*= 5.05), the display didn’t affect the comfort judgment. Regarding the general and specific comfort judgment, the headset is more diverse than the desktop, while the desktop had more outliers on specific elements, like *tap-basin height* and *light*.

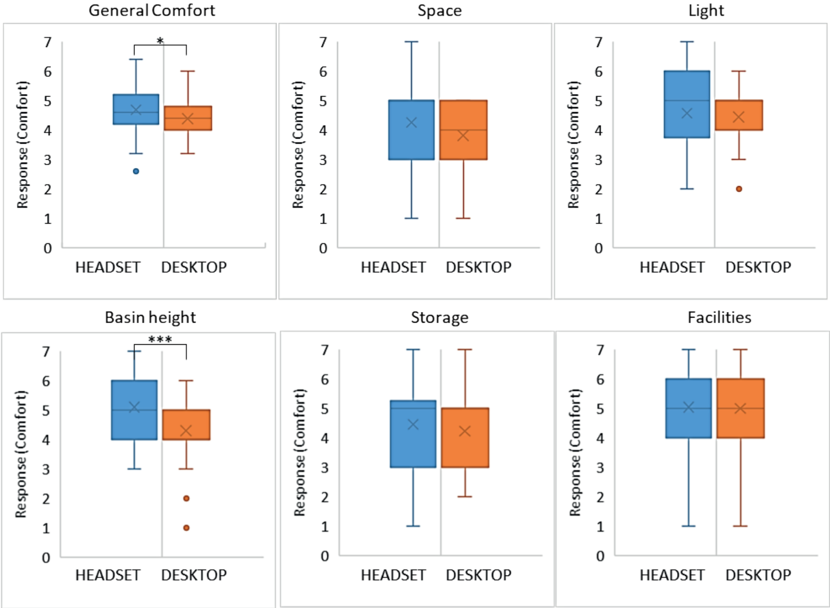
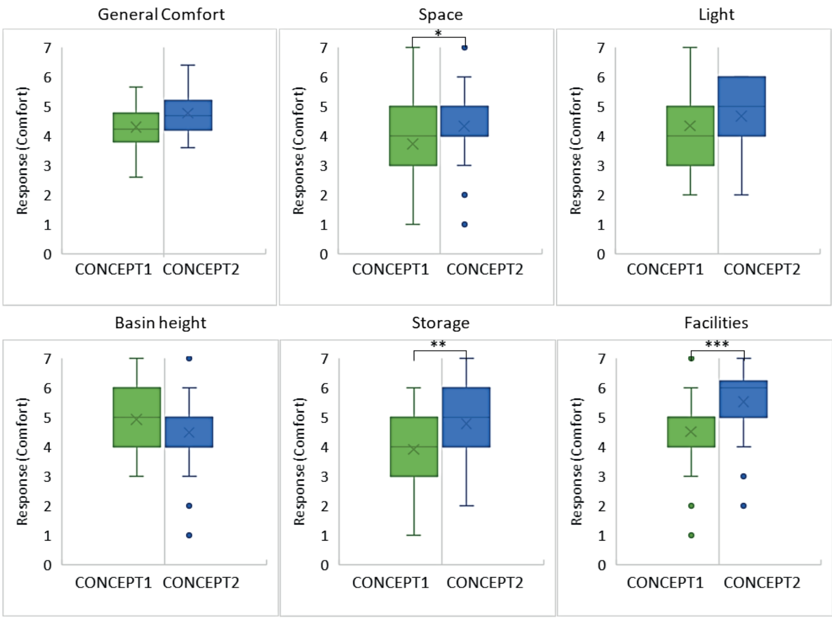


Figure 4.32 The effect of the displays on the comfort experience of the hygiene space.

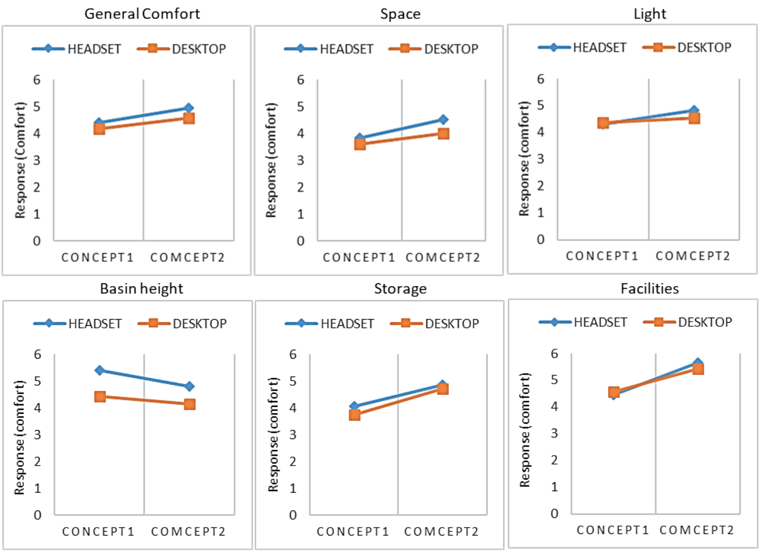
H2: Different concepts will change subjective comfort in general.
Figure 4.33 indicated that the design concepts (concept1 *m*= 4.29; concept2 *m*= 4.77) seemed to change the general comfort judgment, but the difference was not significant. Different designs in specific elements however showed significant differences, including *space* (concept1 'with seat' *m*= 3.74; concept2 'no seat' *m*= 4.33), *storage* (concept1 'less storage' *m*= 3.91; concept2 'more storage' *m*= 4.79), and *facilities* (concept1 'basic' *m*= 4.52; concept2 'high-end' *m*= 5.54) (Figure 4.33). The concepts indicated a preference for *warmer light* (concept1 '3000K' *m*= 4.34; concept2 '3500K' *m*= 4.68) or *low tap-basin height* (concept1 '24cm' *m*= 4.93; concept2 '28cm' *m*= 4.68).

A slight interactive effect was shown in the general comfort and specific elements except for the *facilities* (Figure 4.34). The interactive effect is more obvious on *tap-basin height* and *space*, while on *light* and *storage* is even weaker. This indicates that the comfort of different concepts tended to be differentiated in the headset.



"*" indicates p <0.05; "*" indicates p <0.01; "***" indicates p< 0.001.

Figure 4.33 The effect of the designs on the comfort experience of the hygiene space.



Display * Design interactive effect

Figure 4.34 The interactive effect of display and design on the comfort experience of the hygiene space.

Simulation Sickness

H3: Immersive display will trigger more symptoms of simulation sickness than absorptive display. The simulation sickness results showed no significant differences between the pre- and post-exposure in the headset, while for the desktop there was a significant rise in simulation sickness on oculomotor, disorientation, and the total score (see Table 4.32) after the exposure. The oculomotor symptom was slightly reduced after exposure to VR, as several participants also reflected in their general comments.

Table 4.32 The pre- and post-simulation sickness symptoms in the headset and on the desktop.

Displays	Headset Mean (SD)	*p* (two-tailed)	Desktop Mean (SD)	*p* (two-tailed)
Pre-nausea	6.47(9.38)	.438	8.52(10.50)	.173
Post-nausea	11.58(22.69)		11.58(15.22)	
Pre-oculomotor	17.06(16.19)	.387	13.81(19.14)	.036 *
Post-oculomotor	15.97(22.25)		21.66*(24.82)	
Pre-disorientation	18.39(23.98)	.209	13.42(22.25)	.002 **
Post-disorientation	29.83(47.28)		27.84*(33.67)	
Pre-TS	15.90(16.02)	.948	13.76(18.30)	.014 *
Post-TS	20.44(31.41)		22.71*(26.27)	

Qualitative feedback

Immersive experience During the debriefing after the experiment, participants mentioned that the concept validation with the headset was relaxed and interesting. The participants reported that they felt to be present inside the virtual hygiene space when wearing the headset. Most participants agreed that the haptic feedback from the cardboard enclosure enhanced immersion while the 3D printing taps were noticeable due to their small volume. It was interesting to notice that for the light concepts, most desktop viewers asked if there was a change in the light, while this question was not asked when wearing the headset.

Design-related feedback The headset viewer easily noticed the sharp edge of the shelves. Some headset viewers even bent down or tried to sit to check the seat closely. The headset viewer also often reached out to check whether the heights of hooks, shelves, and the hairdryer were comfortable. Without water simulation, headset viewers were still able to judge their comfort of tap-basin height confidently, which was challenging for desktop viewers.

Simulation sickness Many participants felt refreshed after the evaluation with a headset, especially the fullness of the head often was improved. The desktop viewers reported that they usually felt dizzy when the headset viewers moved their heads fast or turned around or upside down.

4.3.5. Discussion

The participant's comfort perception was more differentiated using the headset compared with the desktop. This has been found before in, for instance, recognizing stressful situations. Kim et al. (2012) compared a desktop system, a headset, and a six-wall system and showed that the more immersive systems performed better. In our case, the comfort perception on the desktop was more neutral than with the headset, which means that the desktop viewer had a different opinion than the headset viewer regarding comfort. Participants' comfort preferences were significantly different in space, storage, and facilities The researchers might speculate that the immersive environment helped users experience the visual cues (hand and headset) and enabled the proprioception (the sense of body movement) to make their judgments. The significantly higher rate in headset on both tap-basin heights from a single participant might confirm this speculation. A similar interactive embodiment has been found valuable in analyzing and optimizing workplace design as well (Grajewski et al., 2013). Besides, the immersive reviewer often gave their rate based on a solid observation, such as the sharp edges of the storage box, or preferring no seat in this narrow space. The headset especially seems able to facilitate the perception of nuances in the design, when the human body-geometry relationship is of importance like in the hygiene space.

Kim et al. (2012) demonstrated that the headset system elicited the most intense symptoms of simulator sickness compared with a desktop and a six-wall fully immersive system. Therefore, sickness symptoms could be expected in the headset condition. Unlike this expectation, in our case, the desktop visualization triggered simulation sickness symptoms such as headache, blurred vision, and dizziness. It may be attributed to the passive interaction of desktop viewers being more difficult to focus on details as they did not manipulate the viewpoint. It might explain why desktop viewers remained more neutral. The passive vision of moving images is well-known for creating simulation sickness due to visual-vestibular conflict (Kennedy et al., 1993). Considering the growing need for remote design review, further studies need to pay attention to how to reduce or eliminate the effect of sub-optimal perspective on the headset-desktop set-up.

The light was the only attribute the participant did not notice, or they did not prefer one of these two concepts: the desktop viewers didn't see the differences, while headset viewers were indifferent to both light effects. The judgment of lighting on the desktop was largely influenced by ambient illumination, which made the desktop reviewer hardly notice the changing of the lighting color. Light tracking is the most intriguing yet complex part of VR modeling and prototyping, designated efforts are needed to simulate realistic lighting effects in a virtual environment. The insights from architecture design show simulating lighting effects in VR "support design stakeholders better perceive and optimize lighting condition to achieve higher satisfaction" (Natephra et al., 2017).

There are the following limitations in this experiment which may open room for future studies. First, the findings were limited by the confounding of display and interaction. Another set of comparative setups should be included to provide richer and more general conclusions on the effect of immersion and interaction: immersive, absorptive, passive, and active (Henry & Furmess, 1993; Pine & Gilmore, 1999). Second, user experience design teams should be involved, since a major benefit of headsets was promoting design discussion (Bennes et al., 2021). Third, the headset asks for training as many participants do not use it daily, as they are used to working with a desktop (Sousa Santos et al., 2009). Besides, the Presence Questionnaire and other questionnaires should also be included to better understand spatial perception and immersion. Another shortcoming is that in the virtual environment, the user's body was simplified as two hands and a headset. Despite the studies in the video game and educational field showing that to visualize body parts providing adequate embodiment perception in VR, the ergonomic assessment probably would be influenced by the missing parts of the body. Further studies should compare the effects of partial embodiment, full embodiment, and multi-embodiment, especially on ergonomic design (Grajewski et al., 2013; Panicker & Huysmans, 2020).

Regarding the research question - Can immersive visualization and design influence the subjective comfort of a public hygiene space? – the immersive display might increase subjective comfort while designs affect comfort mainly on specific design elements.

This could mean that for studying physical ergonomic issues where the relationship between humans and objects comes into play, the immersive review provides richer and more detailed information. This is in line with other studies. For instance, Berg and Vance (2017) clearly show that a team using a headset identified design issues and potential solutions that were not identified or verified using traditional computer tools. They state that participants reported seeing the assembly stations at true scale provided them with a better sense of distance within and across the workstations. The same was found in our experiment, where participants saw the storage and tap-basin height on a true scale related to their bodies.

4.3.6. Conclusion on comparing desktop and headset virtual prototyping

The researchers call the experience of interacting with a design concept displayed through a VR headset "Immersive VR prototyping". This seems to be an efficient tool to support decision-making regarding comfort perception for a conceptual product. The researchers demonstrated this in the specific case of concept evaluation of a hygiene space for a future aircraft. A group of users was exposed to different concept alternatives in VR.

The novelty of this study has demonstrated the influence of immersive visualization and the design of comfort perception. The headset-desktop setup of a collective virtual environment for design review was tested to find the difference between the perception of comfort-related elements such as space, lighting, height, style, and facilities. The results indicated: 1) facilities judgment is not influenced by immersive visualization; 2) the lighting effect needs more sophisticated design in a virtual environment to take effect; 3) body-geometry perception enhanced by immersive visualization to facilitate comfort evaluation.

The researchers found the following characteristics of immersive VR to be of the most value for facilitating users to perceive the nuances of spatial experience: 1) interactive reviewing, 2) interactive embodiment, and 3) active walk-through. These values are acknowledged in the field of future transportation spaces, like autonomous driving, Flying-V, and Hyperloop. The researchers were able to show the differences between immersive VR prototyping compared with a single-screen VR application. Further studies should explore how to take advantage of seeing the objects at a true scale related to the human body in collaborative design.

4.4. Conclusions

This chapter explored the research question: "*How can designers effectively ideate user experience via spatial presence in conceptualization*?"

Section 4.1 described a combination of classic HCD methods and VR prototyping in concept selection and verification. The results showed that the perception of comfort on space-related design elements (like space/seat, height, storage, and facilities) is dictated by the immersive cycle of prototyping and the comfort of design elements can decrease when viewed associated with the spatial experience. Moreover, the differences in participants' preferences appeared to be more obvious with VR prototyping than with narrative prototyping. The "being there" effect of XR systems seemed to activate episodic memories instead of semantic memory.

Section 4.2 probed the feasibility of consolidating an interactive VR prototype with video demos and an online questionnaire to evaluate the comfort and satisfaction of a new concept compared with the current one. The frequent flyers acknowledged the advantage of the XR system as a "high fidelity simulation of an existing experience" enhanced by spatial experience and intuitive interaction.

Section 4.3 investigated the suitability of sharing the immersive viewpoint of a VR prototype with a desktop viewer for a co-design setup. From this case study, the perception of design elements (e.g., space, lighting, height, and storage) was different between the VR review (active-immersive mode) and the desktop review (passive-absorptive mode) and the VR review resulted in a more diverse assessment. The desktop review triggered higher simulation sickness symptoms due to the passive navigation.

The case studies include the following factors of the immersion: 1) non-immersive (narrative and desktop) versus immersive (VR) visualization with touch or sounds for *sensory*; 2) active versus passive navigation, and object manipulation for *interaction*; 3) real-size modeling, basic or texture rendering, digital human and interactive embodiment, and task simulation for *realism*; and 4) isolation (VR headsets) and non-isolation (desktop) for *involvement*. The stereoscopic interactive review, interactive embodiment, and active navigation are critical to perceiving the nuances between concepts that facilitate the problem-solution co-evolution in design processes. The VR headset could isolate the real environment and thus increase the involvement.

First-person immersion is of paramount importance to understand spatial and contextual experiences cost-efficiently or enable true-to-life exploration of concepts under impossible conditions. XR systems showed great potential as a virtual playground for ideating/prototyping not only the products but their experiences despite the socio-technological challenges like simulation sickness and learnability. To further human well-being in the physical/cognitive domain, the fidelity of design elements might require different XR prototypes.

CHAPTER 5

Immersive Training for Cognitive Well-being

The conceptual process (Chapter 3) described case studies in physical, cognitive, and organizational domains in UX. The previous chapter (Chapter 4) explored the generative activities with XR systems for physical well-being. Subsequently, this chapter explores the evaluative activities in the second domain: cognitive well-being. The case studies discuss the research question: “How can designers effectively assess user experience via social presence across different user groups?”

A fundamental need that is important in learning is Competence. Usability is key to enhancing competencies by providing human-system interactions matching cognitive capabilities. Thus, the relevant design elements refer to the intuitiveness of use, task load, physical stress, subjective immersion, and realism. These elements connect the cognitive domain with the organizational one. Competence perception could be highly personal, particularly when feeling yourself within a team, referred to as social presence. Thus, the influences of user characteristics on competence perception will be investigated here.

The first case (5.1) analyses the usability and the perception of immersion for a Virtual Operating Room (VOR) setup with WEIRD participants (Western, Educated, Industrialized, Rich, and Democratic) and sets out the key elements for an immersive environment for procedural training.

The second case (5.2) explores a similar Virtual Operating Room with non-WEIRD participants to determine the effectiveness of XR-based immersive training in a different cultural context.

The last case (5.3) discusses the underlying factors of user groups for immersive training, including professional experience, culture, and XR familiarity.

The case study in Section 5.1 is adapted from the following publication

Li, M., Ganni, S., Ponten, J., Albayrak, A., Rutkowski, A. F., & Jakimowicz, J. (2020, March). Analysing usability and presence of a virtual reality operating room (VOR) simulator during laparoscopic surgery training. *In 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 566-572). IEEE.

The case study in Section 5.2 is adapted from the following publication

Ganni, S., Li, M., Botden, S. M., Nayak, S. R., Ganni, B. R., Rutkowski, A. F., ... & Jakimowicz, J. (2020). Virtual Operating Room Simulation Setup (VORSS) for Procedural Training in Minimally Invasive Surgery–a Pilot Study. *Indian Journal of Surgery*, 1-7.

The case study in Section 5.3 is adapted from the following publication

Li, M., Ganni, S., Albayrak, A., Rutkowski, A.F., Van Eijk, D. and Jakimowicz, J., 2021. Proficiency from Immersion---A User-Centred Design in Cross-Cultural Surgical Training. Frontiers in Virtual Reality, 2, p.65.

5.1. Immersive Training in Virtual Operating Room: The Experts and Novices

5.1.1. Introduction

Laparoscopic surgery, also known as minimally invasive surgery (MIS) or keyhole surgery, is a surgical procedure that allows surgeons access to the inside of the body cavity without making a large incision in the skin. This technique has obvious advantages over open surgery, as patients experience less pain and bleeding, a shorter hospital stay and quicker recovery. Laparoscopic surgery is undergoing fast development and is becoming a standard treatment for many surgical therapies, e.g., cholecystectomy (gallbladder removal surgery) (Spaner & Warnock, 1997). Robotic surgery is among the latest advances in the laparoscopy field.

Nevertheless, the skills required to perform laparoscopic surgery are largely different from open surgery. During laparoscopic procedures, surgeons must perform movements that are more restricted and must work with a narrower field of vision. They must acquire proficiency in non-intuitive motor skills and hand-eye coordination, as well as deal with the ever-changing instruments throughout the procedure (Nisky et al., 2012; Scott et al., 2000). Thanks to the introduction of virtual reality (VR) surgical simulators, surgeons can improve laparoscopic skills without subjecting the patients to unnecessary risk or pain during this learning process (Schijven & Jakimowicz, 2005). Many reasons along with psychomotor skill and procedural knowledge influence the performance and the mental well-being of surgeons in the operating room (OR) (Vereczkel et al., 2003). Research has revealed that distractions are common in the OR and have obvious negative impacts on surgeons' performances and emotions (Persoon et al., 2011; Pluyter et al., 2010). Hence, training surgeons to handle these challenges requires equally advanced tools that replicate the actual intraoperative distractions.

5.1.2. Related Works

VR laparoscopy training

Virtual Reality laparoscopy (VRL) simulation, replicating haptic feedback during procedure-specific tasks, has been proven to accelerate the acquisition of skills of laparoscopic trainees (Dawe et al., 2014). The main drawback of the current VRL simulation is the lack of true representation of the operating theatre experience (Jakimowicz & Buzink, 2015). Most VRL simulators use a 2D display interface that replicates the tasks but not the environment of busy and often chaotic operating theatres (McCreery et al., 2017). Numerous distractions occur in surgical surroundings, which have been identified and broadly classified into equipment factors, environmental factors, social factors, and organizational factors (Persoon et al., 2011). These distractions increase the task demand and stress level of the surgeons.

As Mentis et al. stated, residents should be trained both to achieve proficiency and to exercise self-management with distractions in an Operating Room (OR) (Mentis et al., 2016). Immersive training, representing distraction factors that closely mimic the clinical practice, helps surgical trainees to adapt effectively to their work environments (Pluyter et al., 2014).

VR operating room simulation

To create such a surrounding, the required amount of spatial, financial, personal, and technological resources is demanding and can hardly fit into daily clinical routines (Badash et al., 2016; Jakimowicz & Buzink, 2015). Since the upsurge of high-end VR headsets in 2016, it became accessible and affordable to virtually generate an immersive environment of an OR. That environment reproduces distractions as well as generates a good sense of presence, meaning the perception of "being there" in a real OR (Huber, Paschold, et al., 2018; Mestre et al., 2006; Sankaranarayanan et al., 2016). Clinical pilot studies have investigated several immersive VR laparoscopic simulators, revealing the face validity and the users' preference for these setups (Huber et al., 2017; Huber, Wunderling, et al., 2018; Sankaranarayanan et al., 2016). As no differences in performances appeared between immersive and regular setups, these studies are limited to apparent usefulness or the preferences relating to these immersive environments. However, a key challenge in developing VR-based surgical simulations is to establish usability and a sense of presence from the surgeon's perspective (Koch et al., 2019). This topic rarely has been investigated in previous studies.

User evaluation of VR simulator

It is essential to analyse usability in virtual environments as this analysis demonstrates how intuitively and proficiently users can utilize a product to achieve their objectives (Bowman et al., 2002). Additionally, mental workload and ergonomic assessments should be incorporated in the evaluation of new laparoscopic training tools, as laparoscopic surgery involves a higher level of mental and physical stress than open surgery (Berguer et al., 2001; Carswell et al., 2005; Silvennoinen & Kuparinen, 2009). In medical device development, user evaluation is a common method to identify the usability issues of current setups and indicate potential improvements in future use (Wiklund et al., 2015).

A Virtual Operating Room (VOR) setup connecting a VRL simulator and a VR headset was explored in this study. This study analyses the experience of VOR by surgeons and surgical trainees regarding usability and presence to identify its potential benefits and improvement opportunities in laparoscopic procedure training.

5.1.3. *Materials and Methods*

Participants

Thirty-seven Dutch surgeons and surgical trainees were invited to participate in this study between June and August 2018. All participants voluntarily enrolled in the study and signed informed consent. The hospital ethics committee has approved the study. The inclusion criterion for surgical trainees was their prior experience in laparoscopic simulators or box trainers or real operations. The mean age of the participants (male/female = 22:15) was 32.4 years (SD=11.6). The sample was composed of eight experienced surgeons (more than 200 cases) and twenty-nine residents and trainees (two had 101 to 200 cases; three had 51 to 100 cases; twenty-four had 50 or fewer cases). In this study, the researchers refer to the surgeon as the "expert" and the surgical trainee as the "novice". Twelve participants had experience with VR or AR technologies (4 for high-end VR, 4 for cardboard VR, 2 for AR Apps, and 4 for simulators).

Platform

The VOR setup the researchers applied comprised three components: a VR laparoscopic simulator, a VR headset and a virtual OR environment (Figure 5.11b).

The VR laparoscopic simulator was a LapMentor III (Simbionix™, 3D Systems Corporation, USA) with MentorLearn Software. LapMentor III contains two integrated modules: 1) The interface module is an operation table that simulates the patient's abdomen, the trocars, two instruments, a camera, and a double footswitch. The instruments have five DOFs and haptic feedback. The footswitch activates electrosurgical coagulation during the training. A freeze mode of the camera allows trainees to navigate it by themselves during operations. The entire module is adjustable in height from 62.99" at the lowest position to 70.86" at the highest. 2) The processing module houses a two-unit industrial PC with a 24" touch-screen monitor (1920*1080 dpi): (a) the simulation unit is a 3.1-GHz Intel Core i7-4770S and an Intel™ Motherboard; (b) the VOR unit is an NVIDIA GeForce GTX 1060 graphic card and an Intel™ SHARKBAY Motherboard. Both units run on Windows 7 Professional (x64) operating system.

The software includes a basic skills trainer and a procedural skills trainer. The basic skills trainer allows trainees to practice tasks that are abstractions of those performed during surgery. The procedural skills trainer is a simulation that allows trainees to perform an entire laparoscopic cholecystectomy with virtual patients. The trainee could see a computer-generated body cavity during operations through the monitor. If trainees want to change tools in LapMentor, they need to: 1) pull out an instrument to see a pop-up menu on the screen, 2) hold and pull the instrument left or right to choose one, and then 3) clip the instrument to select and insert it again.

The VR headset was a 2016 Oculus Rift model, providing stereoscopic images (1080 * 1200 per eye, 110° field of view), integrated 3D audio and 6 DOF head-tracking. The virtual OR was a 360-degree computer-generated environment that replicates a real OR, including a full setup of instruments and equipment and as a new feature, a surgical team, and various distractions. The distractions covered the three most frequently occurring types: door movements, phones/pagers/bleepers, and radio, as well as one most distracting type: case-related communication (Figure 5.11a) (Mentis et al., 2016).

The VR headset displays the virtual OR around the simulator while a trainee is practising the cholecystectomy, and a virtual instructor talks to the trainee throughout the procedure (Figure 5.11a right-hand side). If the trainee changes a tool in VOR, there are several differences from the LapMentor: 1) the tool menu is floating at eye level; 2) turn a knot at the front of the handle to choose tools instead of pulling the instrument. To simulate the electrosurgical coagulation, a footswitch is displayed underneath the simulated monitor.

Procedure
Participants performed a task (LapMentor III: complete cholecystectomy) after a standardized introduction from the researchers (Buzink et al., 2012). Researchers informed participants that the purpose of the study is to investigate the use of VOR in surgical procedural tasks for immersive training. A pre-test protocol limited the time of the task to 15 minutes according to the empirical duration to complete it. After completing the task, participants answered four questionnaires regarding usability and presence. A semi-structured interview allowed the collection of the surgeons' narratives.

In this study, the usability of the VOR was evaluated with a combination of three questionnaires. First, intuitiveness, in other words subconsciously applying prior knowledge, was evaluated via the Questionnaire for Intuitive Use (QUESI) (Naumann & Hurtienne, 2010). The QUESI was applied across multiple professions, including healthcare, to quantify the intuitiveness of virtual environments (Li et al., 2019; Saalfeld et al., 2015). The validated assessment asked if the VOR appears intuitive and satisfying using a 5-point Likert scale (1= fully disagree, 5=fully agree). Second, the mental workload of performing the task in the VOR was measured using the NASA-TLX (Hart, 2006). This validated tool has already extensively been used for assessing the task demand of surgeons when performing laparoscopic surgeries or training (Lee et al., 2014; Zheng et al., 2012). The participants gave a score to the levels of mental, physical, and temporal demands they perceived, as well as their effort, performance, and frustration during the task. The Raw Task Load Index (RTLX) and subscales were calculated into a score between 0 and 100 (0=low, 100=high) (Hart, 2006). Third, to assess the physical stress, perceived as discomfort, the researchers used a validated assessment - Localized Postural Discomfort (LPD) (Hamberg-van Reenen et al., 2008; Kruizinga et al., 1998). The participants rated the symptoms of discomfort in every segment of their body via a 10-point scale (0=no discomfort, 10=extreme discomfort). The answers were categorized as insupportable discomfort when participants marked the value as more than 2 according to the ISO/FDIS 11226 (ISO, 2000).

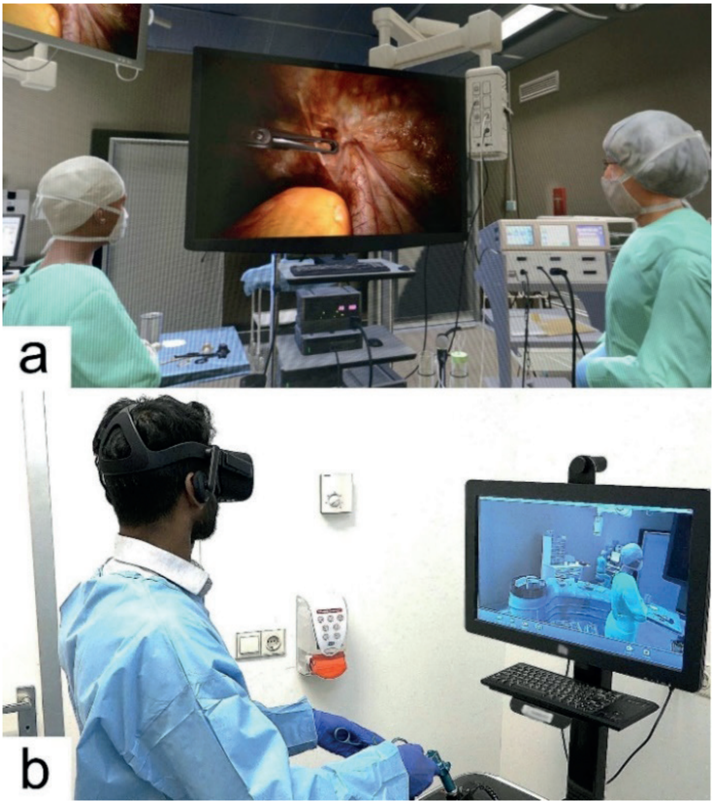


Figure 5.11 The setup of the VOR simulator. a) The replicated OR surrounding in the VOR and b) An external view of the setup of the VOR simulator.

The factors influencing the perception of presence were investigated via a questionnaire followed by an interview. The Presence Questionnaire, a known assessment instrument, was modified and previously validated (Witmer et al., 2005;

Witmer & Singer, 1998). In this study, the researchers added two items (i.e. accuracy of gestures, realistic resistance of tissue) on "haptic" and one item on "sound" (realistic sound effect) according to the features of the VOR, and applied a 21-point scale (1= not at all, 21=completely) to survey the presence in fine gradients (Dyer et al., 1976).

The semi-structured interview consisted of two questions: (1) How satisfied are you with the Virtual OR experience? (2) Which factors were not compelling or not realistic in the Virtual OR experience?

Statistical Analysis

The data were analysed using SPSS v.25. Descriptive statistics of each questionnaire were calculated, including mean and standard deviation (SD), or median and interquartile range (IQR). The comparison of means used a one-sample t-test (normally distributed) or Wilcoxon signed-rank test (non-normally distributed). The differences between novices and experts were tested using a classical independent-sample t-test; otherwise, non-parametric tests such as the Kruskal-Wallis test and the Mann-Whitney U test were utilized where appropriate. A *p*-value of <0.05 was considered statistically significant.

5.1.4. Results

Intuitive Use

The participants, at a minimum, agreed (>score 3 "neutral") that the VOR appeared intuitive and satisfying to perform laparoscopic procedural training (M=3.90, IQR=0.70). The perceived achievement of goals (M=4.00, IQR=1.33) and error rate (M=4.00, IQR=0.50) seemed to be the most intuitive factors, related to a highly effective interaction; the perceived effort of learning is also intuitive (M=4.00, IQR=1.00), related to applying prior knowledge for the first-time use. The novices rated four subscales more intuitive than the experts, while the perceived effort of learning was significantly different (4.00 vs 3.33, $p<0.05$, Mann-Whitney U test) (Table 5.11).

Mental Workload

Thirty-seven participants rated the overall mental workload (RTLX Mean=39.96, SD=14.53) lower than the midpoint of the full range (0-100), indicating the VOR imposed a moderate demand on the users. The subscales varied from 51.49 on the effort to 27.30 on the frustration (Table 5.12). It seemed that the mental demand (M=52.16, SD=22.66) and effort (M=51.49, SD=19.43), i.e., intellectual work and required proficiency, were the key components of the mental workload in the VOR. The novices had a significantly higher workload on mental demand (56.72 vs. 35.63, $p = .019$), physical demand (40.17 vs. 20.63, $p = .011$), temporal demand (37.93 vs. 18.13,

p = .006), effort (55.34 vs. 37.50, p = .019), and overall workload (43.16 vs. 28.23, p =.008) than the experts (Mann-Whitney U Test).

Table 5.11 The level of intuitive use of the VOR (1= "Fully disagree", 5= "Fully agree").

QUESI	Total	Novice	Expert
	Mean (IQR)	Mean (IQR)	Mean (IQR)
Low subjective mental workload	3.67 (1.33)	4.00 (1.17)	3.67 (1.17)
High perceived achievement of goals	4.00 (1.33)	4.00 (0.50)	3.67 (1.75)
Low perceived effort of learning	4.00 (1.00)	4.00 (0.83) *	3.33 (1.25)
High familiarity	3.67 (0.50)	3.67 (0.50)	3.67 (0.83)
Low perceived error rate	4.00 (0.50)	4.00 (1.00)	3.25 (1.75)
Total	3.90 (0.70)	3.90 (0.53)	3.38 (1.33)

Note: *Statistically significant results with p <0.05.

Comfort

The average discomfort in each body segment ranged from 0.05 to 1.16, corresponding to almost no discomfort to very low discomfort. The scores of seven body segments out of all twenty-three parts (30.4%) were above the slightest discomfort level (score 0.5) (Table 5.13), while only the left hand had a significantly higher discomfort (1.16 vs 0.5, p < 0.05, one-sample t-test). In the left hand and both eyes (n= 6, 16.2%), as well as the neck (n= 7, 18.9%), some participants experienced insupportable discomfort. No significant difference was found between novices and experts regarding physical comfort (p > 0.1, Mann-Whitney U Test).

Table 5.12 Self-reported mental workload after training in the VOR. (0-100, the higher score means a higher mental workload)

NASA-TLX	Total	Novice	Expert
	Mean (SD)	Mean (SD)	Mean (SD)
Mental Demand	52.16 (22.66)	56.72 (20.76) *	35.63 (22.75)
Physical Demand	35.95 (21.40)	40.17 (20.68) *	20.63 (17.41)
Temporal Demand	33.65 (21.62)	37.93 (20.24) *	18.13 (20.34)
Performance	39.05 (19.03)	40.34 (19.36)	34.38 (18.21)
Effort	51.49 (19.43)	55.34 (18.51) *	37.50 (16.90)
Frustration	27.30(20.97)	28.45 (18.28)	23.13 (29.99)
RTLX	39.93 (14.53)	43.16 (13.10) *	28.23 (14.11)

Note: *Statistically significant results with p <0.05.

Table 5.13 Localised Postural Discomfort (LPD) of body segments. (0= "No Discomfort", 10= "Extreme Discomfort")

Body segments	Total Mean (SD)	Novice Mean (SD)	Expert Mean (SD)
Neck	0.78 (1.29)	0.79 (1.35)	0.75 (1.16)
Lower neck (L/R)	0.59 (0.93)	0.62 (0.94)	0.50 (0.93)
Hand(L)	1.16 (1.77)	1.34 (1.93)	0.50 (0.76)
Hand(R)	0.70 (1.22)	0.86 (1.33)	0.13 (0.35)
Eye(L/R)	0.97 (1.57)	1.00 (1.56)	0.88 (1.73)

Presence

In the VOR, self-evaluated performance seemed most important to the perception of presence, as participants adjusted to the environment very quickly (M=16.39, SD=1.90), and could move and interact proficiently at the end of the task (M=16.17, SD=2.10) (see Table 5.14 and Supplementary Table). The Sound (M=14.79, SD=2.69) appeared mainly to contribute to presence as well, in that participants could easily recognize and localize sounds and viewed the sounds as realistic. The *Quality of interface* seemed to facilitate the presence perception the least, and the instrument interface had the lowest rank (M=9.97, SD=3.81, see Supplementary Table). Both novices and experts had similar presence levels across the subscales (p >0.2, independent-sample t-test).

Table 5.14 Average rates on subscales of the Presence Questionnaire. (1= "Not at all", 11= "Somewhat", 21= "Completely")

Presence	Total Mean (SD)	Novice Mean (SD)	Expert Mean (SD)
Realism	14.02 (2.75)	14.15 (2.95)	13.55 (1.97)
Possibility to act	14.24 (2.42)	14.08 (2.55)	14.84 (1.92)
Quality of interface	11.70 (3.38)	11.64 (3.55)	11.92 (2.95)
Possibility to examine	14.24 (2.70)	14.67 (2.77)	12.75 (1.88)
Self-evaluation of performance	16.28 (2.10)	16.55 (2.13)	15.31 (1.79)
Haptic	13.33 (2.78)	14.82 (2.90)	14.66 (1.88)
Sound	14.79 (2.69)	13.49 (2.82)	12.75 (2.72)

Interview

Thirty-five participants reported that they felt had been present in an OR and were engaged by the scenario. The majority (25/37) of the participants mentioned the talk and the sounds enhanced their presence. The participants, particularly the surgical trainees, were highly engaged and excited to complete the procedure. The researchers broadly categorized participants' narratives on the presence of VOR into user interfaces, VOR environment, team interaction and personalization considering the factors of distractions (Persoon et al., 2011).

User interfaces

Trocar: Eight participants, especially surgeons, struggled with many slips and were annoyed by the way of switching instruments. The surgeons and experienced trainees (>100 cases) reported the haptic resistance as too low. A delay in changing instruments was found.

Headset: Especially for people with corrected vision, participants often encountered a problem seeing a clear image from one or both eyes. The low graphic resolution was also reported. The participants with eyewear (4 in total) had difficulty putting on the VR headset correctly on top of their glasses. The VR headset could press on the glasses and cause a high level of discomfort or even pain in the face.

VOR environment

OR setup: Two participants noted that they could not find the footswitch in the VOR because the feet were missing. The additional factors included the incorrect OR layout, disproportionate elements, and unrealistic rendering, e.g., the wrong direction of the monitor towards the patient's bed, or the size of the monitor.

Surgery steps: Two participants commented that the procedures of the laparoscopy would vary slightly from case to case, while the steps in the VOR seemed to be more rigid.

Sounds: Three participants stated that the sound seemed too loud considering the space of the VOR.

Team interactions

Instructions: Four participants were confused by the repetitive instruction from the avatar when the action had already been performed.

Camera assist: Most participants noticed that teamwork was missing, so they had to lay down the instruments carefully and navigate the camera by themselves. The participants who had real OR experience suggested that an assistant should hold the camera and follow the surgeon's manoeuvre throughout operations.

Mood: Two participants remarked that the communication was impersonal and needed some added emotion. An additional comment was that the team was mainly motionless; in reality, the team would move around, if only slightly.

Personalization

Nine participants said they ignored the instructions as background noise because the other surgeon's name was called. Two surgeons asked for background music that they could switch on or off. Four surgeons expected communication in their native language.

5.1.5. Discussion

Training procedural tasks under immersive virtual contexts are already in widespread use in the military and aviation industry (Osterlund & Lawrence, 2012; Pallavicini et al., 2015). Immersive training simultaneously facilitates the acquisition of technical and non-technical skills (e.g. communication and teamwork) owing to distraction simulation (Flin et al., 2002). Creating immersive training in skills labs is crucial in acquiring skills and intellectual abilities to optimize patient safety and preserve surgeons' resources essential to the laparoscopy process (Pluyter et al., 2010; Schijven & Jakimowicz, 2005). The VOR outlined and evaluated in this study built on the advantages of VR laparoscopy simulation, and integrated the immersive experience of an OR. The results demonstrated clearly that immersive training via a VR headset heightens the motivation of trainees and demonstrates a new dimension to integrate immersive OR context in surgical procedural training. The surgical trainees in most European countries were kept from simulation-based training by various external demotivating factors, such as long working hours, limited free time, and the overload of clinical work (Jakimowicz & Buzink, 2015). It is therefore relevant to develop a training setup to boost and sustain trainees' motivation, which is a key element of the successful delivery of laparoscopy training curricula (Jakimowicz & Buzink, 2015).

Usability and Presence

The results of the usability questionnaires indicated a good sense of intuitiveness, little physical stress, and moderate mental workload when performing tasks in the VOR. The simulation of auditory distractions, such as radio, phone calls, pagers, and bleeps, most frequently occurring in the OR, enhanced participants' sense of familiarity as they commented. Auditory distractions might result in increased mental effort on inexperienced trainees, which has been suggested by several experimental studies (Mentis et al., 2016). In this study, the researchers also found that the mental workload was perceived as significantly higher by the novices than the experts. The visual stimuli, such as door movement, either in real operating rooms or in simulated conditions, did not affect the flow of procedures (Mentis et al., 2016; Persoon et al., 2011). The mental distraction, i.e. case-related communication, was perceived as less annoying when the participants were highly absorbed (Pluyter et al., 2010). The participants rated mental demand as high and frustration as low, indicating that they tended to enjoy intellectual challenges created by the VOR, which was also confirmed by their narratives (Pluyter et al., 2014).

As the researchers expected, the novices recognized effort as the main source of mental workload, indicating that the distractions in the VOR influenced the flow of their performance. The increased mental workload, triggered by the integrated tasks and distractions, created the condition for novices to perform better in a real work environment. This also has been suggested by a previous study, which investigated the role of distraction and mental load during a VRL simulation (Pluyter, 2012).

Most factors of the presence questionnaire revealed that the VOR was perceived as adequately immersive. The participants were satisfied with their quick adaption and proficiency of interaction in the VOR as shown by the QUESI as well. The sound aspect was compelling to the participants in that they could easily recognize and localize different sounds. In addition, the sound effect was perceived as realistic like in a real OR.

The improvements of the VOR

The presence questionnaire and the participant's comments pinpoint the user interfaces as the most salient limitation of the current VOR. The haptic interface provided accurate feedback on gestures, but a less realistic experience of interaction and the resistance of tissues. This appeared to relate to the intuitiveness of the experts and the discomfort in hands. As the researchers observed, the surgeons slowed down and made most of their errors during instrument switching. The surgeons also reported their struggle to adapt to the unnatural way of switching tools. The fatigue on the left hand might be attributed to a tight hold of the instrument caused by the low fidelity of the haptic feedback, which is well-recognized in VR surgical simulators (Koch et al., 2019). Considering the visual interface, the participants with corrected vision often experienced insupportable discomfort in the eyes due to the incompatibility of the headset for glasses or contact lenses. The discomfort in the neck may be associated with the weight of the headset.

The environmental setup such as OR layout and team placement was viewed to be fundamental for a realistic OR experience. To match the VOR to a real OR, the researchers assume that panoramic video or volumetric video is a promising alternative or complement as it regenerates OR scenarios by filming them in a real OR (Huang et al., 2018; Huber, Wunderling, et al., 2018). These technologies could therefore accurately replicate what happens within a real OR including distraction factors.

The creation of an immersive team interaction largely attributed to mimicking mental distractions happening throughout the surgical procedure. These distractions range from procedural distractions, such as camera manipulation, and procedure-related conversations, to social distractions, like case-irrelevant or medical-irrelevant communication. Novices needed a considerable number of mental resources to construct cognitive schemata of the surgical procedure; and accomplishing tasks with additional distractions required extra mental resources, which is even more demanding (Pluyter et al., 2014). Social distractions, like patient-irrelevant and case-irrelevant conversations, play a role in reducing stress, particularly when task engagement is high. The researchers may thus infer that introducing a virtual team with better-designed distractions reduces required mental resources and helps novices concentrate on their flow. In this way, the trainees would accelerate the construction of these schemata (Pluyter, 2012). This approach might contribute to the transfer from conscious competencies to unconscious competencies. As the Crew Resource Management (CRM) strategy is missing in current laparoscopy curricula, the virtual team might offer the potential to integrate CRM into procedural laparoscopy training curricula soon (Undre et al., 2007).

Additionally, the semi-structured interview showed a strong emphasis on users' (surgical trainees and surgeons) needs for personalization. It was viewed as the main factor to enrich a realistic and immersive experience. Personalization of instruction and language, instrumentation, and background music is expected to match the user's needs, wishes and expectations in a real OR. The potential of customizing the environment should be given some serious thought, considering specific demands, related to the region, the country or even the institution where the training takes place.

Limitations

The outcome of this study demonstrates the effectiveness of a VR-based distractive environment for laparoscopic procedural training. This explorative analysis has the following limitations that point out chances for future studies. (1) The researchers deliberately avoided comparing the VOR with either regular VR laparoscopic simulators or real cholecystectomies. The next step will involve analysing and comparing experiences in both settings. (2) The current study mainly included self-assessment, while participants possibly over-assessed their performance in a new immersive training (Ganni et al., 2017). Hence, the researchers suggest that future studies may include self-assessment, objective measurements, and expert assessment to triangulate the evaluation of the performance. (3) Future studies should also investigate and compare how the different types of distractions would influence usability, presence, and performance.

5.1.6. Conclusion on immersive training for experts and novices

The VOR showed potential to become a useful tool in providing immersive training during laparoscopy simulation based on the usability and presence analysed in this study. The researchers suggest four improvements for a higher level of presence: 1) optimize haptic and visual interfaces; 2) create a virtual OR environment applying alternative solutions, such as cinematic technologies; 3) include a virtual team facilitating non-technical skills training and stress-reducing; 4) investigate the needs of the surgeons for personalized training. The researchers believe that these improvements will increase the effectiveness of the VOR for laparoscopy training, increase the motivation and speed up the process of adaption of the trainees to the real OR setting.

5.2. Immersive Training in Virtual Operating Room: Outside the WEIRD Culture

5.2.1. Introduction

Minimally invasive surgery (MIS) is rapidly becoming the standard of treatment for many surgical pathologies (Van Dijk et al., 2014). However, the skills required to perform MIS are significantly different to that of open surgery. The surgeon has to cope with restricted movement and visual field, fulcrum effect, hand-eye coordination, and ever-changing instruments and equipment (Eyal & Tendick, 2001). Training surgeons to adapt to these challenges requires equally advanced tools that replicate them.

Historically, MIS training has adapted techniques from other fields of technology mostly notably from aviation training (Cooper & Taqueti, 2004). Virtual reality (VR) simulation has been the cornerstone of training pilots in flight simulation training in that it offers an immersive visual and physical representation and replication of real-world scenarios (Strachan, 2000). This has been possible with the use of mock cockpits that are fitted with screens in place of windows and actuators that move the enclosure around making it true to a real-life setting (Barton et al., 2011). However, VR simulation in MIS training has not truly achieved the immersion that their counterparts offer.

Current VR simulators for MIS training are equipped with a monitor and instrument handles and foot pedals to perform procedure-specific tasks that replicate tissue-specific haptic feedback (Zhang et al., 2008). Several validation studies demonstrate the effective transfer of technical skills from the skills labs to the operating room

(OR) with the use of procedural VR simulators (Munz et al., 2004; Schijven et al., 2005; Seymour et al., 2002). However, a major deficiency of the current procedural VR simulation is its distraction-void and therefore lack of immersive environments. They are set up in isolated skills labs or rooms where they seldom replicate the busy and often chaotic operating room (OR) environment. As Pluyter et al. state "Surgeons cannot operate in a bubble and thus should not be trained in one" (Pluyter et al., 2014). Surgeons must be trained in circumstances that replicate the real OR environments. Training in environments that replicate distractions increases the mental load and stress level of the surgeons and helps surgical trainees to adapt faster to the real OR environment (Pluyter et al., 2010).

Distractions that occur during the surgical procedure have been identified and broadly classified into environmental factors, social factors, equipment factors, and organizational factors (Persoon et al., 2011). These range from procedural distractions, such as changing instruments, the procedure-related conversations between teams, to social factors, such as music, non-procedure-related conversations, etc. Nowadays available VR headsets have made it accessible and affordable to create immersive environments that replicate true-to-life with distractions and a sense of being (Almeida et al., 2016). The combination of VR simulators and VR headsets for virtual operating room simulation setup (VORSS) for procedural simulation will be explored in this study. The researchers aim to analyse the experience of VORSS by surgeons and surgical trainees and the potential added benefit to the existing procedural VR simulation.

5.2.2. Materials and Methods

Participants

The aim was to include all surgeons and surgical residents from GSL Medical College, Rajahmundry, India to participate in this study. All the participants had prior experience either in real MIS surgery or in using laparoscopic VR simulators or box trainers, laparoscopic instruments, and equipment. They were divided into two groups based on their professional background: novices consisted of the surgical residents and the experts were made up of the surgeons. This was based on the demographic questions on the questionnaires completed by the participants. A total of 28 participants enrolled in the study, of which 15 were residents and 13 were surgeons. Throughout this study, the researchers refer to the residents as "novices" and surgeons as "experts". Of the experts in this study, four had completed > 200 cases, three 101–200, three 50–100, and three had performed < 50 clinical procedures. Of the novices, 14 had performed fewer than 50 clinical procedures previously and one performed none.

Virtual Operating Room Simulation Setup (VORSS)
The VORSS contains three essential components: a VR laparoscopic simulator (1), a VR headset (2), and a virtual OR environment (3).

The VR laparoscopic simulator (1): LapMentor III (Simbionix™, 3D Systems Corporation, the US) with MentorLearn Software. The specific hardware includes a 24" flat touch-screen monitor, a keyboard with trackball, two instrument handles offering tactile feedback and a double footswitch for activating simulated electrosurgical coagulation. **The VR headset (2):** 2016 Oculus Rift provides stereoscopic images (1080*1200 per eye, 110°field of view), integrated 3D audio and six-degrees-of-freedom head-tracking. **The virtual OR environment (3):** A panoramic VR scene regenerates a real OR including a full setup of instruments and equipment, and as a new feature, also a surgical team and various distractions. The distractions cover some of the distractive events observed in a real OR (Mentis et al., 2016) (Figure 5.21a). The virtual OR can be simultaneously seen on the monitor and in the VR headset from the same point of view (Figure 5.21b).

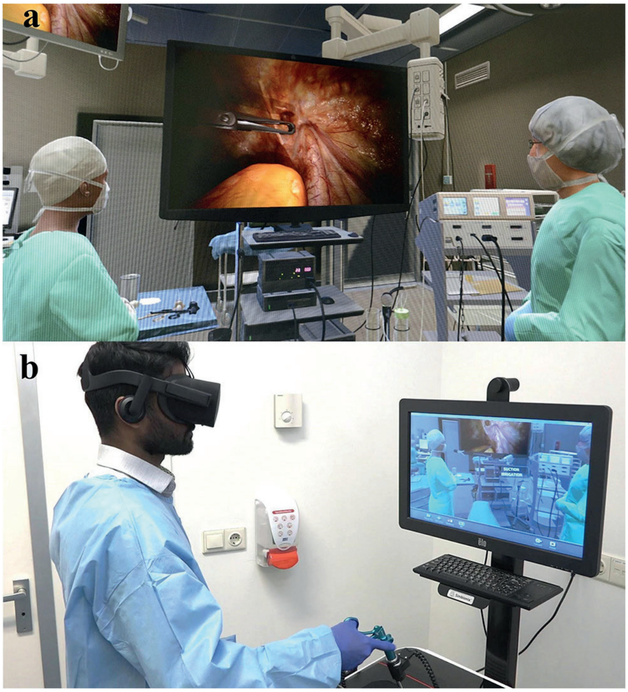


Figure 5.21 The simulated operational environment and the technical setup of the VORSS. ***a.*** the replicated OR setup of the VORSS. ***b.*** an external view of the setup of the VORSS.

Task

Firstly, the purpose was introduced to the participants to the VORSS system, to evaluate the use of VORSS in procedural VR simulation training in a realistic OR context. Participants were introduced to the VORSS and given time to familiarize themselves with the system. Informed consent was completed by the participants before the start of the study.

After the participants put on the VR headset, the VR simulator was adjusted ergonomically according to their height. Then they started a hands-on task “Complete Laparoscopic Cholecystectomy Procedure”, which was previously validated as a basic procedural module of the Laparoscopic Surgical Skills Grade 1 Level 1 course (Buzink et al., 2012). A predefined protocol required participants to interact with the VORSS for 15 min. Since the task was not aimed at assessing their performance, participants could stop whenever they thought it was enough to evaluate the VORSS.

After completing the task, the participants were asked to complete four questionnaires related to the VORSS experience. In the end, general suggestions and comments could be made regarding the realism of the VORSS by participants.

Assessment Methods

The participants were asked to score questions regarding the immersion, usability, and reality of the VORSS experience. Since this is an efficacy study, power calculations were not performed a priori. While our sample size is small, one of the strengths of our approach in this study is that the researchers present the results of multiple validated tools to assess each criterion (Zhang et al., 2019). The responses were analysed via Presence Questionnaire (PQ) (Witmer & Singer, 1998), Questionnaire for Intuitive Use (QUESI) (Naumann & Hurtienne, 2010), NASA-Task Load Index (NASA-TLX) (Hart, 2006), and a heuristics questionnaire. To avoid variability in response due to inconsistent protocol for each of the methods the researchers followed the protocol listed in the references given above.

The Presence Questionnaire was modified and previously validated (Cronbach a = 0.878) to measure the immersion at a sensory level (Witmer et al., 2005; Witmer & Singer, 1998). The PQ contained twenty-four items reflecting seven influencing factors for self-reported immersion, including Realism, Possibility to act, Quality of interface, Possibility to examine, Self-evaluation of performance, and haptic and sound factors. The study added two items on haptic and one item on sound according to the VORSS. An extended 7-point scale was used in fine gradient in which one is not immersive and 21 completely (Dyer et al., 1976). A baseline of the high level of immersion was assigned as 15 (Deb et al., 2017).

The Questionnaire for Intuitive Use (QUESI) indicated the subjective satisfaction of interacting with the immersive VORSS (Naumann & Hurtienne, 2010). The QUESI measures five aspects of satisfaction using a 5-point Likert scale in which one represents low usability and 5 represents high usability. The baselines of the subscales and total were set respectively according to Hurtienne and Naumann (2010).

The NASA-TLX assessed the mental workload or performance problem when performing the task in VORSS (Hart, 2006; Li et al., 2019). The subscales measured six factors of mental effort from very low (1) to very high (21). A baseline value was assigned as 11 represented a medium level of workload.

A questionnaire was developed based on the ease-of-use heuristics for medical devices (Zhang et al., 2003). Participants used heuristics as a guideline to rate their experience with a 5-point scale at the system level, in which 1 means not realistic and 5 completely. A baseline of reality was considered as 4, indicating that only appearance problems were encountered by participants when using the VORSS.

As the final step of the assessment, participants were interviewed with two questions: (1) How satisfied are you with the virtual experience? (2) Which factors were not compelling or not realistic in the virtual experience?

Statistical Analysis

The data was analysed using SPSS v.25. The mean and standard deviation of each questionnaire of the sample, novices and experts were calculated. The means and the baselines were then compared using a one-sample t-test (normally distributed) or a Wilcoxon signed-rank test (non-normally distributed). The differences between novices and experts were tested using classical independent-sample t-test, otherwise non-parametric tests such as the Kruskal-Wallis test and Mann-Whitney U test where appropriate.

5.2.3. Results

Participants

A total of 28 participants enrolled in the study, of which 15 were novices (surgical residents) and 13 were experts (surgeons). Of the experts in this study, four had completed > 200 cases, three 101–200, three 50–100, and three had performed < 50 clinical procedures. Of the novices, 14 had performed fewer than 50 clinical procedures previously and one performed none. There were 8 male and 7 female novices and 9 male and 4 female experts. The groups are approximately comparable in terms of demographic characteristics, with 17 males and 11 females.

Immersion: Presence Questionnaire

Table 5.21 presents the results of the self-reported immersion from the subscales of the Presence Questionnaire. In summary, the four subscales - Realism, Possibility to act, Quality of interface, and Haptic - as well as the overall total had a significantly lower level of immersion than the baseline (PQ subscales = 15, $p < .05$). Both novices and experts had similar immersion levels across the subscales and overall, which were also all significantly different from the threshold. There were no significant differences between the opinions of the novices and experts.

Usability: QUESI and NASA-TLX

The QUESI and NASA-TLX both reflected the usability of VORSS at a cognitive level. The five subscales and total scores of the QUESI were calculated to discover whether the participants were satisfied when performing the task within the VORSS (Table 5.22). None of the sub-scales nor the total score of VORSS was significantly lower than the baselines (W = 2.94, G = 2.89, L = 3.00, F = 2.88, E = 3.04, total = 2.95). However, the score of subjective mental workload and perceived achievement of goals for VORSS were significantly lower for the novices than experts ($p < .05$).

Six subscales of NASA-TLX were calculated to detect the main sources of mental workload (Table 5.23). The *mental demand* was significantly higher than the baseline, while *frustration* and *performance* were significantly lower than it (NASA-TLX subscales= 11, $p < .05$). In addition, the novices had a significantly higher mental workload in *mental demand* than experts ($p < .05$).

Reality: Heuristics Questionnaire

Fourteen heuristics were analysed to judge the reality of VORSS at the system level. Table 5.24 shows the criteria of the heuristics instead of the full guideline. All fourteen heuristics scored significantly lower than the baselines (heuristics = 4, $p < 0.05$). The experts showed significantly higher agreement on the heuristic of the VORSS *Prevent errors* and *Reversible actions* categories ($p < 0.05$) than the novices did.

Table 5.21 shows summary data for self-reported immersion from the subscales of the presence questionnaire with (*) indicating a significant ($p < .05$) difference between the mean for the whole data set and the threshold. The presence questionnaire contains three descriptors indicating the level of immersion. (1= "Not at all", 11 = "Somewhat", 21 = "Completely")

Presence questionnaire Realism		1 Possibility to act	2 Quality of interface	3 PTE	4 SEOP	5 Haptic	6 Sound	7 Total	8
Novice	Mean (SD)	13.30 (0.89)	12.77 (0.72)	9.71 (0.6)	13.98 (0.91)	13.53 (0.82)	13.33 (0.79)	14.10 (0.99)	13.04 (0.68)
Expert	Mean (SD)	13.35 (0.56)	13.23 (0.91)	9.69 (0.99)	13.79 (0.67)	14.08 (1.13)	13.77 (0.61)	13.83 (0.53)	13.16 (0.5)
All	Mean (SD)	13.33 (0.53)	12.98 (0.56)	9.7 (0.55)	13.89 (0.57)	13.79 (0.67)	13.54 (0.5)	13.97 (0.58)	13.1 (0.43)
	P value (2-tailed)	0.004*	0.001*	< 0.001*	0.061	0.082	0.007*	0.085	< 0.001*

Table 5.22 shows summary data for the level of intuitive use of the VORSS with (**) indicating a significant ($p < .05$) difference between the mean for novices and experts. The descriptors of the questionnaire show an opposite attitude toward usability. (1 = "Fully disagree" and 5= "Fully agree")

QUESI subscales		Subjective mental workload (W)	Perceived achievement of goals (G)	Perceived effort of learning (L)	Familiarity (F)	Perceived error rate (E)	Total
Novice	Mean (SD)	2.51** (1.03)	2.80 ** (0.72)	3.27 (1.03)	3.00 (1.00)	3.23 (1.07)	2.99 (0.86)
Expert	Mean (SD)	3.38** (0.9)	3.28** (0.76)	3.44 (0.95)	3.38 (1.04)	3.15 (1.21)	3.33 (0.87)
All	Mean (SD)	2.92 (–1.05)	3.02 (0.76)	3.35 (0.97)	3.18 (1.02)	3.2 (1.12)	3.15 (0.86)
	P values (2-tail)	0.91	0.36	0.07	0.13	0.46	0.24

5

Table 5.23 shows summary data for the self-reported mental workload after using the VORSS with (*) indicating a significant ($p < .05$) difference between the mean for the whole data set and the threshold and (**) indicating a significant ($p < .05$) difference between the mean for novices and experts. The descriptors of the questionnaire show the level of mental workload. (1=" Very low", 21=" Very high")

NASA-TLX		Mental demand	Physical demand	Temporal demand	Effort	Frustration	Performance
All	Mean (SD)	13.04 (4.32)	12 (4.9)	9.96 (3.47)	11.46 (3.52)	9 (4.42)	8.46 (4.77)
	P values (2-tail)	0.02*	0.29	0.13	0.49	0.02*	0.01*
Novice	Mean (SD)	15.01** (3.03)	12.33 (5.05)	11.15 (4.15)	12.16 (3.02)	9.47 (3.85)	7.96 (4.87)
Expert	Mean (SD)	11.23** (4.66)	11.62 (4.91)	9.15 (3.11)	10.62 (3.99)	8.46 (4.81)	8.54 (4.94)

Table 5.24 shows summary data for the level of reality of the VORSS with (*) indicating a significant ($p < .05$) difference between the mean for the whole data set and the threshold and (**) indicating a significant ($p < .01$) difference between the mean for novices and experts. The descriptors show opposite attitude on reality (1= fully disagree, 5= fully agree)

	Consistent and standardized	Visible	Match with real world	Minimalist	Minimizes memory load	Informative feedback	Flexible and efficient
Novice Mean (SD)	3.33 (1.76)	3.13 (0.76)	2.43 (1.23)	2.97 (1.43)	2.45 (1.54)	3.15 (1.15)	2.62 (1.76)
Expert Mean (SD)	3.46 (1.05)	3.23 (1.17)	2.54 (0.97)	2.85 (1.46)	2.92 (1.44)	3.31 (1.03)	2.69 (1.32)
All Mean (SD)	3.04 (1.43)	3.04 (1.17)	2.5 (0.96)	3 (1.28)	2.68 (1.49)	3 (0.98)	2.54 (1.4)
P values (2 tail)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Semi-structured Interview

Comments solicited from the participants were broadly categorized into Virtual OR experience-related, OR team-related and Personalization related:

Virtual OR Experience

Participants were critical of a few aspects of the VOR experience on the interaction between the VOR and the VR simulator. Some could not see their legs and foot pedals because the system did not allow them. Some comments were related to the procedural steps of the laparoscopic cholecystectomy depicted in the VR simulator and perceived as being different from their way of practice. Overall, the participants were intrigued with the novelty of the system and were proactive in using and validating the system.

OR Team

Several participants commented on the OR team and how it affected their perception of the level of system realism. The team would normally be located differently from the placement depicted in the VORSS. The team spoke English as opposed to the local language. The interaction between the team is not realistic and distracting. The voices in the background were unfamiliar and unrelated. The aggregate perception towards the OR team reproduction was negative.

Personalization

Overall, the participants felt the system could benefit from personalization to meet individual preferences and realistic workplace replication.

5.2.4. Discussion

VR simulators have been successfully implemented in different training curricula in MIS, significantly. They have been shown to contribute to the acquisition of clinical skills, which is mandatory for the safe performance of MIS surgery (Jakimowicz & Buzink, 2015). The outcome of multiple validation studies of VR simulators indicates that they adequately reproduce clinical surgical procedures, operative techniques and instrumentation to a level deemed adequate for training and certification (Dawe et al., 2014). This has proven to be of value in providing a constant objective evaluation of the task and procedural performance. The challenges of current VR simulators and simulation settings face a lack of system realism and immersion that are otherwise present in other fields of simulation training, such as aviation, military training, and even in entertainment.

The VORSS outlined and validated in this study builds upon the strength of the VR procedural simulation, and provides additional immersion experience of the operating room. The outcome of the usability, by applying QUESI and NASA- TLX tests, reflects the usability of the VORSS, at the cognitive level. It indicates a good sense of satisfaction when performing the procedure within VORSS. The difference in mental workload was perceived significantly differently by experts than novices, indicating that performing the task itself was more demanding for the surgical residents (novices) than the more experienced surgeons (experts).

Increased mental load created by the VOR environment with additional distractions and tasks, with the introduction of the OR team, implicates that trainees will be better prepared and will adapt to the work environment in the real OR more easily and faster. This has been proven in prior research when exploring the role of the distractors and increased mental load in the course of procedural VR training in a skill lab setting (Pluyter et al., 2010). The outcome of this study has demonstrated clearly that training in an environment mimicking the real workplace shows higher efficiency of training shortening of adaptation period to the real OR environment. The benefits of this approach are demonstrated and proven by using immersive training programs for military personnel, emergency crew training and ICU personnel showing shorter learning curves and shortened adaption period to a real-world setting (Bhagat et al., 2016; Hamilton, 2019).

Regarding the issue of self-assessment from our prior studies, the researchers found that self-assessment has a good correlation with expert assessment and VR simulator assessment (Ganni et al., 2017). However, it is interesting to note that both experts and novices over-assess their performance in this study. While it seems to be possible to over-assess their performance in a new immersive training environment (Pluyter et al., 2010), it is crucial to develop objective criteria, next to the existing VR simulation criteria, for accurate self-assessment in the VORSS setting. Implementing the self-assessment component within the VORSS could importantly contribute to the self-development and proficiency awareness of trainees.

The semi-structured interviews of the participants show a strong emphasis on the user perception of personalization. All users appreciated the immersive environment, created by the VORSS. The lack of personalization on language, crew placement, crew interaction, instrument-specific personalization, and OR layout was less realistic. This indicates the need to improve the realism of the virtual environment, focusing on the above-mentioned aspects. One should also consider potentially customizing the environment, considering specific conditions, related to the region of the world, country, or even specific institution where training takes place. This approach could lead to optimizing the procedural VR simulation training, resulting in the improvement of the safety and quality of MIS surgery. Furthermore, with the increased training demands of trainees and trainer constraints in India, there is an imminent need to address these challenges with effective tools that prepare a trainee for the operating room (Chintamani & Rastogi, 2019). Future extensions of this work could include a study into the cost-effectiveness of this approach compared with mentor-mentee training, the use of simulated OR experience in a skills lab setting and a multi-national validation study to confirm the effects seen here.

5.2.5. Conclusion on immersive training with non-WEIRD users

The VORSS for procedural training has the potential to become a useful tool to provide immersive training in MIS surgery. Further optimization of the VORSS improving realism and introduction of distractors in the VOR should result in an improvement in the effectiveness of the procedural training by shortening the learning curve and speeding up the adaption of trainees to the real OR setting.

5.3. Proficiency from Immersion---A User-Centred Design in Cross-Cultural Surgical Training

5.3.1. Introduction

Ensuring surgeons are well-trained in different kinds of skills is of paramount importance to patient safety. Despite the benefits of saving costs for healthcare systems and improving patient's well-being, mastering laparoscopy (also known as minimally invasive surgery, keyhole surgery, or microsurgery) challenges the limitations of training budget and duration, as well as the trainee's mental and physical capabilities (Berguer et al., 2003; Berguer et al., 2001). It takes 60 months for a resident to become a surgeon (PRISMA Health 2021). Simulation-based training is at the cornerstone of learning demanding tasks such as piloting and driving in that it allows immersive visualization and replicates real-world scenarios (Strachan 2000). Surgical simulators were introduced to laparoscopy training during the last two decades, which effectively helps the acquirement of basic laparoscopic skills, such as eye-hand dexterity and surgical procedures (Munz et al., 2004; Schijven et al., 2005; Seymour et al., 2002).

In a real operating room (OR), numerous distractions occur during operations, which increases the task demand and stress level of the surgeons (Wiegmann et al., 2007). Surgeons have to demonstrate high dexterity, concurrently appraise the intraoperative situation, and control the surgical flow to avoid adverse events as well (Parker et al., 2010). Surgeons are thus not only required to remember the proper sequence of a given procedure but also avoid distractions while conversing with the teams. Patient safety has been proven to be negatively impacted when surgeons are inadequately trained to use complex technology or perform new procedures with long learning curves. Such tasks are particularly taxing on the surgeon's resources. The surgical profession is one of the most stressful occupations. While surgeons are generally in a healthy state, it has been demonstrated that the long hours of work, as well as ongoing disruptions, significantly drained out their physiological and mental resources (Pluyter et al., 2010). Training the awareness of the impact of these factors is rising in the field of surgery (Taekman & Shelley, 2010).

The main drawback of current simulation-based laparoscopy training is their lack of true representation of the intraoperative experience (Jakimowicz & Buzink, 2015). Most laparoscopic simulators replicate surgical tasks in a 2D display without the environments containing busy and often chaotic operating theatres. To create a complete surgical surrounding, the required amount of spatial, financial, personnel and technological resources is demanding (Badash et al., 2016; Jakimowicz & Buzink, 2015). Besides, organizing team training burdens the already busy daily clinical routines (Van de Ven et al., 2017). Since the upsurge of high-end VR headsets in 2016, it became accessible and affordable to virtually generate an immersive environment of an OR. Different studies highlighted that the presence of immersive virtual environments, the "being there" effect, brings new opportunities to turn the impossible possible for learning and training fields (Bowman & McMahan, 2007). Despite the heightened motivation and engagement of surgical trainees, immersive environments are necessary but not sufficient (Sandeep Ganni et al., 2020; Li et al., 2020). Pilot studies revealed that personalization and localization are the key needs of surgical trainees.

Human-centred design is a well-known approach to developing safe, easy-of-use, and affordable products and services for end-users, especially in the healthcare field (Bowman et al., 2002). However, the majority of current user studies or user cases were done with the WEIRD population (Western, Educated, Industrialized, Rich, and Democratic), and then generalized the results applying to human beings in general (Henrich et al., 2010; Nisbett, 2004). In product and service development, a lack of careful consideration of local culture leads to market failures or even fatal incidents (Hao, 2019). Culture alters the way users perceive, understand, and communicate with the surrounding individuals, the local communities, and the world. According to the cultural psychologist Henrich, one has to differentiate people from industrialized Western countries, like the Dutch, and the more traditional societies of countries like India regarding how culture shapes their cognition: the Western mindset (WEIRD) is more individualist, concerned with universal values, and focused on abstract thinking; in contrast, peoples' mindsets in traditional cultures are more collectivist, concerned with particularistic values, and stressing holistic thinking (Henrich, 2020).

Several studies showed that cultural differences do exist in several virtual environments (Hornbeck & Barrett, 2013; Lin et al., 2020). The authors hence focused on the following research questions in this study:

RQ: Are there differences in the perception of the VOR system in the sense of immersion and usability on the following factors:

Sub-Q1 – Level of expertise of the surgical knowledge and skills
Sub-Q2 – The adaptability to the trainee's culture
Sub-Q3 – With or without experience in VR technologies

5.3.2. Method

Participants

Sixty-four surgical practitioners enrolled as participants from Catharina Hospital, Eindhoven, The Netherlands, and GSL Medical College, Rajahmundry, India from June 2018 to February 2019. Among them, twenty-one were surgeons and forty-three were surgical trainees. In this study, the surgeons were referred to as "experts" while the surgical trainees as "novices". There were thirty-nine males and twenty-five females at an average age of 33 (SD=8). 68.8% of the participants had experience with the box surgical trainer while 71.9% of them had experience with laparoscopic simulators. Twenty-seven participants (42.2%) have used low-cost or high-end VR or AR devices (Table 5.31). Every participant took part in the study voluntarily and was given informed consent. The study was approved by the ethical committees both from the Catharina Hospital and the GSL Medical College.

Table 5.31 Participant's Information

	Surgical knowledge		VR Experience			
	Experts	Novices	Yes	None	NA	Total
Dutch	8	28	12	17	7	36
India	13	15	15	13	0	28
Total	21	43	27	30	7	64

Materials

Measurements

In this study, the factors influencing the perception of presence and immersion were investigated via two questionnaires. The Presence Questionnaire (PQ), a well-known presence assessment scale, was modified on sound and haptic aspects following the context of the VOR. Previous studies validated PQ except for "haptic" and "sound" factors (Witmer, Jerome, and Singer 2005, 308-310; Witmer and Singer 1998, 235-236). In this study, the researchers added two items (i.e., the accuracy of gestures, and realistic resistance of tissue) on "haptic" and one item on "sound" (realistic sound effect) according to the features of the VOR, and applied an extended 7-point scale (1= not at all, 7=completely) to survey the level of immersion in fine gradients. A scale was developed based on the fourteen heuristic principles for medical devices (Zhang et al. 2003, 25-26). An example of these heuristics is shown in Table 5-3-2. Participants used these principles as guidelines to rate their experience with a 5-point scale at the system level, in which one means a low level of realism and five is high realism.

Table 5.32 The heuristic principles and their sub-principles. ("Consistent and Standardized" as an example, and the full version is in supplementary materials)

Heuristics	Sub-principles
The system is Consistent and Standardized	a. Sequences of actions (skill acquisition); b. Colour (for categorization); c. Layout and position (spatial consistency); d. Font, capitalization (levels of the organization); e. Terms (e.g., delete, del, remove) and language (words, phrases); f. Interaction rules (e.g., for unvisited hyperlinks); g. Touch (e.g., the textures, force, movement)

The usability of the VOR was evaluated with a combination of two questionnaires. First, intuitiveness, in other words subconsciously applying prior knowledge, was evaluated via the Questionnaire for Intuitive Use (QUESI) (Naumann & Hurtienne, 2010). The QUESI was applied across multiple professions, including healthcare, to quantify the intuitiveness of virtual environments (Li et al., 2019; Saalfeld et al., 2015). The validated assessment asked if the VOR appears intuitive and satisfying using a 5-point Likert scale (1 = fully disagree, 5 = fully agree). Second, the mental workload of performing the task in the VOR was measured using the NASA-TLX (Hart, 2006). This validated tool has been extensively used for assessing the task demand of surgeons when performing laparoscopic surgeries or training (Lee et al., 2014; Zhang et al., 2003). The participants gave a score to the levels of mental, physical, and temporal demands they perceived, as well as their effort, performance, and frustration during the task. The Raw Task Load Index (RTLX) and subscales were calculated into a score between 0 and 100 (0 = low, 100 = high) (Hart, 2006).

Participants reflected on their personal experience of the VOR with two questions: (1) How satisfied are you with the VOR experience? (2) Which factors were not compelling or not realistic in the VOR experience?

Setup

The VOR system the researchers applied comprised three components: a VR headset, a graphic virtual OR surrounding, and a VR laparoscopic simulator. This system is the mainstream of commercially available immersive laparoscopy training platforms. Hence the researchers chose it as the object for this evaluation.

The system contained an Oculus Rift VR headset, providing stereoscopic images (1080 * 1200 per eye, 110° field of view), 3D audio, and 6 DOF head-tracking. The virtual OR surrounding was a graphically generated virtual reality application that replicates typical laparoscopic ORs in Western countries, including a full setup of instruments and equipment, a surgical team, a patient, and various distractions. The simulated distraction covered the typical types, such as door openings, phones/pagers/beepers, radio, as well as case-related communication (Van Houwelingen et al., 2020). The simulated auditory distraction and communication distraction are all in English.

LapMentor VR™ (Simbionix, 3D Systems Corporation, USA) with MentorLearn Software was applied as the laparoscopic simulator. It contains two integrated modules: 1) The interface module replicated an operation table including a patient's abdomen, two trocars and handholds, a camera, and a double footswitch. These handholds quipped five DOFs and haptic feedback. The footswitch could activate electrosurgical functions. The camera could be frozen allowing trainees to finish the training alone. The height of the interface module is adjustable from 62.99" (1.60m) to 70.86" (1.80m). 2) The processing module contained a two-unit industrial PC with a 24" touch-screen monitor (1920*1080 dpi): (a) the simulation unit is a 3.1-GHz Intel Core i7-4770S and an Intel™ Motherboard; (b) the VOR unit is an NVIDIA GeForce GTX 1060 graphic card and an Intel™ SHARKBAY Motherboard. Both units run on Windows 7 Professional (x64) operating system. The MentorLearn software includes a basic skills trainer and a procedural skills trainer. The basic skill modules allow trainees to practice tasks for basic psychomotor abilities. The procedural skill module simulated an entire procedure of laparoscopic cholecystectomy. The trainee could see a computer-generated cavity from virtual patients through the monitor.

The VOR system displays a graphic virtual OR surrounding the simulator via the VR headset (Figure 5.31). If the trainee changes a tool in VOR, there are several differences from the LapMentor: 1) the tool menu is floating at eye level; 2) turn a knot at the front of the handle to choose tools instead of pulling the instrument. To simulate the electrosurgical coagulation, a footswitch is displayed underneath the simulated monitor. A video from Simbionix.com demonstrated the interactions with the VOR system (https://simbionix.com/simulators/lap-mentor/lap-mentor-vr-or/).

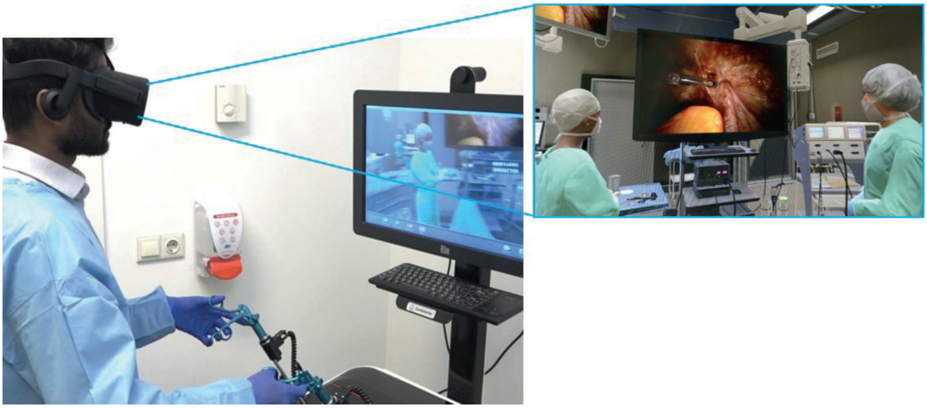


Figure 5.31 The VOR system with VR headset, virtual OR, and laparoscopic simulator.

Procedure

A protocol was developed for the experiment, starting with a standard introduction to the objective of the study and the VOR system. The participants then filled in their informed consent. During the experiment, the participants could explore the virtual OR freely with the LapChol task "LapMentor VR: complete cholecystectomy" for a maximum of 15 minutes to control the symptoms of simulation sickness. After the hands-on session, participants filled in the questionnaires on the presence and usability of the VOR experience. In the end, the participants were interviewed to collect their qualitative feedback.

Data analysis

Mean and standard deviation (SD) were calculated with SPSS v.25 for each questionnaire. To compare different groups in novice and expert surgeons, Euro-Asian cultures, and with or without VR experience, a two-step process was applied: 1) tests of normality were conducted using Kolmogorov-Smirnova test at a significant level of 0.05; 2) when the significant value was less than or equal to 0.05, indicating a non-nominal distribution of the data, the Mann-Whitney U test was utilized to compare the two groups; If the value was larger than 0.05, the classical independent-sample t-test was applied. Then the two-way ANOVA was used to indicate the main effects and interactive effects among surgical experience, culture, and VR experience on presence, realism, mental workload, and intuitiveness via interaction plot, interaction effect value, and significance. A p-value of < 0.05 was considered statistically significant (*), while $p < 0.01$ indicates statistically moderate significance (**) and $p < 0.001$ indicates statistically high significance (***).

5.3.3. Results

Sub-Q1: Level of expertise of the surgical knowledge and skills

Immersion: Presence Questionnaire & Heuristic Scale

In general, both novices and experts experienced moderate presence (PQ means: Total=13.64, SD=2.90) with the VOR system except for the "quality of interface" (Novices=10.97, SD=3.28; Experts=10.54, SD=3.45). The novices rated between 13.45(2.90) to 15.50 (2.90), while experts ranged between 13.38(2.40) to 14.55(3.38). There were no significant differences between them. The "Self-evaluation of performance" (Novices= 15.50, SD=2.90; Experts=14.55, SD=3.38) and "sound" (Novices=14.56, SD=3.26; Experts=14.14, SD=1.89) provided the highest presence (Figure 5.32).

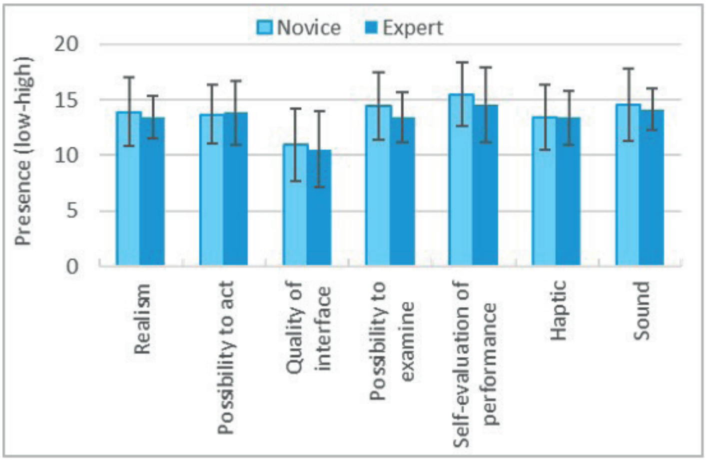


Figure 5.32 Presence experienced by novices and experts. In the PQ, "1" means "not immersive at all", and "21" means" completely immersive".

According to the heuristics shown in Figure 5.33, the VOR was properly designed (HE means: Novices=3.20, SD=1.28; Experts=3.12, SD=1.21), except for "Flexible and Efficient" (Novices=2.93, SD=1.40; Experts=2.95, SD=1.16), "Reversible actions" (Novices=2.79, SD=1.41; Experts=2.90, SD=1.51), and "Help and documentation" (Novices=2.49, SD=1.64; Experts=2.67, SD=1.53). No significant differences between the novices and experts on the perception of realism.

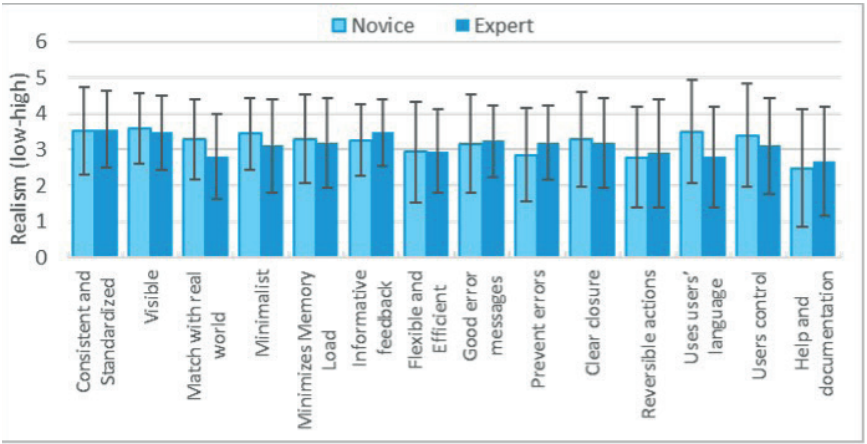


Figure 5.33 Rates on heuristics by novices and experts. In the heuristic scale, "1" means "low realism", and "5" means "high realism".

Usability: NASA-TLX & QUESI

The Raw TLX showed that the novice's mental workload of using the VOR around the mid-point (50) both for the novices and experts (RTLX: Novices=54.28, SD=12.24; Experts=48.65, SD=14.40) (Figure 5.34). The "performance" (Total=67.97, SD=22.28) associated with non-success tasks, was the subscale with the highest mental workload, especially for the experts (Experts=71.67, SD=22.99). The second high subscale "Mental Demand" was significantly higher for the novices than the experts (Novices=65.12, SD=18.95; Experts=50.24, SD=23.79). On the contrary, the perception of "frustration" (Total=37.58, SD=22.20) was the lowest.

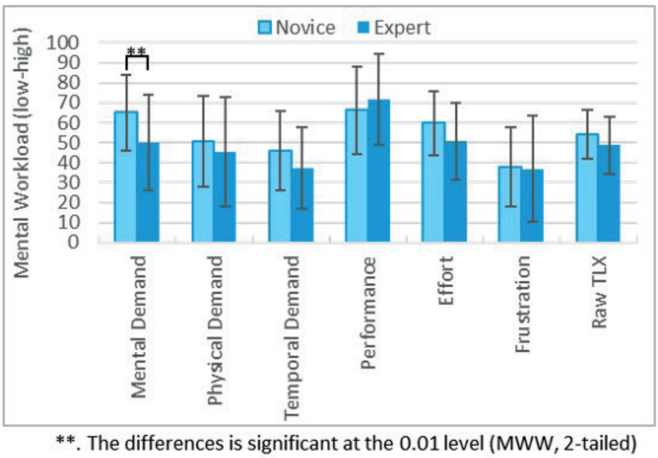


Figure 5.34 The mental workload of the VOR from novices and experts. In the NASA-TLX, "0" means "no mental workload" and "100" means "very high mental workload".

Both novices and experts thought the VOR was intuitive to use (Total QUESI: Novices=3.54, SD=0.77; Experts=3.37, SD=0.79) (Figure 5.35). The "low perceived effort of learning" (Dutch=3.68, SD=0.86; Indian=3.40, SD=0.83), "low perceived error rate" (Novices=3.60, SD=0.86; Experts=3.17, SD=1.06), and "high perceived achievement of goals" (Novices=3.60, SD=0.84; Experts=3.40, SD=0.86) were the most intuitive factor for the VOR experience.

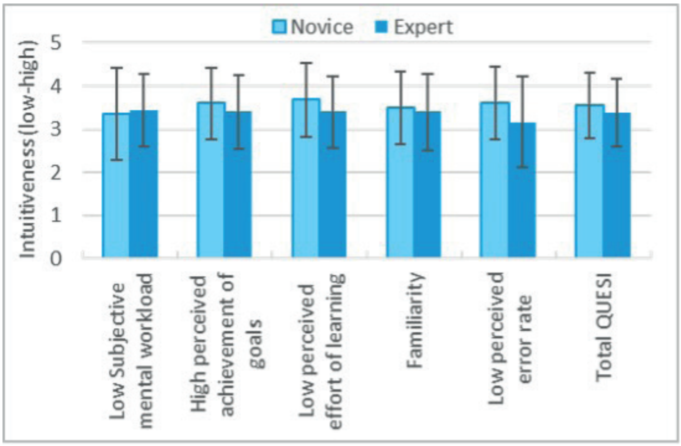


Figure 5.35 The intuitiveness of VOR from novices and experts via the QUESI. In the QUESI, "1" means "low intuitive" and "5" means "highly intuitive".

Sub-Q2: The adaptability to the trainee's culture

Immersion: Presence Questionnaire & Heuristic Scale

The perception of immersion significantly differentiated across the Indian and the Dutch groups (Figure 5.36) (PQ means: Indian=13.03, SD=2.99; Dutch=14.11, SD=2.70). For the Indian participants, the degree of immersion was evenly distributed in every aspect of presence except for "Quality of Interface" (Indians=9.70, SD=2.91); in contrast, the Dutch participants attributed a higher degree of immersion to "Self-evaluation of performance" (Dutch=16.28, SD=2.10). The Indian participants rated "Possibility to act" (Indians=12.98, SD=2.97; Dutch=14.33, SD=2.40) and "Quality of Interface" (Indians=9.70, SD=2.91; Dutch=11.70, SD=3.38) significantly lower than the Dutch. The difference in "Self-evaluation of performance" (Indians=13.79, SD=3.56; Dutch=16.28, SD=2.10) was highly significant.

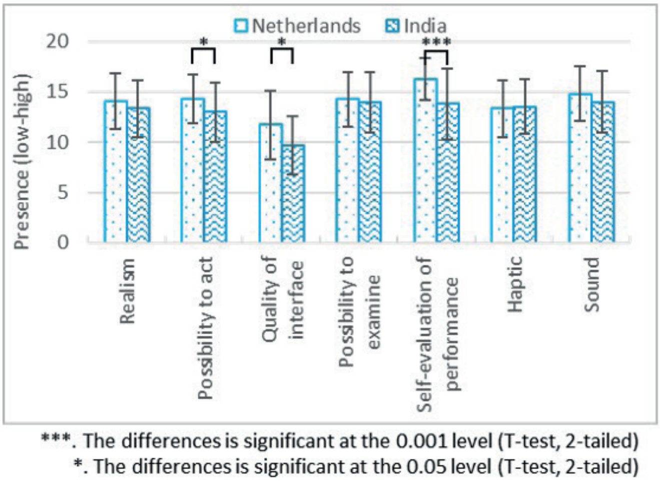
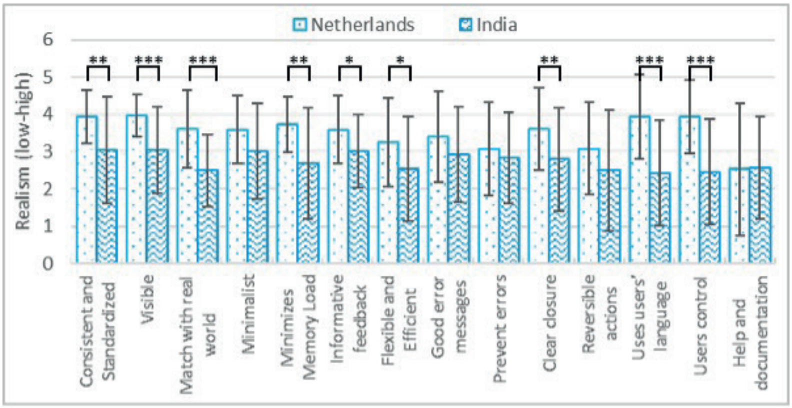


Figure 5.36 Presence experienced by Dutch and Indian participants. In the PQ, "1" means "not immersive at all", and "21" means" completely immersive".

The majority of the fourteen heuristics were rated lower by the Indian participants than the Dutch (HE means: Indian=2.74, SD=1.31; Dutch=3.51, SD=1.05), and they significantly differentiated on nine items (Figure 5.37). Among these heuristics, four items were highly significant, including "Visible" (Dutch=3.97, SD=0.56; Indian=3.04, SD=1.17), "Match with the real world" (Dutch=3.61, SD=1.05; Indian=2.50, SD=0.96), "Use user's language" (Dutch=3.92, SD=1.13; Indian=2.43, SD=1.40) and "User's control" (Dutch=3.94, SD=0.98; Indian=2.46, SD=1.43). The differences were modestly significant between Dutch and Indian in "Consistent and Standardized" (Dutch=3.94, SD=0.72; Indian=3.04, SD=1.43), "Minimizes Memory Load" (Dutch=3.72, SD=0.74; Indian=2.68, SD=1.49), and "Clear closure" (Dutch=3.61, SD=1.10; Indian=2.79, SD=1.37). The items related to system efficiency such as "Informative feedback" (Dutch=3.58, SD=0.91; Indian=3.00, SD=0.98) and "Flexible and Efficient" (Dutch=3.25, SD=1.18; Indian=2.54, SD=1.40) were significantly lower for the Indian participants than the Dutch.

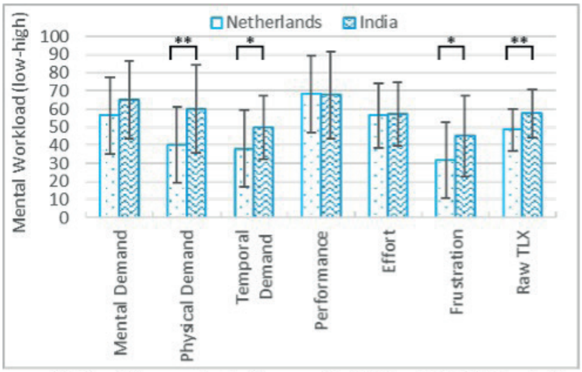
Usability: NASA-TLX & QUESI

Figure 5.38 showed that the Indian participants had a significantly higher mental workload than the Dutch counterparts (RTLX: Dutch=48.50, SD=11.62; Indian=57.50, SD=13.45). The subscales "Performance" (Dutch=68.19, SD=21.32; Indian=67.68, SD=23.66), "Mental Demand" (Dutch=56.39, SD=21.17; Indian=65.18, SD=21.62), and "Effort" (Dutch=56.39, SD=17.91; Indian=57.32, SD=17.61) were the main mental workload resources of the VOR system indifferently for Indian and the Dutch.



***. The differences is significant at the 0.001 level (MWW, 2-tailed)
**. The differences is significant at the 0.01 level (MWW, 2-tailed)
*. The differences is significant at the 0.05 level (MWW, 2-tailed)

Figure 5.37 Rates on heuristics by Dutch and Indian participants. In the heuristic scale, "1" means "low realism", and "5" means "high realism".



**. The differences is significant at the 0.01 level (MWW, 2-tailed)
*. The differences is significant at the 0.05 level (MWW, 2-tailed)

Figure 5.38 The mental workload of the VOR from the Dutch and Indian participants. In the NASA-TLX, "1" means "very low mental workload" and "100" means "very high mental workload".

Dutch participants had significantly lower mental workload than Indian on these subscales: "Physical Demand" (Dutch=40.14, SD=20.72; Indian=60.00, SD=24.49), as well as on the "Temporal Demand" (Dutch=38.06, SD=21.29; Indian=49.82, SD=17.35) and "Frustration" (Dutch=31.81, SD=20.78; Indian=45.00, SD=22.11).

The degrees of intuitiveness were also significantly different across the Indian and the Dutch responders. The Dutch rated total QUESI significantly higher than the Indian counterparts (Total QUESI: Dutch=3.75, SD=0.58; Indian=3.15, SD=0.86), and the scores of "Low subjective mental workloads" (Dutch=3.75, SD=0.58; Indian=2.92, SD=1.05) and "High perceived achievement of goals" (Dutch=3.85, SD=0.63; Indian=3.12, SD=0.91) were significantly higher (Figure 5.39). The Dutch participants significantly felt more familiar with the VOR than the Indians (Dutch=3.69, SD=0.61; Indian=3.18, SD=1.02). Both Dutch and Indian participants perceived "low effort of learning" (Dutch=3.78, SD=0.70; Indian=3.35, SD=0.97) and "low error rate" (Dutch=3.67, SD=0.74; Indian=3.20, SD=1.12).

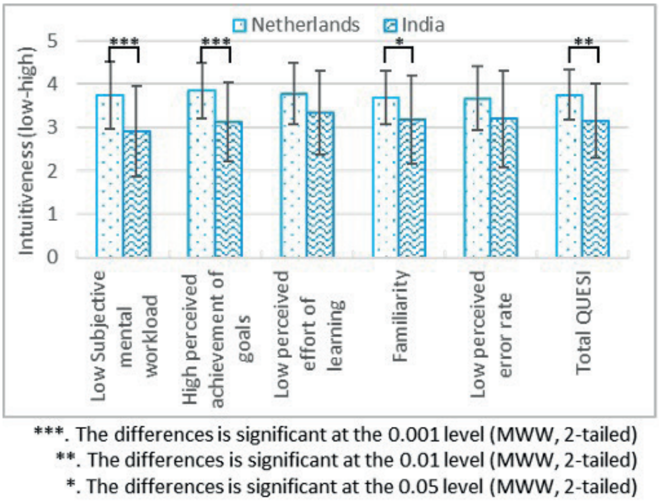


Figure 5.39 The intuitiveness of VOR from Dutch and Indian participants via QUESI. In the QUESI, "1" means "low intuitive" and "5" means "highly intuitive".

Sub-Q3: With or without experience in VR technologies

Immersion: Presence Questionnaire & Heuristic Scale

In general, non-VR and VR users would have a similar experience on immersion (PQ means non-VR=13.57, SD=2.92; VR=13.58, SD=2.80), except for "Quality of interface" (Figure 5.310). The VR users rated the interface quality of the VOR significantly lower than the non-VR users ("Quality of interface": non-VR=12.07, SD=2.91; VR=9.63, SD=3.31).

In Figure 5.311, the VR users demonstrated a significantly higher need for autonomy such as "Reversible actions" (HE means: non-VR=12.07, SD=2.91; VR=9.63, SD=3.31). The requirements associated with customization such as "Use user's language" (non-VR=3.37, SD=1.61; VR=2.96, SD=1.32) and "User control" seemed also higher for the VR users (non-VR=3.50, SD=1.41; VR=2.93, SD=1.47).

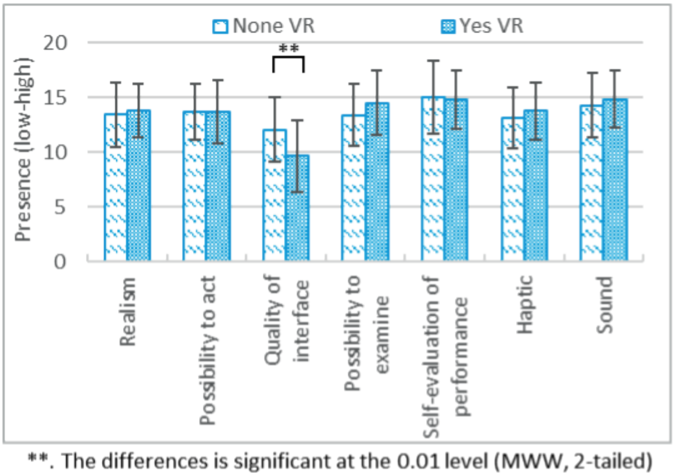


Figure 5.310 Presence experienced with or without VR experience. In the PQ, "1" means "not immersive at all", and "21" means" completely immersive".

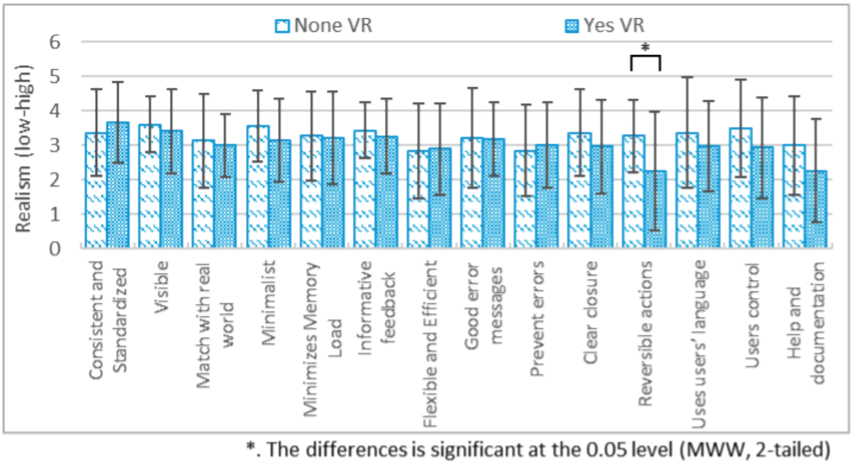
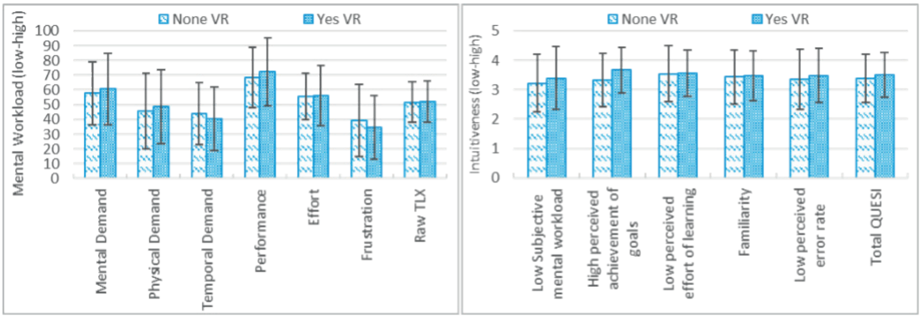


Figure 5.311 Rates on heuristics with or without VR experience. In the heuristic scale, "1" means "low realism", and "5" means "high realism".

Usability: NASA-TLX & QUESI

In brief, the workload of using the VOR was proper (RTLX: non-VR=51.78, SD=13.78; VR=52.31, SD=13.91), and VR users seemed to have a slightly higher mental workload. "Performance" (non-VR=68.50, SD=20.39; VR=72.22 SD=22.84), "Mental Demand" (non-VR=57.83, SD=21.32; VR=60.74, SD=24.21), and "Effort" (non-VR=55.50, SD=15.61; VR=56.11, SD=20.58) were the main resources of mental workload for both groups, while the "Frustration" was the lowest mental workload (Total=37.02, SD=23.01). The

VR and non-VR users showed no significant differences in the subscales of mental workload (Figure 5.3 12).



a) the mental workload via NASA-TLX

b) the intuitiveness via QUESI

Figure 5.312 The perceived mental workload a) and intuitiveness b) with or without VR experience. In the NASA-TLX, "1" means "very low mental workload" and "100" means "very high mental workload"; in the QUESI, "1" means "low intuitive" and "5" means "highly intuitive".

Using the VOR system was modestly intuitive (Total QUESI: non-VR=3.38, SD=0.82; VR=3.52, SD=0.76) with or without VR experience. The VR users seemed to rate the intuitiveness slightly higher than the non-VR users, especially on "Low Subjective mental workload" (non-VR=3.22, SD=0.98; VR=3.40, SD=1.06), "High perceived achievement of goals" (non-VR=3.33, SD=0.91; VR=3.67, SD=0.77), and "Low perceived error rate" (non-VR=3.35, SD=1.03; VR=3.48, SD=0.92). The differences were not significant.

Main Effect and Interaction Effects

There were obvious interaction effects between surgical knowledge and cultural differences except for mental workload, where the effect of surgical knowledge was dominant (Figure 5.313).

Surgical knowledge vs. cultural difference

The differences in the perception of presence, realism, and intuitiveness among the cross-culture novices groups tended to become larger, while the mental workload was slightly smaller. The main effects of the following factors were significant: culture on realism ($p < 0.001$), culture ($p < 0.001$) or surgical ($p < 0.01$) knowledge on mental workload, and culture on intuitiveness ($p < 0.05$). The interaction effects were not significant.

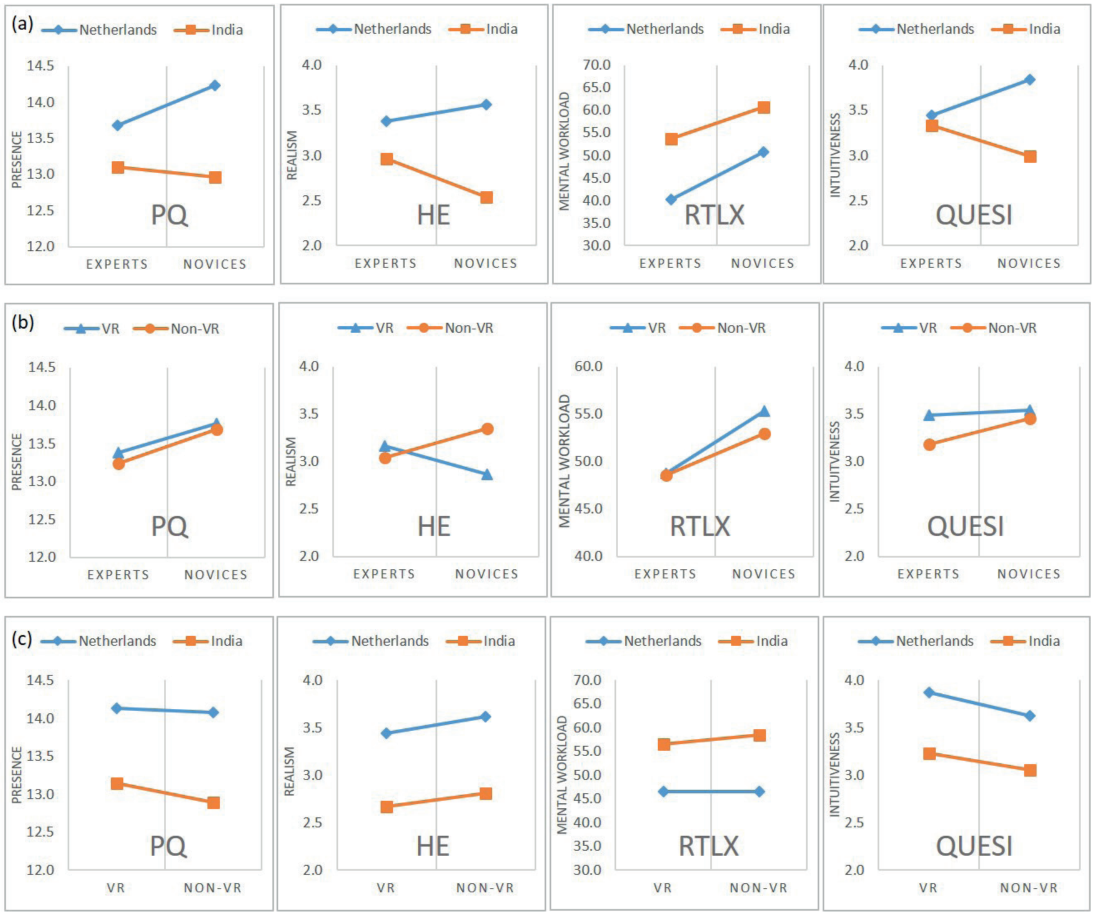


Figure 5.313 the interaction effect between a) Surgical knowledge and Cultural difference, b) Surgical knowledge and VR experience, c) Cultural difference and VR experience on the presence (PQ), realism (HE), mental workload (RTLX), and intuitiveness (QUESI).

Surgical knowledge vs. VR experience

The interactive effect of surgical knowledge and VR experience was also distinct other than immersion (Figure 5-3-13). The surgical knowledge determined the level of perceived immersion. The VR experience made the realism perception either drop or rise among the novices. Unlike the mental workload, the experts without VR experience might feel the VOR the most unintuitive, while the difference between novices with or without VR experience was smaller. The main effects and interaction effects were not significant.

Cultural difference vs. VR experience

The cultural difference and VR experience seemed to have almost no interactive effect; hence the cultural difference was the determining factor (Figure 15). The different perceptions of immersion and mental workload became larger between the cross-cultural non-VR groups, while the different perceptions of intuitiveness became slightly smaller between the non-VR group. The main effects were significant: culture on the presence ($p < 0.05$), realism ($p < 0.05$), mental workload ($p < 0.01$), and intuitiveness ($p < 0.01$).

According to the interaction effects, the cultural difference was stronger than surgical knowledge and then the VR experience on the perception of immersion and usability. The strongest interaction effect seemed to appear between surgical knowledge and VR experience (interaction effect=12.19), which seemingly was positively enhancing. The second large interaction effect was between surgical knowledge and cultural differences (interaction effect=6.80). The main effects of cultural differences were significant in each aspect of immersion and usability, while surgical knowledge showed its influence on mental workload. among the cross-culture expert groups, at the same time increased the differences in immersion, realism, and intuitiveness across the novice groups in a different culture.

Qualitative Feedback

Experts versus novices

The qualitative feedback from the experts concentrated on the stiffness of the haptic interface and the rigidness of the surgical procedure. Most of the experts were annoyed by the tool-changing interaction, which violated real tool-changing manoeuvres. Besides, the correct OR layout and the availability of preferred instruments were also of concern to the experts. The novices felt immersed by the sound simulation within the VOR, and the blurring lens was their focus.

The Dutch versus Indian participants
Both the Dutch and Indian participants expressed a strong need for localizing the communicating language as well as some surgical practices. The Indian surgeons pointed out: a) the OR team would normally be in a different placement other than the VOR; b) the team interaction was distracting and unrealistic; c) the background sound was unfamiliar and unrelated. The Dutch surgeons commented: a) the team communication was repetitive and disrupting; b) the camera assistant was missing; c) the team interaction was impersonal; d) the background music was pleasant but needed to be personalized.

With VR experience versus without VR experience
The experienced VR user often mentioned the "screen-door" effect of the VR headset and the game-like feeling during the training. They appeared to be more relaxed even for the first hands-on, while the non-experienced VR users tended to be more stressed when some errors appeared during the testing. Both groups tended to forget the time when using the VOR system.

5.3.4. Discussion
This study aims to understand the effect of surgical knowledge, cultural differences, and VR experience on the immersion and usability of a VOR system. Considering the surgical knowledge, when the authors combined the surgeons and surgical trainees from different cultures, interesting results happened. Unlike the results comparing the experts and the novices in the Netherlands and India respectively, the only significant differences between the experts and the novices presented only on "Mental Demand". It was also identified independently via Dutch and Indian studies (S. Ganni et al., 2020; Li et al., 2020). The scores from the Dutch novices were significantly higher on the "perceived effort of learning" of QUESI, as well as the Raw TLX and sub-scales like "Physical Demand", "Temporal Demand" and "Effort" disappeared (Li et al., 2020). The higher rates from Indian experts on "subjective mental workload" and "perceived achievement of goals" of QUESI, as well as "Prevent errors" and "Reversible actions" of the heuristics, vanished alike (S. Ganni et al., 2020). The researchers might infer that the interaction between surgical knowledge and cultural differences would probably neutralize the significance of surgical proficiency, as observed in Section 5.3.3.

The most out-of-expectation finding of this study is the dominant effect of cultural differences. Despite the well-known phenomenon "WEIRD" in academics, few pieces of evidence show the cultural differences in an immersive training setup. The people from paddy rice regions, such as east India, where Rajahmundry is located, tend to use more holistic thinking (55%) than analytic thinking (45%) (Henrich, 2020). The proportion of analytic thinking is 75% for the Dutch (Henrich, 2020). The researchers would hence infer that the differences in the Presence Questionnaire and heuristic scale, e.g., “Consistent and Standardized”, “Visible”, and “Matches with the real world”, might be attributed to the holistic thinking of the Indian participants. Joseph Henrich found that a person from an intensive kinship culture would favour familiar relationships in teamwork, which was a rare case for those with weaker relational connections (Henrich, 2020). This might explain the significant differences in “familiarity”. Our brain needs more mental resources to handle the strange information, which might explain why Indian participants wanted to “Minimize memory load” and needed “informative feedback”. Using the native language, as a prominent symbol of local culture would increase familiarity as pinpointed both in the questionnaires and the interview. People from rice paddy areas often have less “self-inflation” than the “WEIRD” people (Henrich, 2020). It might tell why the Indian participants had significantly lower scores on “self-evaluation of performance” and “perceived achievement of goals”.

The effect of the VR experience was mainly on immersion where the interfaces and the fault tolerance. The familiarity of the technologies, such as desktop displays versus stereoscopic displays, might alter the focus of the perception (dos Santos et al., 2009). The knowledge of VR displays enabled the experienced VR to hold pre-defined focuses, e.g., resolution and “screen-gate effect”, and recognize related phenomena in the testing, as found in the interview as well. Another interesting finding is the interaction effects between surgical knowledge, cultural differences, and the VR experience. The VR experience showed a strong confounding effect with surgical knowledge, especially on mental workload, while had very little influence on cultural differences. The low intuitiveness of non-VR surgical experts indicated that domain proficiency sometimes might hinder the acquisition of new skills, especially those against their automated manoeuvres.

Regardless of the effect of surgical knowledge, cultural differences, and VR experience, the participants concurrently experienced high mental demand, high-performance challenge, and low frustration state. It seems to be impossible, however, might imply that the participants were under a sort of “flow state” (Pilke, 2004). Flow refers to the optimal experience, which is the state between frustration and boredom where the mental state becomes an extremely rewarding concentration (Csikszentmihalyi, 2008). The enjoyment of immersion stems from the perception of “being in a complete absorption” with the unified novel narrative schema (Douglas & Hargadon, 2000; Hekkert et al., 2003). The pleasure of engagement appears to come from interactivity with an array of pre-established schemas (Douglas & Hargadon, 2000). In medical education, immersive and interactive training such as simulation-based learning recently has gained significance (Taekman & Shelley, 2010). The virtual environments provide all the prerequisites for flow. When it integrates team-based learning to stimulate team interaction, enhanced immersion and engagement will merge into the flow (Douglas & Hargadon, 2000; Taekman & Shelley, 2010).

The following limitations of this study would open room for further research: 1) Despite shedding light on cross-cultural issues of VR-based training, the sample size was not large enough to explain these phenomena in depth. This evaluation protocol needs to be applied to other cultural contexts in healthcare education. 2) The immersive and engaging effect was discovered, but the understanding of how each type of distractor would influence presence and usability has not been reached yet. Systematic investigating, categorizing, and simulating distractors are the benchmarks of this work. 3) Subjective assessments are susceptible to personal bias and low replicability. Future studies should introduce "data-driven methods" that collect objective data, such as error rate, and task completion time and physiological data, such as eye-tracking, EEG, and facial EMG. 4) The VR experience of seven novices is not available. Considering the sample size, further studies should verify the results with a larger sample size focusing on the VR experience. To facilitate the future design of VR immersive training, a design guide is under development for a highly personalized experience.

5.3.5. Conclusion on immersive training across different cultures

This study explored the effects of surgical knowledge, cultural differences, and VR experience on the presence and usability of an educational VR environment. The novelties of this study are 1) demonstrating the cultural differences between sixty-four novices and experts in presence, realism, mental workload, and intuitiveness; 2) the interaction effects of these main factors were shown, especially the strong interaction between surgical knowledge and culture difference; 3) proposed "flow state" as a key feature for the future VR-based professional training. Despite the limited applications, VR-based immersive training is attracting attention both from academic and industrial fields. Integrating immersive technologies via Human-Centred Design is opening a brand-new horizon for healthcare and similar professional training. The numerous expert views collected in this study provide a solid base for a design guide for VR-based immersive training focusing on healthcare.

1.1. Conclusions

This chapter explored the research question: "*How can designers effectively assess user experience via social presence across different user groups?*"

Section 5.1 explored the key elements of immersive training by introducing distractors into a virtual operating room simulator both with novice and expert surgeons. A higher surgical experience (Dutch participants) reduces the task load on the subscales (except for *performance* and *frustration*) and the raw TLX during the training but increases the perceived effort of learning. The simulated audio environment enhances the perception of immersion, where auditory distractors might increase the mental effort of novice participants. The high mental demand with low frustration indicates that distractor simulation with XR brings situational challenges to engaged participants throughout the training sessions.

Section 5.2 analysed the responses of trainees from different cultural backgrounds on the above-mentioned virtual environment and its distractors. The surgical experience in a different cultural background (Indian participants) plays a similar role in reducing the task load on the *mental demand* subscale in NASA-TLX, as well as on a *low subjective mental workload* and a *high achievement of goals*.

Section 5.3 compared the above-mentioned elements between user groups with different proficiency, cultural backgrounds, and XR familiarity. Proficiency can affect the *mental demand* subscale of NASA-TLX. Cultural background differentiates in every element, especially in *self-evaluation of performance, match with the real world, uses users' language, users' control,* as well as *the low subjective mental workload* and *high perceived achievement* of goals. The familiarity with XR systems mainly changes the rates on *quality of interfaces*, where experienced XR users perceived lower quality than novice users. Cultural background significantly influences mental workload, intuitiveness, and realism, whereas proficiency alters mental workload.

The factors of immersion in these case studies include 1) immersive (VR) visualization with haptic feedback and auditory feedback for sensory; 2) active navigation, object manipulation, and 3D control for interaction; 3) real-size modelling, texture rendering, avatars, task and team interactions, and environment simulation for realism; and 4) isolation (VR headsets) and challenges (distraction) for involvement. The most salient barrier of XR systems is associated with the *sensory* factor, especially the haptic and visual interfaces that cause a lot of discomfort for long-term usage. Considering both the *interaction* and *realism* factor, the challenge is to replicate true-to-life manoeuvres and procedures that could convey the tactic knowledge matching with the real-world experience. For *involvement*, simulating environmental and procedural distractors creates challenges that might trigger the "flow state" for better learning efficiency. The improper virtual UI within XR might annoy trainees and disturb their learning flow.

The perception of immersion is largely influenced by personalization and localization, especially in the field of simulation-based learning. The distractors, especially the social distractors like intraoperative team interaction, have different effects on learning behaviours under different cultural contexts. For evaluation activities, XR systems identify the variation of users' behaviours from different cultural backgrounds in response to the same context that would facilitate the cross-culture design.

CHAPTER 6

Immersive Collaboration for Organizational Well-being

The conceptual framework in Chapter 3 outlined case studies in physical, cognitive, and organizational domains in UX. The previous chapters analyzed physical and cognitive aspects respectively. Chapter 6 hence focuses on observing activities for organizational well-being and consists of two case studies using collaborative work as examples. The research question discussed in this chapter is "*How can designers facilitate user experience via co-presence in remote collaboration?*"

Relatedness is the universal need that indicates a feeling of having intimate or trustworthy contact with people who care about you and your actions, which not only happens between friends and families but is also important for teamwork. *Co-presence* plays an important role in satisfying the desire to be related in a remote team, referring to the perception of being co-located with colleagues in a shared workspace. The corresponding design elements refer to *task load*, *intuitive use*, *subjective immersion*, and particular *situation awareness* that influence the quality of teamwork to ensure job satisfaction and commitment in an organization. These elements scatter in the organizational-physical domain in product-service systems.

The first case (6.1) develops a scenario of redesigning a robotic line based on real-world tasks and compares the task load, intuitive use, presence, and situation awareness of three augmented reality interfaces on the expert's side: 'desktop, 'real-size', and 'god-mode', as well as the same measurements from local sides when co-creating with the experts.

The second case (6.2) explores how two-way augmented reality (AR) can support the collaboration between captains and doctors for a better quality of care by applying HCD approaches, including field study and user testing.

The case study in Section 6.1 is adapted from the submitted publication as
Meng Li, Doris Aschenbrenner, Daniëlle H. van Tol, Radoslaw Dukalski, Jouke Verlinden, Stephan Lukosch. Augmented Reality Co-location for Co-creating Robotic Factory in Industry 4.0. *Frontiers in Virtual Reality. Submitted*.

The case study in Section 6.2 is adapted from the publication
Meng Li, Tom Slijkhuis, Remco Huigen, Armagan Albayrak, Daan van Eijk (2021). Two-way Augmented Reality Co-Location Under Telemedicine Context. *ISMAR2021 (adjunct proceedings)*, October 4-8, 2021, Bari, Italy.

6.1. Augmented Reality Co-Location in Co-Creating Robotic Factory for Industry 4.0

6.1.1. Introduction

Industry 4.0 is a main trend in the manufacturing and fabrication field nowadays. It is centered on the important concept of a "smart factory", i.e., the interaction between manufacturing robots and humans (Gordon et al., 2018). When factories are becoming automatic worldwide and travel expenses are soaring, the idea of involving remote operators together in a shared virtual space becomes more and more fascinating for researchers and businesses (Ens et al., 2019). The desire for this digitalization transition has been accelerating by the need for faster feedback iterations and more resilient production networks as global challenges become more and more frequent, such as COVID-19 and climate change (Cai & Luo, 2020).

When envisioning Industry 4.0, digital twins (virtual copies of real objects) and technical assistance (augmented visualization and operation) are two pillars in creating collaboration styles (Brynjolfsson & McAfee, 2014). A digital interface combining these two has the advantage of enhancing remote collaborations by co-locating local and remote workers together virtually. The rapid development of consumer augmented reality (AR) devices, like the Microsoft HoloLens (Microsoft, 2023), suggests using the 'enrichment of real images with virtual information' to provide a shared virtual space (Milgram et al., 1995). Various possible settings of the shared virtual space are available to incorporate remote supervisors into a local scene: research started with astronaut training (Cater & Huffman, 1995). It has been recently adapted to many application domains, including security (Lukosch, Lukosch, et al., 2015a) and manufacturing (Aschenbrenner et al., 2016).

As automated equipment like robots become more affordable and easier to program, an increasingly common scenario in Industry 4.0 is upgrading manual tasks by introducing these automated pieces of equipment for higher productivity and/or safety (Brynjolfsson & McAfee, 2014). Factory- and automation design teams face a unique problem every time because the production task is unique, involving various kinds of products, machines, facility layouts, and resources (Dukalski et al., 2017). The design processes with current methods and facilities are often time-consuming due to the information-sharing challenges, such as poorly analyzed spatial constraints, suboptimal communication, knowledge asymmetry, limited possibility to explore and visualize solutions, and obscure tacit knowledge (Cencen et al., 2016; Dukalski et al., 2017). Augmented digital interfaces like AR are proven to be of value in collaborative tasks such as factory maintenance by providing visual annotations like drawing (Aschenbrenner et al., 2019). However, unlike collaborative maintenance, factory upgrading usually involves numerous spatial objects, large-scale systems, and local contexts. A practical question is rarely studied: Which AR interfaces are suitable to support remote co-creation in the context of Industry 4.0?

The study hence focuses on collaborative experiences of AR interfaces in supporting co-creation during factory upgrading. Most studies on collaborative AR used simplified topics like LEGO blocks which could reflect the psychological principles of remote collaboration. Their outcomes are less applicable in manufacturing (Aschenbrenner et al., 2019). This study needs to develop realistic scenarios to provide a reference for real-world implementations. Based on real-production experiences, the stakeholders of factory upgrading include a *customer*, who upgrades a factory line with robots and automated conveyors; a *consultant,* who supports the customer in planning the line on-site; and an *expert,* who remotely designs the line with the customer owning special knowledge about the equipment (Figure 6.11). The researchers will create this scenario using computer-generated virtual objects.

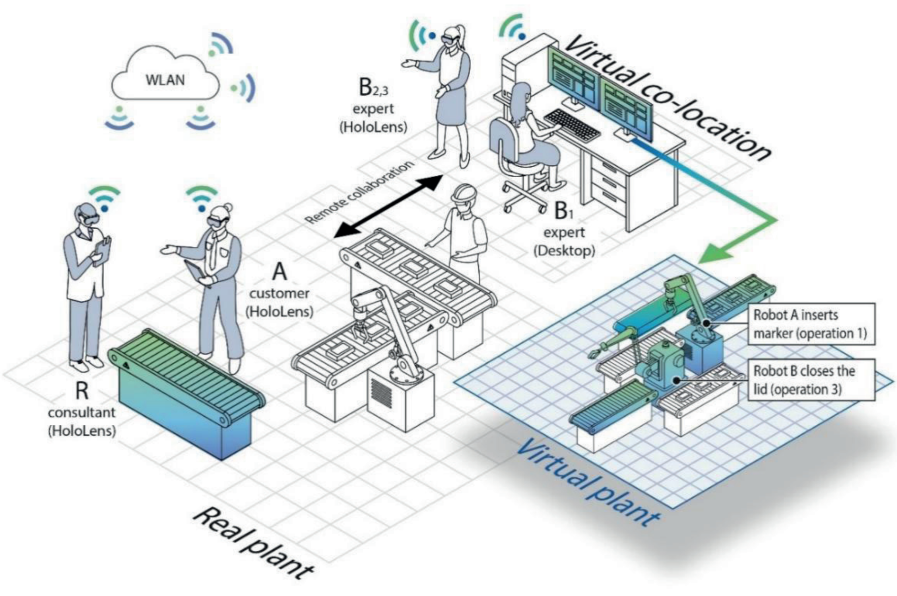


Figure 6.11 Collaborative production line planning with AR co-location. Customer (A) upgrades his/her factory with robots and automated conveyors. For this, he or she wearing a HoloLens works with a remote expert through different AR interfaces (B1, B2, and B3). A consultant (R) wearing a HoloLens helps the customer in manipulating the virtual objects on-site. The team can see a virtual plant (the color one) projecting on top of a real plant (the black-white one).

This study aims to understand what is a "better" AR interface in supporting co-creation for fabrication. Most collaborative AR studies focus on the local side. Nevertheless, the influences - how the local site perceives the quality of collaboration, when the remote site uses different interfaces - are less studied. *Task load* and *usability* reflect the perceived competence and intuitive application knowledge when people interact with an interface (Li et al., 2019). *Presence* represents the perceived immersion towards an experience, and collaborative experiences alike (Lingan et al., 2021). *Situation awareness* refers to the perception of elements in the current situation, the comprehension of the situation, and the projection of future status (Endsley, 2013). It serves as a key indicator of the feeling of co-location (Lukosch, Lukosch, et al., 2015b). This study thus measures *task load*, *usability*, and *presence* together with *situation awareness* to indicate the quality of collaboration.

The presumed contributions of this study are:

1) Developing an AR application for planning a robotic factory line that represents a realistic workflow.
2) Exploring the remote user's perception of quality of collaboration via AR interfaces.
3) Discussing the influences of the remote user's interfaces on the local user's perception when working together with large-scale objectives.

This study is structured as follows: After the related work section (6.1.2), the researchers explain the AR application in detail (6.1.3) with a special focus on different conditions of interactions. Then the researchers conduct a user study (6.1.4) and present the raw results (6.1.5), which will be discussed in the section afterward (0). The researchers close with the conclusion (6.1.7).

6.1.2. Related Work

An early study in the area of collaborative work investigated two workers designing an office interior remotely, supported by desktop AR (Ahlers et al., 1995). From a desktop interface on both ends, one worker could add, delete, and rearrange furniture while seeing the changes made by the other co-worker simultaneously. For a remote constellation via shared-view video, a study showed that the collaborators in the same workplace performed better than spatially separated teams (Kuzuoka, 1992), but also showed the potential of multimedia systems. Other early works investigated the technological innovations that enhanced face-to-face collaboration. Rekimoto (1996) developed transvision using a camera-mounted hand-held display, while Billinghurst et al. (1998) and Schmalstieg et al. (2002) used see-through headsets for manipulating three-dimensional information.

The specific field of "Industrial Augmented Reality" was defined by Fite-Georgel (2011) as 'applying Augmented Reality to support an industrial process'. This study gives an overview of using AR in industrial processes, covering maintenance and repair operations in cooperative and asynchronous telepresence scenarios. Regarding AR in assembly tasks, Wang et al. (2016) provide a recent survey and note the demand for more user studies and collaborative applications. To reach an optimal combination of digital fabrication and human skill/intuition, several augmentation scenarios have been developed. These change the role of human labour for the good, as argued by Davenport and Kirby (2016). It has been called "Augmented Fabrication" (Ashbrook et al., 2016), which has shown applications during design and manufacturing (Verlinden & Bekker, 2017). Studies also mentioned tech-augmented operators together with virtual operators as the "operator 4.0" paradigm (de Giorgio et al., 2017; Romero et al., 2016). A recent systematic review on collaboration through Mixed Reality (MR), which collected 110 publications, indicated that only four studies focused on industrial and design processes (Ens et al., 2019). In addition, only 5% of AR-based cooperative work systems support both remote and collocated settings (Ens et al., 2019). Therefore, it's necessary to investigate the state-of-the-art AR-facilitated fabrication from published use cases.

Augmented Fabrication

The researchers reviewed 13 AR use cases from *Scopus* which addressed various collaboration styles in fabrication processes. Then they used six dimensions in AR collaboration taxonomies to analyze these cases, which are defined by Ens et al. (2019) and Benford et al. (1998). These dimensions are necessary to understand the design space of AR-based collaboration (Ens et al., 2019):

> **Time-Space matrix** - the classic computer-aided cooperative work grid that maps systems that support processes of teams, including chronological (*synchronous/asynchronous*) and geographical (*co-located/remote*) values (Johansen, 1988).
>
> **Symmetry** - This dimension indicates whether the collaborators have the same roles and tasks (*symmetric*) or whether they have different roles and tasks (*asymmetric*).
>
> **Artificiality** - Benford et al. (1998) proposed "artificiality" as a dimension to classify collaborative AR, spinning the extremes from entirely physical to entirely digital. The researchers applied the values *mostly physical* and *mostly digital* with a mid-point *hybrid*.

Focus - This dimension describes the target of collaborative systems following the values of *environment*, *workspace*, *person*, and *object* (Ens et al., 2019).

Scenarios - It provides an overall summary of each case regarding its users and tasks with a concise set of values *remote expert*, *shared workspace*, *shared experience*, *telepresence*, and *co-annotation*.

In the *Time-Space* matrix, it is not surprising that these cases were mostly falling into the 'synchronous-remote' quadrant where the "remote interactions" took place (Johansen, 1988). A few studies investigated both remote and co-location conditions where the co-location condition served as a baseline (Kim et al., 2019).

Considering the *Symmetry* dimension, 70% of the collected cases were asymmetric, which is quite different from the relatively even distribution found by a previous review. It indicates that collaborators usually play different roles in a workflow. For instance, S. Kim et al. (2018) and Piumsomboon, Dey, et al. (2019) explored different collaborative styles: expert-guided or shared-task in remote collaboration. Kim's group focused on view independence, while Piumsomboon's team proposed adaptive avatars to enhance the collaborative experience. Another study from Piumsomboon's team compared two types of virtual representations in giant-miniature collaboration between a local AR user and a remote VR user (Piumsomboon, Lee, et al., 2019).

In the *Artificiality* dimension, *hybrid* covered most of the cases, emphasizing both physical surroundings and virtual artifacts. For example, remote video conferences allowed local collaborators to share a first-person view with remote supporters (S. Kim et al., 2018; P. Wang, S. Zhang, X. Bai, M. Billinghurst, L. Zhang, et al., 2019). Remote co-creation often uses various avatars to provide co-presence on both sides (Piumsomboon, Lee, et al., 2019; Yoon et al., 2019). Sharing virtual cues improved the collaborator's performance, usability, and preference in remote assembly and searching tasks, like posture, head-pointing, and eye-gaze ray (P. Wang, S. Zhang, X. Bai, M. Billinghurst, W. He, et al., 2019).

The *Focus* of these AR cases was mainly on the *environment* (50%). The secondary focus in these cases was the *person* (21%), the virtual avatars in various styles of representation. *Workspace* is the missing target in collaboration through AR.

The most common *scenario* in augmented fabrication cases is *telepresence* which focuses on the presence experience in a remote location. The secondary frequent setup is *co-annotation* which aims at sharing different virtual cues in a common work environment in AR. *Shared experience* usually covered the set-up, sharing the first-person view of the local collaborator. The *remote expert* and *shared workspace* are the missing scenarios in current studies.

Regular factory planning systems rarely engage all stakeholders in a spatial context to facilitate design and simulation (Dukalski et al., 2017). The researchers will develop an AR application based on a mobile co-design App from the “Factory in a Day” project. According to the reviewed cases, this AR application shall apply the *synchronous-remote* setup to simulate real-time interactions between the collaborators. Like in a real factory planning process, *asymmetric* roles represent different stakeholders, like the customer, the expert, and the consultant. Like in most augmented fabrication cases, the *hybrid* mode allows collaborators to view the virtual plant on a real factory floor. The target of this AR application is a *shared workspace* that co-locates the three stakeholders via AR interfaces.

Lukosch, Lukosch, et al. (2015b) analyzed recent studies on AR virtual co-location and emphasized the importance of situation awareness in information sharing and collaboration. The researchers speculate that the viewpoint of the remote user on a scene might influence the situation awareness of the local persons, and therefore the capability to collaborate with them. The researchers hence propose the following research questions, on which this study hopes to provide some insights.

The main research question is “*What are effective AR interface design approaches for remote collaboration in a team of multiple local and remote persons?*”

Sub-question RQ1: Which design approach for the remote person’s interfaces is superior regarding the collaborative experience?

- 2A: Is there a measurable improvement by using an AR interface on task load, usability, and presence? If yes, in which aspects can the AR interfaces help in comparison to a desktop interface?
- 2B: What are the aspects that the remote person valued most regarding the feeling of co-location?

Sub-question RQ2: Is there a difference in the collaborative experience of a local person when teaming up with a remote person via different AR interfaces?

- 1A: Does a change in the remote collaborator’s interface affect the experience of the local person on task load, usability, and presence?

- 1B: What are the aspects that the local person valued most regarding the feeling of co-location?

6.1.3. The AR Fabrication Application

To study the above-mentioned questions, the researchers first developed an AR application for collaborative production line planning following the factors of immersion (Ch3).

Narrative

It is a fictitious customization service in that a factory produces a personalized product - an engraved wooden box containing an individual selection of felt-tip markers (shown in Figure 6.12 a). The original production was a mixture of manual tasks, automation, and customization, in which the text to engrave and the color combination of the markers can be customized (Dukalski et al., 2017). Figure 6.12 illustrates the operations to make this product:

Operation 1 - A worker grabs markers and inserts them in the bottom part of a wooden box.
Operation 2 - A robot does the laser engraving on the lid.
Operation 3 - The lid is closed by a worker.

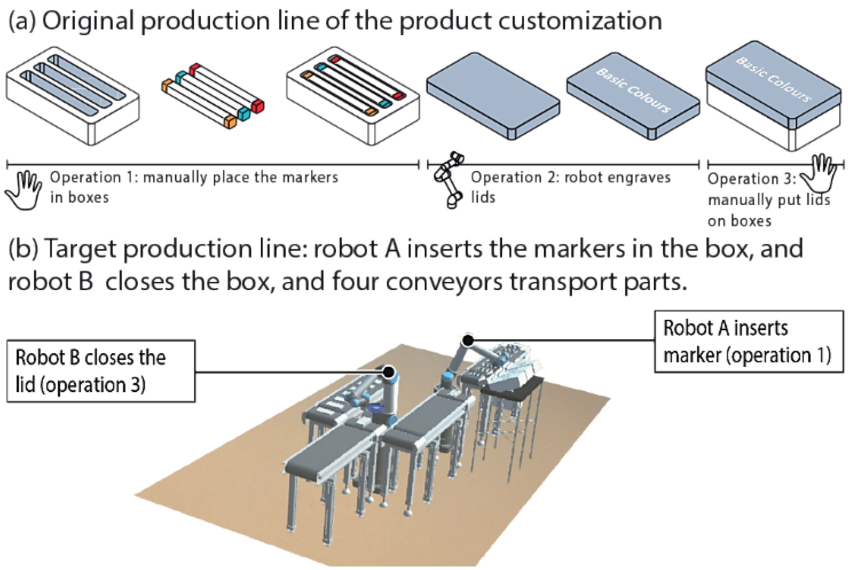


Figure 6.12 The background information of the factory planning task. ***a)*** the original production steps of the customized product, ***b)*** the target production line.

The planning task is upgrading the entire line (shown in Figure 6.12 b) with the help of AR interfaces. In *Operation 1, robot A* puts markers into the box; in *Operation 2,* the laser engraving robot is the same in the new line; in *Operation 3, robot B* closes the box. Four conveyors are used to transport the items. Based on this narrative, a video is created to show this background knowledge to the customers in the user study.

Realistic Scenario

This AR application uses a role-play approach to replicate the co-creation process of the three stakeholders in factory planning. A *customer (A)* is the factory owner who knows the product, the operations, and the location. A *consultant (R)* knows which robot or conveyor can be used to automate each operation. An *expert (B)* in a remote office can show/hide virtual objects (i.e., robots and conveyors) to collaborators, and can activate the operations of these objects. An AR workspace with virtual objects in real sizes and basic textures is modeled using Unity3D. The production operations of these objects are simulated via animation in advance.

In a virtual workspace (Figure 6.13), the customer and the consultant can place virtual objects on a floor via hand gestures and orientate them using vocal commands via their AR headsets. Through different AR interfaces, the expert can see the changes in the objects, show/hide the required objects, and replay their operation of them. The three collaborators communicate the requirements and the customer's needs via a voice call, like the information about the product or showing the operation of robot B. Considering the embodiment, the collaborator can see the virtual headsets and gaze beams of others in the workspace. The interaction section will explain the interactions of each condition.

The tasks are designed as in a real-world situation: the customer (A) creates a conceptual production line with the help of the consultant (R) by manipulating virtual objects in a real site. During the planning, they need information on a specific object from the expert (B), as the needs of customers are normally investigated during the planning in a real case. Throughout the task, the expert could see all objects, whereas the local persons (i.e., the customer and consultant) could only see those that the expert made visible to them. As most remote collaborations happen between the *customer* and *expert,* participants in the follow-up user study will play their roles, while a researcher will play the role of the *consultant*. The scripts of the customer and the expert in the user study are written based on this task design.

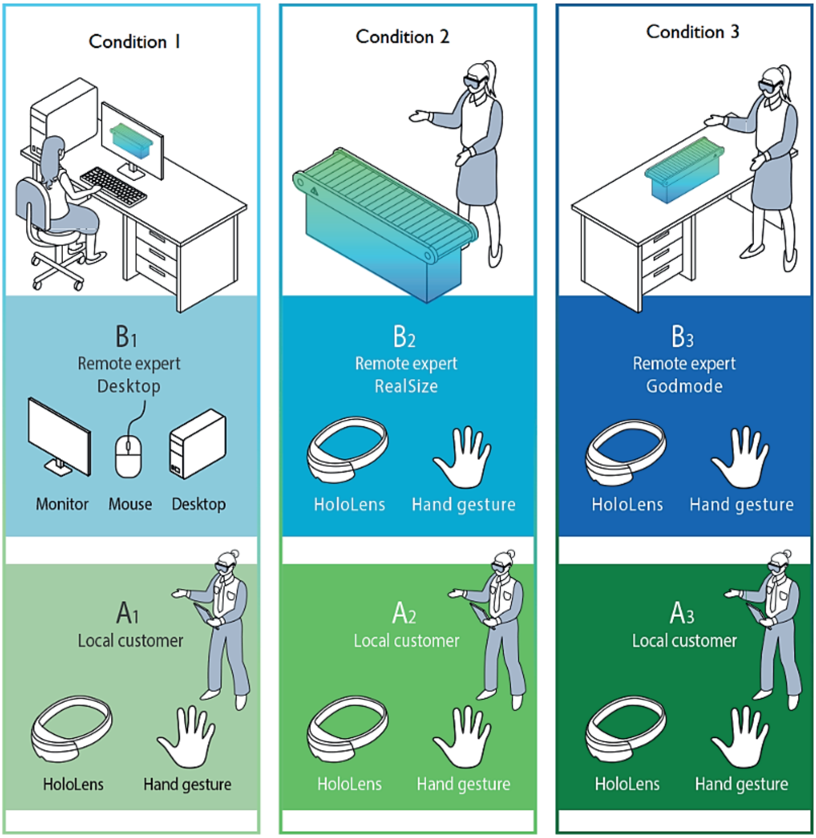


Figure 6.13 The AR workspace with 3 conditions of interactions. The color code and the name of the conditions will be used in the data analysis.

Interaction

The researchers developed three AR interfaces to co-locate the remote expert in the co-creation activities. The interactions of these interfaces on both the remote and local sides are presented respectively in each case (Figure 6.14). Three conditions of these interactions are named: **Desktop**, AR **RealSize**, and AR **GodMode**.

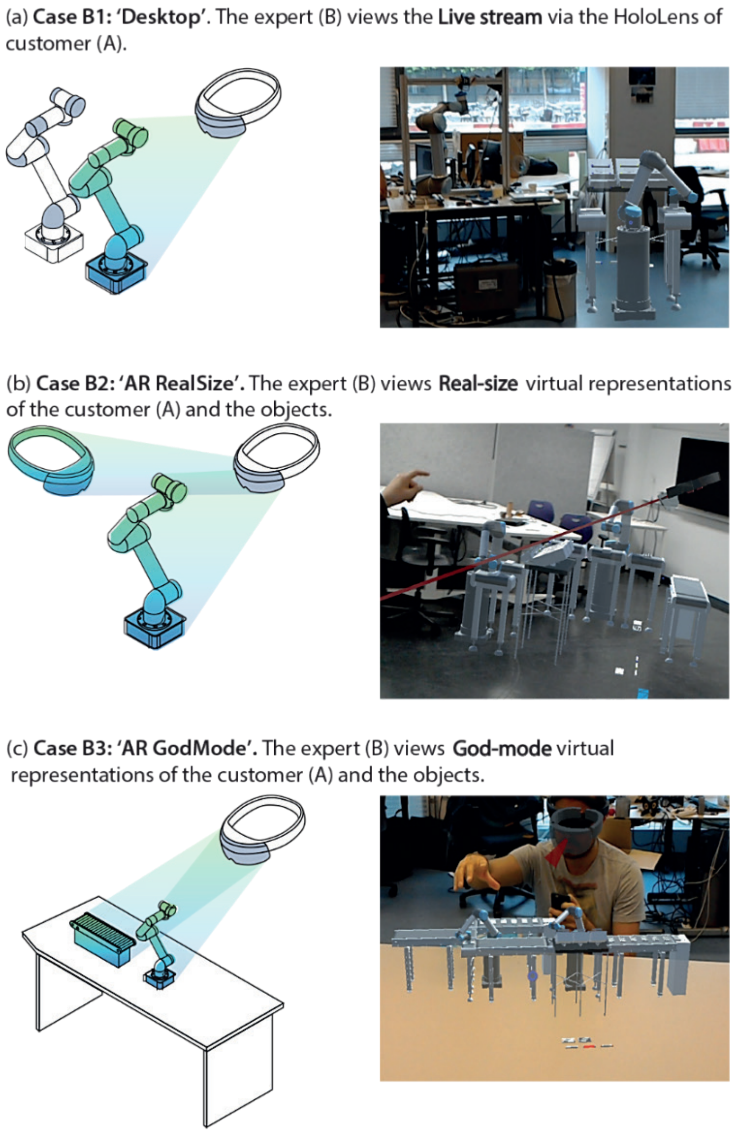


Figure 6.14 The different conditions of the interactions in schematic visualizations and screenshots.

Case B1: The **'Desktop'** interface provides the remote expert with a "similar" perspective as the local person by sharing a video stream of their first-person view (Figure 6.14a). This interface demonstrates the virtual objects in the local context but is limited by 2D visualization and passive viewpoint control (Lukosch, Lukosch, et al., 2015b). To generate comparable results of the user study, it is preferred to keep the video consistent for each participant. Therefore, the viewpoint of a researcher acting in the consultant (R) role was used. The expert could see both the real and virtual scenes on a 2D screen and interact with the objects using a mouse to click its menu.

Case B2: The **AR 'RealSize'** interface shares the real-time spatial distribution of real-size virtual objects with the remote expert (Figure 6.14b). This condition benefits the precise spatial analysis but might require large physical spaces (Brown et al., 2003). The expert could see the virtual workspace and the representations of the customer in his/her place through the HoloLens. He/she interacts with virtual objects using hand gestures.

Case B3: The **AR 'GodMode'** interface offers a puppet-size overview of the same scene in the 'RealSize' condition for the remote expert (Figure 6.14c). This condition serves as a fundamental function of desktop CADs but is less studied in AR (Stafford & Piekarski, 2008). The expert interacts with the objects like in the 'RealSize' condition.

Sensory

The local persons: the *customer (A)* and the *consultant (R)* both wear *Microsoft HoloLens 1* headsets (1280 x 720 pixels per eye with a 34-degree field-of-view) to co-locate collaborators and manipulate the same set of virtual objects (Microsoft, 2020). They can perceive 3D-vision feedback.

The remote person: the expert in **Case B1 'Desktop'** achieved the viewing capability through the *Mixed Reality Capture* functionality, viewing the scenario from a web browser on a laptop. Thus, there is only 2D vision feedback for the expert. The expert in **Case B2 'RealSize'** and **Case B3 'GodMode'** both use *HoloLens v1* headsets and have the same 3D-vision feedback as the local persons.

The HoloLens headsets and the laptop were connected to the same Wi-Fi to synchronize the data stream. An instant messenger was used to make a voice call between the collaborators.

Involvement

Though either the AR headsets or the web browser cannot isolate the persons from their environments, the asymmetric task design could engage them in real-time communication and frequent interactions. The hand gestures and vocal commands replaced visual UI and helped the persons to focus on their tasks.

6.1.4. *User study*

Participants

Thirty design students and professionals voluntarily participated in this study. Their mean age was 32.4 years (SD=11.6) and the male/female ratio was 1:2. Their average years of design experience was 3.17. The participants were randomly assigned the 'customer' or the 'expert' roles in each test. The role of 'customer' was 4.74 years of design experience, and the 'expert' was 1.60 years. Eighteen participants had experiences with CAD, robot modeling, or production planning software, and eleven of them played the role of the 'customer'.

Measurements

The *immersive tendency* demonstrates a natural likelihood of a person becoming highly immersed in media, like a book, film, or game. It was measured by the *Immersive Tendencies Questionnaire* (ITQ) from Witmer and Singer (1998), which included a 7-point scale to indicate four factors of the immersive tendencies and their total from low to high (1= never; 7= often).

Task load represents the perceived workload when interacting with these AR interfaces. To measure task load, the *NASA-TLX* was applied by Hart and Staveland (1988). NASA-TLX is a classic, subjective, multidimensional measurement to assess a team's effectiveness and other aspects of performance, particularly AR-supported operations (Aschenbrenner et al., 2019). The participants rated their *mental*, *physical*, and *temporal* demands, as well as the *effort*, *performance,* and *frustration* after the tasks. The *Raw Task Load Index* (RTLX) and subscales were calculated with their raw data between 0 and 20 (0= low, 20= high) (Hart, 2006).

Intuitiveness, in other words, applying prior knowledge without effort, was evaluated via the *Questionnaire for Intuitive Use* (QUESI) (Naumann & Hurtienne, 2010). Researchers have applied QUESI in different sections, including manufacturing, to quantify the intuitiveness of immersive environments (Saalfeld et al., 2015). This assessment asked if an interface appears intuitive and satisfying using a 5-point Likert scale (1= fully disagree, 5= fully agree). The sub-factors of QUESI are *low subjective mental workload* (Workload), *high perceived achievement of goals* (Goals), *low perceived effort of learning* (Learning), *high familiarity* (Familiarity), and *low perceived error rate* (Error rate).

To measure the presence, a *Presence Questionnaire* (PQ) was used (Witmer & Singer, 1998). PQ is a well-acknowledged and standardized tool to assess the perceived immersion of an immersive experience, which has been evaluated in hundreds of virtual reality, mixed reality, and augmented reality applications (Aschenbrenner et al., 2019; Kim et al., 2012; Li et al., 2020). PQ included nineteen questions with 7-point scales to assess the presence and its sub-factors like *realism*, *possibility to act*, *quality of interface*, *possibility of examine*, and *performance* from low to high (1= not at all, 7= completely).

Situation awareness (SA) was investigated using the *Situation Awareness Rating Technique* (SART) (Taylor, 2011). SART uses ten dimensions to measure three aspects of SA, like *understanding the situation*, *attentional demands*, and *attentional supply*. SART asked each participant to rate each dimension from low to high on a 7-point scale (1= low, 7= high). The total SART and its factors were calculated according to Taylor (2011).

Procedure

This study applied a between-subject design and performed five runs for each of the three conditions ('Desktop', 'GodMode', and 'RealSize'). Each run took approximately one hour with a pair of participants (one as the *customer* and one as the *expert*), and two researchers (one as the *consultant*, while another assisted the expert). Throughout the test, the two participants were separated by a physical wall to simulate the remote collaboration situation. A predefined testing protocol was developed, including an introduction, a video of the background, communication scripts for customers and experts, and scripts for the researchers. The experiment followed the steps as marked by the numbers in Figure 6.15 after a welcome and informed consent session:

1) First, the two participants were asked to fill in pre-test questionnaires (gender, age, design experience, etc.) and the ITQ.
2) They received a standardized introduction individually, including the scripts of their roles. The customers watched the video detailing the production operations (as in Figure 6.12 a) to ensure they had the same knowledge about the planning task.
3) The participants were trained to use the HoloLens with the standard Microsoft tutorial provided in HoloLens 1 and then had a free try-out of the AR application.
4) When a test began, the customer called the expert to explain the planning task. The expert listened to the description and asked several questions according to the script. The communication created a realistic experience, so that the expert decided upon the objects for this production line, and then showed them to the local people. The local people discussed and manipulated the objects concerning the real space, while the expert watched the scene and was able to show/hide/animate an object when the customer requested. The agreement between the customer and the expert on the layout of the line was the end of the task.

5) After the planning task, the participants filled out four questionnaires, measuring the task load (NASA-TLX), intuitiveness (QUESI), presence (PQ), and situation awareness (SART).
6) Lastly, each researcher undertook a debriefing with the associated participant and noted oral comments.

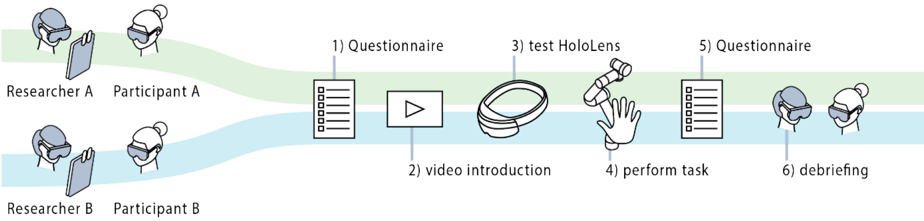


Figure 6.15 In the steps of the experiment, Researcher A and Participant A are separated from Researcher B and Participant B by a physical barrier, they communicate via phone.

Data Analysis

The normal distribution of the data sets is firstly examined via the Shapiro-Wilk test (Shapiro & Wilk, 1965) with $\alpha = 0.05$. If significant, non-parametric analysis is applied. The medians (*m*) for each measurement have been computed. For comparison, ANOVA tests (parametric) or Kruskal-Wallis tests (non-parametric). If the tests showed the results with $p < 0.01$, $p < 0.05$, or $p < 0.10$ (the last is considered as a mere indication), the researchers give the *F*-statistics, the corresponding *p*-values, as well as the effect-size $\omega 2$. Afterward, the researchers made pairwise comparisons of each condition using the Bonferroni correction (Abdi, 2007). All results will be presented rounded to two decimal places, only *p* values will be shown with three decimal places to show values below 0.01. The significances in figures and tables are marked as '**' ($p < 0.01$), '*' ($p < 0.05$), and '†' ($p < 0.1$).

For data visualization, the researchers use box plots from the Seaborn Library1[1]. The box extends from the Q1 to Q3 quantile values of the data, with a line at the m (Q2). The whiskers extend from the edges of a box to show the range of the data. The researchers use the same colors and naming system as introduced in Figure 6.13.

1 https://seaborn.pydata.org/

6.1.5. Results

Remote Experts Preferred Interfaces for Spatial Collaboration

This section compares the expert's conditions, where the difference in the interface has been made between them: 'Desktop', 'RealSize', and 'GodMode' (Figure 6.16).

Immersive Tendency

Figure 6.16a displays the immersive tendencies between the experts. There appeared no significant differences, and the medians ranged from 84 (RealSize) to 86 (Desktop) and 88 (GodMode). The sub-factors of immersive tendencies were not significant either. On the sub-factor *Focus*, Desktop (*m*= 25.00) was slightly higher than RealSize (*m*= 23.00) and GodMode (*m*= 22.00). On the sub-factor *Implication*, GodMode (*m*= 27.00) was higher than Desktop (*m*= 25.00) and RealSize (*m*= 23.00). On the sub-factor *Emotions*, Desktop (*m*= 20.00) and RealSize (m= 19.00) were slightly higher than GodMode (*m*= 17.00). On the sub-factor *Game*, Desktop and GodMode were the same (*m*= 12.00), and both were higher than RealSize (*m*= 7.00).

Task load

Figure 6.16b displayed a medium level of task loads in the three AR interfaces for remote experts. Desktop (*m*= 8.50) had the highest RTLX value, while RealSize (*m*= 4.67) had the lowest one, with GodMode (*m*= 5.50) in between. The differences were not significant. All sub-factors were again not significant. Desktop had the highest workload on *Mental Demand* (*m*= 8.00), *Physical Demand* (*m*= 6.00), and *Temporal Demand* (*m*= 10.00). GodMode (*m*= 5.00) has a slightly higher *Mental Demand* than RealSize (*m*= 4.00). On *Physical Demand* and *Temporal Demand*, the rates of RealSize ($m_{Physical}$= 3.00; $m_{Temporal}$ = 4.00) were higher than GodMode (*m*= 2.00). On *Performance*, Desktop (*m*= 12.00) had higher rates than GodMode (*m*= 8.00) and RealSize (*m*= 4.00). Regarding *Effort*, Desktop (*m*= 7.00) was also higher than GodMode (*m*= 6.00) and RealSize (m= 5.00). Regarding *Frustration*, Desktop (*m*= 9.00) was the highest compared to GodMode (*m*= 5.00) and RealSize (*m*= 4.00).

Usability

An overview of the QUESI rates is displayed in Figure 6.16c. Realize (*m*= 3.33) was the most intuitive and GodMode (*m*= 2.80) was the least, with Desktop (*m*= 3.20) in the middle. The ANOVA test was not significant. The four sub-factors were also not significant. On the sub-factor *Workload*, Desktop and Realize were the same (*m*= 3.33), and both were slightly higher than GodMode (*m*= 3.00). On the sub-factor *Error rate*, Desktop and GodMode (*m*= 3.00) had the same rates, and both were higher than RealSize (*m*= 2.50). On the sub-factor *Goals*, GodMode (*m*= 4.00) was the highest followed by Desktop (*m*= 3.67) and RealSize (*m*= 3.33). On sub-factor *Learning*, RealSize (*m*= 3.67) was higher than Desktop (*m*= 3.33) and GodMode (*m*= 2.00). The ANOVA test was only significantly different with the sub-factor *Familiarity* as in Figure 6.16d. The results of pairwise comparisons can be found below:

Familiarity ANOVA ($p = 0.02; F\,(2.0, 12.0) = 5.32, and\ \omega 2 = 0.37$):

'GodeMode' (*m*= 2.00) was significantly lower than 'Desktop' (*m*= 3.33; $p < 0.10$, $F = 4.74$) as well as 'RealSize' (*m*= 4.00; $p < 0.01$, $F = 15.47$).

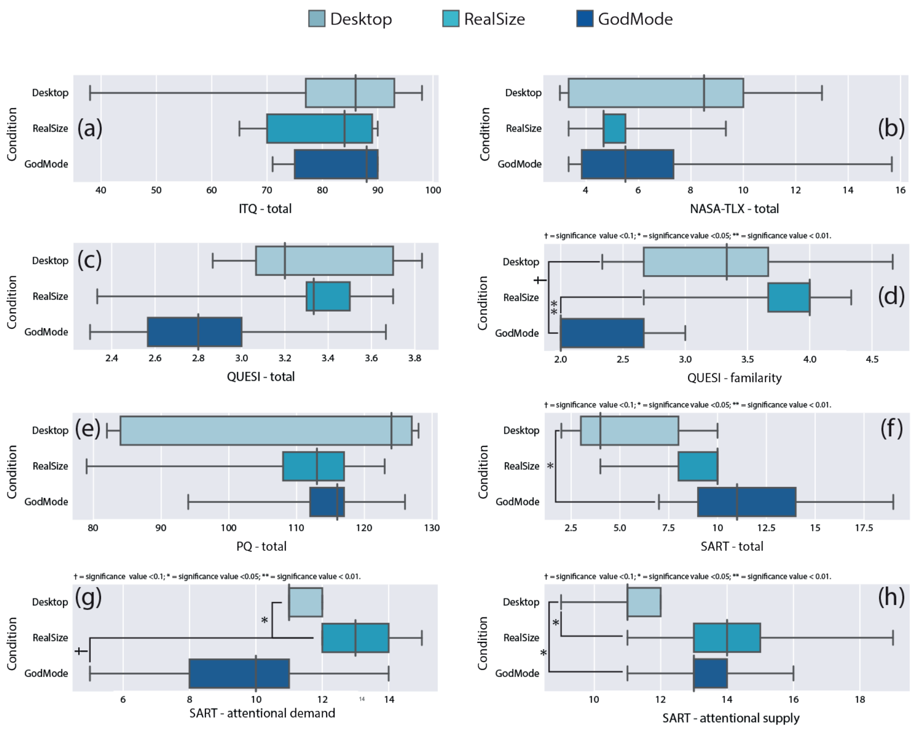


Figure 6.16 Results for the expert conditions on a) immersive tendencies (ITQ), b) NASA-TLX, c) QUESI, d) QUESI familiarity, e) PQ, f) SART, g) SART attentional demand, and h) SART attentional supply.

Presence

Figure 6.16e showed the results of the presence of the remote experts, and the ANOVA test was not significant. The Desktop had the highest rate (*m*= 124.00), while GodMode (*m*= 116.00) and RealSize (*m*= 113.00) had similar levels of immersion. The sub-factors were not significantly different either. On *Realism*, Desktop (*m*= 38.00) was higher than GodMode (m= 32.00) and RealSize (m= 30.00). About *Possibility to Act*, Desktop and GodMode had the same rates (m= 21.00) and were slightly higher than RealSize (m= 20.00). Regarding the *Quality of Interface,* RealSize (m= 13.00), Desktop (m= 12.00) and GodMode (m= 11.00) had similar rates. Considering the *Possibility of Examine*, GodMode (m= 15.00) was slightly higher than Desktop and RealSize (m= 13.00). And about *Performance*, RealSize and GodMode (m= 11.00) were both higher than Desktop (m= 10.00).

Situation Awareness

The results of the SART can be found in Figure 6.16f. The ANOVA test was significant. The sub-factors 'Attentional Demand' and 'Attentional Supply' had an indication of significant differences displayed in Figure 6.16g and Figure 6.16h. The sub-factor 'Understanding' was again not significantly different, with GodMode (m= 8.00) having a higher value than Desktop (m= 5.00) and *RealSize* (m= 6.00). The pairwise comparisons were summarized below:

6

Total Situation Awareness ANOVA ($p = 0.046$; $F (2.0, 12.0) = 4.03$, and $\omega2 = 0.29$):

'GodMode' (m= 11.00) had a significantly higher value than 'Desktop' ($m = 4.00$; $p < 0.05$, $F = 6.44$).

Attentional Demand ANOVA ($p = 0.06$; $F (2.0, 12.0) = 3.65$, and $\omega2 = 0.26$):

'RealSize' (m= 13.00) had a significantly higher value than 'Desktop' (m= 11.00; $p < 0.05$, $F = 8.10$) and 'GodMode' (m= 10.00; $p < 0.10$, $F = 4.98$).

Attentional Supply ANOVA ($p = 0.07$; $F (2.0, 12.0) = 3.37$, $\omega2 = 0.24$):

'Desktop' (m= 11.00) had a significantly lower value than 'RealSize' (m= 14.00; $p < 0.05$, $F = 5.61$) as well as the 'GodMode' (m= 13.00; $p < 0.05$, $F = 6.00$).

Summary of expert conditions comparison

Within the comparison of the remote expert conditions, there were no significant improvements in an AR interface:

- The three interfaces showed no significant differences regarding overall task load, usability, and presence, as well as on most sub-factors. The sub-factor *Familiarity* of usability showed a significant unfamiliarity in the 'GodMode' condition.

The remote experts valued most aspects of co-location are:

- The overall situation awareness showed a significantly high value for GodMode, which had low attentional demand and high attentional supply for a slightly better level of understanding.
- On the sub-factors, the RealSize condition seemed to have the lowest amount of *attentional demand*, while the RealSize and GodMode conditions seemed to have a higher amount of *attentional supply*.

The Effects on Collaborative Experience for Local Customers

This section investigated the differences in the local conditions (Figure 6.17), who teamed up the remote experts via different AR interfaces, like **Local1** with Desktop, **Local2** with Realize, and **Local3** with GodMode.

Immersive Tendency

Figure 6.17a showed the differences between the local conditions on the immersive tendencies (Local1 *m*= 84.00; Local2 *m*= 85.00; Local3 *m*= 77.00), which were not significant. Also, the analysis of the sub-factors didn't yield significant differences, like *Focus* (Local1 *m*= 26.00; Local2 *m*= 27.00; Local3 *m*= 23.00); *Implication* (Local1= Local2 *m*= 25.00; Local3 *m*= 23.00), *Emotions* (Local1 = Local2 = Local3 *m*= 19.00), and *Game* (Local1 *m*= 9.00; Local2 *m*= 10.00; Local3 *m*= 11.00).

Task Load

Figure 6.17b showed the ANOVA test of the total task load between local conditions, which indicated a significant difference, as well as the sub-factor *Frustration* in Figure 6.17c. The sub-factor 'Temporal Demand' was significantly different (Figure 6.17d). The other sub-factors were not significant, like *Mental Demand* (Local1 *m*= 10.00; Local2 *m*= 4.50; Local3 *m*= 9.00), *Physical Demand* (Local1 *m*= 10.00; Local2 *m*= 4.50; Local3 *m*= 4.00), *Performance* (Local1 *m*= 12.00; Local2 *m*= 12.50; Local3 *m*= 5.00), and *Effort* (Local1 *m*= 12.00; Local2 *m*= 8.00; Local3 *m*= 6.00). The pairwise comparisons were shown as follows:

Total Task Load ANOVA ($p = 0.08$, $F(2.0, 12.0) = 3.13$, and $\omega 2 = 0.22$):

Local3 (*m*= 5.00) was significantly lower than Local1 (*m*= 10.67; $p < 0.05$, $F = 6.21$).

Frustration ANOVA ($p = 0.05$, $F(2.0, 12.0) = 3.84$, *and* $\omega 2 = 0.27$):

Local3 (m= 7.00) was significantly lower than Local2 (m= 15.00; $p < 0.05$, $F = 10.69$).

Temporal Demand ANOVA ($p = 0.015$, $F(2.0, 12.0) = 6.09$, *and* $\omega 2 = 0.40$):

Local3 (m= 5.00) was significantly lower than Local2 (m= 10.00; $p < 0.05$, $F = 7.71$) and 'Local1' ($m = 13.00$; $p < 0.01$, $F = 18.16$).

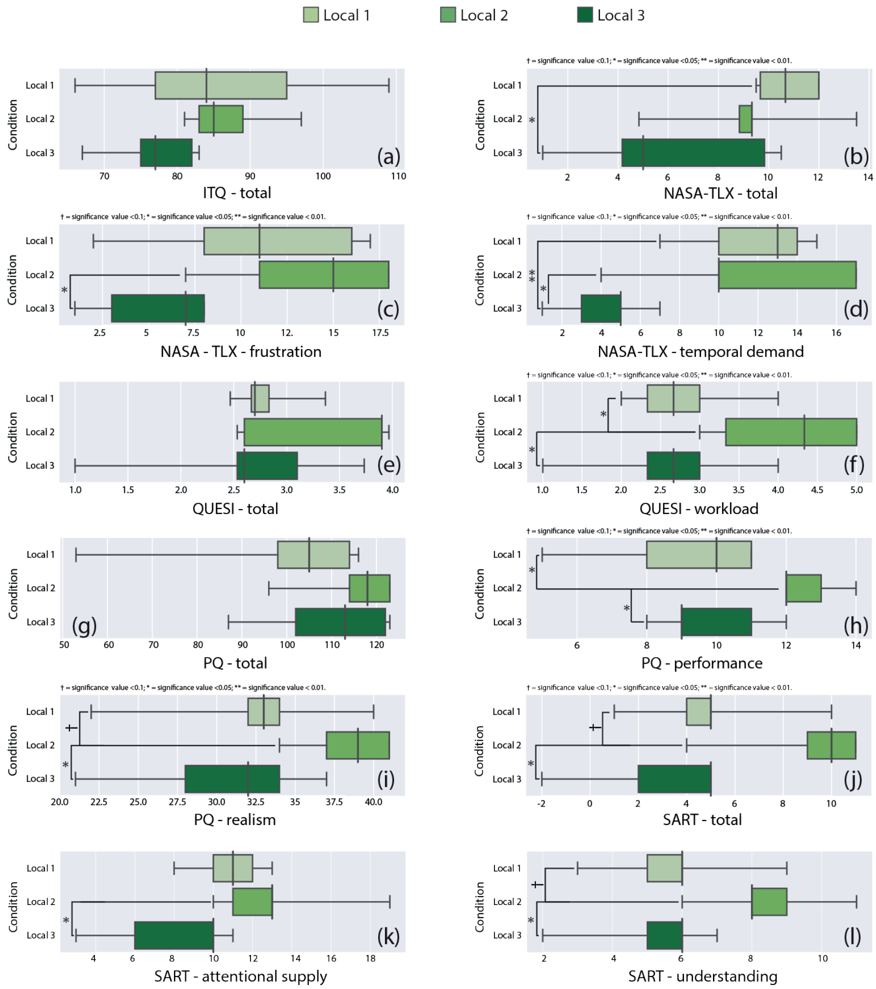


Figure 6.17 Results for the local customers, where 'Local1' with Desktop, Local2 with RealSize, and Local3 with 'GodMode'. Results on a) the immersive tendencies (ITQ), b) NASA-TLX, c) NASA-TLX frustration, d) NASA-TLX temporal demand, e) QUESI, f) QUESI workload, g) PQ, h) PQ performance, i) PQ realism, j) SART, k) SART attentional supply, and l) SART understanding.

Usability
Figure 6.17e displayed that the QUESI results among the local conditions were not significant. The results of the sub-factor 'workload' were significantly different as displayed in Figure 6.17f. The rest of the sub-factors were not significant, like *Goals* (Local1 *m*= 3.00; Local2 = Local3 *m*= 2.67), *Learning* (Local1 *m*= 3.00; Local2 *m*= 3.50; Local3 *m*= 3.67), *Familiarity* (Local1 *m*= 3.33; Local2 *m*= 3.83; Local3 *m*= 3.17), and *Error rate* (Local1 *m*= 2.50; Local2 *m*= 2.00; Local3 *m*= 2.85). The pairwise comparison showed significant results as follows:

> **Workload** ANOVA ($p = 0.0483$, $F (2.0, 12.0) = 3.94$, and $\omega 2 = 0.28$):
>
> Local2 (*m*= 4.33) was significantly higher than Local1 (*m*= 2.67; $p < 0.05$, $F = 6.11$) and Local3 (*m*= 2.67; $p < 0.05$, $F = 5.72$).

Presence
Figure 6.17g showed the comparison of the overall presence between the local conditions (Local1 *m*= 105; Local2 *m*= 118; Local3 *m*= 113), which was not significant. The sub-factor *Performance* was significant, as displayed in Figure 6.17h. The sub-factor *Realism* indicated a significant difference (Figure 6.17i). Some sub-factors were again not significant, including *Possibility to Act* (Local1 *m*= 18.00; Local2 *m*= 19.00; Local3 *m*= 17.00), *Quality of Interface* (Local1 *m*= 13.00; Local2 *m*= 11.00; Local3 *m*= 12.00), and *Possibility to Examine* (Local1 *m*= 14.00; Local2 *m*= 12.00; Local3 *m*= 17.00). The results of the pairwise comparisons can be found below:

> **Performance** ANOVA ($p = 0.02$; $F (2.0, 12.0) = 5.36$ and $\omega 2 = 0.37$):
>
> Local2 (*m*= 12.00) was significantly higher than Local1 (*m*= 10.00; $p < 0.05$, $F= 8.87$) and Local3 (*m*= 9.00; $p < 0.05$, $F= 11.20$).
>
> **Realism** ANOVA ($p = 0.090$; $F (2.0, 12.0) = 2.96$ and $\omega 2 = 0.21$):
>
> Local2 (*m*= 39.00) was significantly higher than Local1 (*m*= 33.00; $p < 0.1$, $F= 8.87$) and Local3 (*m*= 32.00; $p < 0.05$, $F= 6.79$).

Situation Awareness
Figure 6.17j displayed the self-reported situation awareness of the local persons. The ANOVA test of the overall comparison was significant. For sub-factors 'Attentional Supply' and 'Understanding', there were indications of significant differences. Figure 6.17k and Figure 6.17l displayed their results. The sub-factor 'Attentional Demand' had

the same value on these conditions (Local1 = Local2 = Local3 *m*= 11.00). The pairwise comparisons were given as follows:

Total Situation Awareness ANOVA ($p = 0.03$; $F(2.0, 12.0) = 4.91$, and $\omega 2 = 0.34$): Local2 (*m*= 10.00) was significantly higher than Local1 (m= 5.00; $p < 0.10$, $F = 4.21$) and Local3 (m= 5.00; $p < 0.05$, $F= 10.00$).

Attentional Supply ANOVA ($p = 0.06$, $F(2.0, 12.0) = 3.71$, and $\omega 2 = 0.27$):

Local2 (*m*= 13.00) was significantly higher Local3 (*m*= 10.00; $p < 0.05$ and $F = 4.23$).

Understanding ANOVA ($p = 0.06$; $F(2.0, 12.0) = 3.71$, and $\omega 2 = 0.27$):

Local2 (*m*= 8.00) was significantly higher than Local1 (*m*= 6.00; $p < 0.10$, $F= 4.21$) and Local3 (*m*= 6.00; $p < 0.05$, $F = 7.31$).

6

Summary of local conditions comparison
The comparison among the local conditions is interesting because all of them use the same interface, nevertheless, significant differences can be measured:

The local customers did perceive significant differences or indications when teamed up with remote experts using different interfaces:

- For the overall *task load*, Local3 (with GodMode) seemed to be significantly lower than Local1 (with Desktop). On the sub-factor *Frustration*, Local3 (with GodMode) was significantly lower than Local2 (with RealSize). On the sub-factor *Temporal Demand*, Local3 (with GodMode) had a significant advantage over the other two.
- In the *presence*'s the sub-factor *Realism* and *Performance*, the Local2 (with GodMode) condition was superior to other conditions. However, on *usability*'s sub-factor *Workload*, Local2 was the highest.

The local customers valued most aspects regarding co-location:

- On overall *situation awareness*, the Local2 condition had a significant advantage over the others.
- Local2 condition also indicated significant advantages on situation awareness's sub-factors *Attentional Supply* and *Understanding*.

General Summary

From the oral briefing, the participants reflected that the realistic scenario engaged them to work together and motivated them to finish the task. Many participants of the local side complained about fatigue and discomfort as they had to continuously look up and down because the parts in real size easily exceeded the Field-Of-View (FOV) of the HoloLens 1. The interaction protocol of vocal and hand gestures in HoloLens is hard to control for first-time users and prone to slips. For example, the local customer had problems moving virtual parts around thus led to delay, or the expert could not activate or deactivate features correctly. Therefore, the observed error rate was higher than the usual desktop interaction.

To maintain an overview for the following discussion, Table 6.11 summarizes all results from this section. In the expert-condition comparisons, the situation awareness measurements were significantly different in the AR interfaces, where GodMode was significantly higher than the other two conditions. The RealSize and GodMode had significantly higher attentional supply rates than the desktop condition.

Table 6.11 Overview of all significant results

Main factors	p	Sub-factors	p
Expert			
ITQ	ns.	none	ns.
TLX	ns.	none	ns.
QUESI	ns.	Familiarity	< 0.05
Presence	ns.	none	ns.
SART	< 0.05	Attentional Supply	< 0.1
		Attentional Demand	< 0.1
Local			
ITQ	ns.	none	ns.
TLX	< 0.1	Frustration	< 0.05
		Temporal Demand	< 0.05
QUESI	ns.	Workload	< 0.05
Presence	ns.	Realism	< 0.1
		Performance	< 0.05
SART	< 0.05	Attentional Supply	< 0.1
		Understanding	< 0.1

The AR interfaces on the remote user side could influence the experiences of the local user, significant differences showed in every measurement, for instance:

- For the task load, Local3 (with GodMode) had a significantly lower *Temporal Demand* than Local1 (with Desktop) and Local2 (with RealSize). It had a significantly lower *Frustration* rate than Local2.
- As for usability, Local2 (with RealSize) was significantly higher in *workload* rate than Local1 (with Desktop) and Local3 (with GodMode).
- For presence, Local2 (with RealSize) had a significantly higher *Performance* rate than the other two, and it had a significantly higher rate of *Realism* on Local3 (with GodMode).

6.1.6. Discussion

Realistic context matters

The realistic scenario investigated in this study helps understand collaborative AR interfaces under true-to-life contexts. The realistic task simulation would increase the participant's engagement and motivation in tasks (Li et al., 2020). The sizes and layouts matter in a real factory planning task, which is less mentioned in the studies with simple tasks like Lego blocks. Using large-scale parts is also associated with the comfort of AR interfaces, in which limited FOV causes continuous head and body movements that may easily trigger fatigue and discomfort. Comfort has always been a core issue of XR interfaces in their implementation (Li et al., 2020), and could be an interesting topic for the follow-up studies. Although the setting of this experiment is quite complex, the researchers advocate for more studies under realistic contexts to develop efficient AR interaction for complex techno-social environments. In the presented lab study, the researchers still chose a controlled environment to ensure repeatability, and critical issues like time zone differences only appear in real-world settings.

RealSize versus GodMode: better for spatial information?

In addition to the findings mentioned above, the remote condition RealSize itself has the highest familiarity value among all expert conditions and a significantly higher value on Familiarity than the GodMode (Figure 6.16c). It also has a higher overall situation awareness rate than Local3 (with GodMode). But the RealSize condition sticks out for the situation awareness sub-factors as well. It has the overall highest attentional demand value and a significantly higher attentional supply value compared to the conditions Desktop (Figure 6.16g).

The GodMode created a significantly higher attentional supply across all conditions. Maybe due to a better overview, GodMode also provides a significantly higher overall situation awareness than the Desktop condition. As explained above, its team Local3 has significantly lower temporal demand, and the same goes for the frustration value and the overall task load. But compared to the other local persons, Local3 (with GodMode) has less attentional supply and lower overall situation awareness. Furthermore, its rate on 'Familiarity' for usability was the lowest (Figure 6.16d).

The researchers derive from these contradictory findings that both RealSize and GodMode have their advantages and limitations. On the one hand, the RealSize interface is well suited for communicating spatial information, and users perceive a high familiarity and usability, it's hard to keep the overview. On the other hand, the GodMode allows the user to zoom out to get a better overview. The participant's comments in the debriefing also confirmed that they benefited from seeing the whole scene immediately. Still, the different perspective of the remote user limits the understanding (and thus the attentional supply) of the local user. The collaboration and communication quality are improved by the interfaces' ability to share self-referenced spatial information and gaze direction and hand gestures (Bai et al., 2020). The optimal AR interface can switch between real-size and god-mode to fit the shift of abstraction in design cognition during planning processes (Gero & Mc Neill, 1998).

Expert interfaces affect local perception

The main finding of this study is the interface of the remote ends might influence the human factors on local ends, as shown by the results in the previous section. The immersive AR interfaces of remote experts, either with the RealSize or GodMode condition, increase the local workers' measured usability. So, the same interface on the local side has different usability when collaborating with experts via a different interface, especially affecting the *workload* factor. The RealSize interfaces that mutually share the gaze beams and hand postures to both experts and locals might help to limit the time pressure, and thus reduce the frustration (Bai et al., 2020).

In earlier studies (Aschenbrenner et al., 2019), the researchers found that AR applications have a positive effect when used in a collaborative setting. While the study merely compared the interface type used on the local side, the researchers found that a less recent AR HMD led to lower scores on usability than other methods like a tablet PC with an AR application. As both study settings differ, the researchers cannot draw a direct conclusion. Still, the researchers can speculate that in the case of a less advanced AR HMD like in the older study, the usability of the device overwrites the interface's usability. Furthermore, both tasks are different, although both communicate spatial information. Whereas the older study's maintenance task operates on a relatively small scale in a switch cabinet, the factory planning task discussed in this study operates at a room-scale.

Next to providing better usability, the remote interface also affects the situation awareness of the local user. The RealSize interface used by the remote expert created the highest overall situation awareness and attentional supply at the pairing Local2 condition. The users with this condition also experienced a significantly higher understanding and attentional supply value than the Local3 (with the GodMode). These differences are interesting because the interface could not provide more information elements (it was in both cases the same). The researchers assume that the expert side's AR interfaces helped communicate space-related information to the local user better. This is supported by other findings, like that the Local3 condition (with GodMode) had a significantly lower temporal demand and indications of a lower frustration value and overall task load. As the interface of all local conditions is the same, the effect needs to come from the interaction.

The researchers discovered a similar finding concerning the presence measurements. It was exciting that Local2 (with RealSize) experienced differences in various presence sub-factors: for the sub-factor r*ealism*, it is only an indication, whereas, for the sub-factor *performance*, it is a significant difference. As performance is connected to the task, this aspect could be derived from the already explained differences in usability and situation awareness. However, the researchers cannot easily explain the differences in 'Realism'. The researchers assume that the communication of the expert user with the 'RealSize' condition might have included more specific spatial references (especially with "to your right / to your left"), which might have increased the feeling of realism for the local user. This alignment of spatial references was possible because the remote expert experienced the scenario just like the local customer did.

Whereas the local user profited from the AR experience of the remote expert, the participants using the AR experience on the remote location did not share their feelings. On the 'Desktop' interface condition, the usability aspects 'Goals' and 'Familiarity' received the highest score. As people are used to desktop applications, the interface is more familiar to them, which is a similar result as in a previous study of the *Factory in a Day* project (Dukalski et al., 2017).

Limitations and future work

First, the researchers want to mention the issues that prevented the experiment's more comparable task execution. Participants showed a highly different ability to operate the interfaces smoothly and efficiently. Thus, the researchers didn't use the task completion, number of errors, or task duration as the researchers initially planned.

Better-designed familiarization protocol. The users were unfamiliar with the interfaces and the task, which required a long training time that overlapped too much with the experiment operation. Although the researchers provided a training sequence and briefing phase, each participant needed a different time to adjust. In the next iteration of this or another study, the researchers would need an individual "familiarization" phase where no user is under stress from the other participant (both need to be ready for the same time slot). In addition to a more extended familiarization phase, a failure and error protocol should be introduced in future studies to collect valid performance data.

Better network control. Furthermore, the experiments suffered from technical problems, such as the stream feed resolution and latency, which were affected by the Wi-Fi connection between the two sides. Therefore, reliable measurements of task duration would require a better training setup. Furthermore, it would be helpful to monitor and adjust the network quality during the experiment, allowing latency as a dependent variable.

Domain-savvy participants. As the participants of this study mainly were design students who have a different mental model as experienced designers (Cross, 2001), the needs of immersive interfaces for experienced professionals can be very different from the current study (Li et al., 2021). Besides, some participants were completely overwhelmed by the idea of robot manufacturing and had problems understanding the context quickly. Therefore, in future studies, the experts who have domain knowledge should be included as participants, the same as the novices. Moreover, a larger sample size is needed to ensure the normal distribution of the data under each condition.

Measurement of mental model alignment. The researchers discovered that video or audio taping might provide deeper and more critical insights into the mental model alignment in an AR collaboration. The researchers got many valuable insights during the debriefings, but the experiment would benefit from a more thorough analysis of the qualitative findings, such as thematic analysis or protocol analysis. Furthermore, the initial mental model of the expert should have been better calibrated to ensure that they have acquired enough process knowledge during the briefing.

Different measurement methods for situation awareness. The interaction between the customer and expert roles was still limited, as both participants were occupied with their tasks. It might be good to measure additional situation awareness with questions during the experiment (like the local persons standing now? What have they done last?). Still, the researchers decided against a freeze probe technique because the researchers initially wanted to measure task duration.

6.1.7. Conclusion on AR co-location in the co-creating a factory line

This study conducted a collaborative Augmented Reality task with co-location between two collaborators, the remote expert, and the local customer. The scenario is derived from a real-world factory planning task, and it is schematically depicted in Figure 6.11. In this setup, the two users were virtually co-located in the same co-creating workspace with the help of AR. The study compared three different interfaces for AR visualization on the expert side: the Desktop, RealSize, and GodMode conditions.

Our results generate the following insights into co-creating a robotic production line via AR interfaces:

1. The AR interfaces have the benefit of communicating space-related information efficiently. Hence, the AR interfaces add value to the tasks in which the space information plays an important role, usually missing in simplified tasks.
2. Sharing natural interactions, such as gaze direction and hand gestures, helps to increase the perception of co-location within remote teams.
3. The optimal AR interfaces for real-world tasks should support a smooth switch between real-size and god mode. Moreover, the suitable proportion of the AR interface is the shared workspaces that need to be seen immediately within the field-of-view of AR headsets.
4. Realistic scenarios are valuable to investigate the AR interactions to collect true-to-life insights. However, keeping the balance between realism and complexity is critical to collecting valid data. The researchers recommend recording qualitative and quantitative data for a comprehensive understanding. A test protocol should be defined and validated beforehand to calibrate the participants and the setup.

As shared collaboration has been becoming the new normal, factories intend to adopt more and more new technologies to cope with the situation. From this study, the researchers can infer how the AR interface could information sharing during remote co-creation. Therefore, the application is promising for large-scale factory planning tasks, as shown in the studied robotic production line planning.

6.2. Two-way Augmented Reality Co-Location under Telemedicine Context

Figure 6.21 Two-way AR service concept in marine medical care

6.2.1. *Introduction*

As the International Maritime Organization (IMO) emphasizes, medical care is a substantial part of the onboard safety operation (IMO, 2018). Doctors are only available for large commercial vessels with more than a hundred crews, so medical training of seafarers is of paramount importance. Despite the emphasis on medical care and safety, the first aid and medical training for officers (captains and first mates) are only forty hours every five years (Sekimizu, 2010). The limited amount of training neither equips enough skills to handle on-board medical care independently nor releases stress when handling first aid. Mobile training apps thus were applied to facilitate onboard medical training. However, captains and first mates still need guidance to cope with complex and urgent situations under time pressure, like open injuries and first aid.

Augmented Reality (AR) techniques are used to support such context-related information exchange (Lukosch, Billinghurst, et al., 2015). The co-location, which provides a shared virtual space, is the key characteristic of AR to enable this information exchange (Ens et al., 2019). In a review of AR usability studies from 2004 to 2015, Dey and his team found twelve studies focused on collaborative AR and forty-three on medical AR (Dey et al., 2018). Among them, only three AR collaboration studies were performed under true-to-life setups, and one study on medical VR applications used handhold-based AR. The mainstream of AR-based collaboration involves remote connection, asymmetric tasks, and synchronous responses, and focuses on remote expert involvement (Dey et al., 2018; Ens et al., 2019).

Handhold-based AR (e.g., smartphones or tablets) has lower development and implementation thresholds than headsets, thus the industry shows higher interest in it. Pilot studies of handhold-based AR applications that promote collaborative medical care however are very rare. The goal of this study is to develop and test a two-way AR service concept using a tablet to bring remote medical experts to locations wherever and whenever they are needed (Figure 6.21). To achieve this goal, the researchers will focus on the following research question:

How to develop two-way AR services on handholds to support telemedical treatments?

6.2.2. Method

In this study, the human-centered design is applied in a set of pilot studies from local-remote AR collaboration with Lego models, to define the workspace from the doctor's side, and finally compare two set-ups from both the captain and doctor's sides (Desmet & Fokkinga, 2020). In a pre-study, custom journey mapping was used to discover users' needs and potential AR services. The *Minimum Viable Product* (MVP) of two-way AR services was implemented on iPads or Samsung tablet computers (Gothelf & Seiden, 2013). All participants took part in the studies voluntarily and informed consent was collected before each test.

Study One: 2-Way AR Collaboration

Two captains participated in this pilot study to investigate where to place the camera to share context-related information better: from the tablet or on glasses. They both played the roles of captain and remote doctor to build two Lego models together via a prototype of the AR service. In condition 1, the captain used a tablet to both share the view and get visual and vocal instruction from the doctor; in condition 2, the captain used a camera on glasses and received only visual instructions from the tablet. Doctors used their hands and/or voice to guide the captain via the second tablet. A pre-defined questionnaire with a seven-point Likert scale was used to collect feedback, where "1" for "fully disagree" and "7" for "fully agree". In the end, researchers asked open questions concerning how easy was the experience, their likes, or dislikes, and how smooth was the communication.

Study Two: 2-way AR workspace

The main requirement for the doctor was to control the oversized virtual hands to give accurate instructions. The researchers thus defined a 50cm envelope as a doctor's workspace according to the 50^{th} percentile arm length of the Dutch gender-mixed population. Four combinations of the height and angle of the tablet support (*0cm 10°*, *10cm 20°*, *20cm 30°*, and *25cm 30°*) were tested. Five participants with a height from 170 to 182 cm (two females and three males at an average age of 34) joined the test and matched their virtual hands with sample images on an AR app. Their task load was measured and analyzed via NASA-TLX (twenty-point scale) and the task duration was recorded (Rubio et al., 2004). In the end, a set of open questions were asked to collect qualitative feedback regarding comfort and accuracy.

Study Three: 2-way AR Full Set-up

The study compared two set-ups (Figure 6.22) of AR telemedicine services that simulated an onboard medical treatment. Six captains (one female and five males with an average age of 38.2 and two doctors from Radio Medical Services took part in this test. Each team of captain and doctor needed to perform with both set-ups. Four captains had medical care training, one trained in basic safety and one had no relevant training. The task loads on both sides were measured via NASA-TLX (Rubio et al., 2004). The following behaviors were observed: mutual communication, mutual understanding, ease of use, performance, understanding of the situation (doctor), and understanding of instructions (captain).

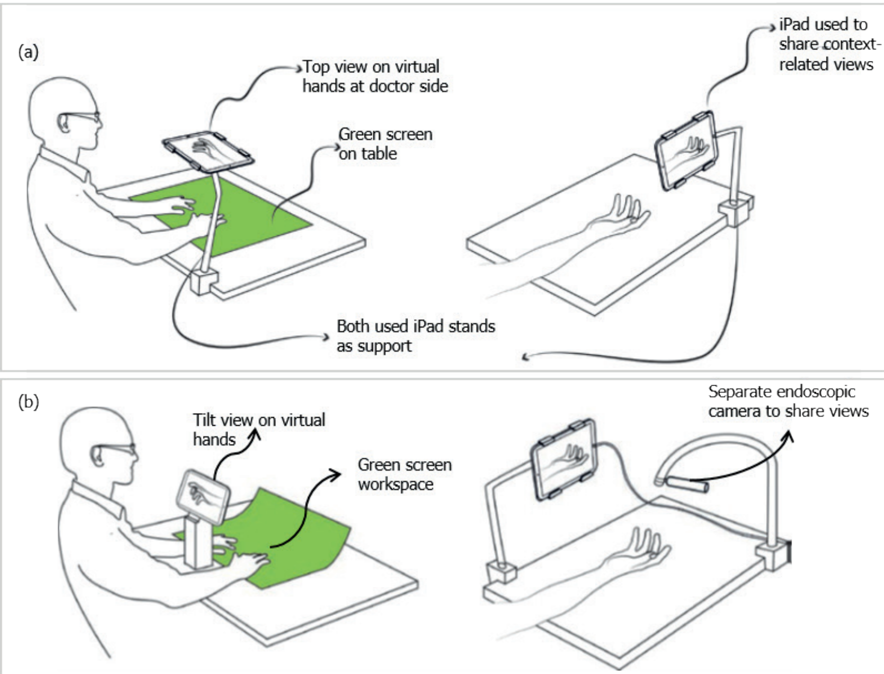


Figure 6.22 Two set-ups of AR telemedicine services. Set-up 1 uses flexible stands on both sides (a) and Set-up 2 uses a separate camera on the captain side (b).

6.2.3. Results

Sharing the first-person view of the captain plus vocal instruction and (hand) pointing was effective in communicating context-related information between the local worker-

-the captain, and the remote expert—the doctor. However, the remote expert needed a stable view to check the overall. Hence, a flexible, fixable camera tethered to a tablet is of value to serve the goal.

Controlling the virtual objects, e.g., virtual hands, from the remote expert side, is critical to provide accurate guidance. Hence, a suitable workspace needs to be taken into consideration as well as the AR app itself.

The adjustable cameras and tablet support showed their importance in reducing task loads and durations, which are critical resources for handling emergencies. Environmental factors such as light play important roles in using tablet-based AR apps, especially under safety-critical scenarios such as telemedical treatment in the marine sector.

There are the following limitations of this study that open new rooms for future studies on collaborative AR in healthcare: 1) The sample sizes of pilot studies were very small due to the limited population of a cargo ship captain and the doctors of radio medical services. Further studies should test their setup with a broader context in telemedicine. 2) The 2D hands were helpful but still limited in their functionalities, more tools are needed to show different types of actions. 3) The doctors reported the virtual hands as larger than in real life, which needs in-depth investigation on the influencing factors of their perception.

6.2.4. Conclusion on two-way AR co-location for telemedicine

To develop two-way AR services on handholds for telemedical treatments, this study focused on the following key aspects. The researchers started by acknowledging the current limitations in captain training and the reliance on conventional remote support systems. By innovating with 2-way AR technology, this study merged realities of two sites using tablets and a green screen. It designed setups that optimize tablet and camera positions for both doctors and captains, emphasizing clear communication and ease of implementation during various medical scenarios. These setups were tested and validated, noting the value of an additional camera on the captain's side for enhanced understanding and seamless instruction execution. Ultimately, this study creates a comprehensive, intuitive system that boosts captain's confidence and supports them in performing critical medical procedures effectively at sea.

Two-way AR has low development and implementation costs as major advantages, and sharing the first-person view with vocal communication and visual pointers can share context-related information effectively. A human-centered design combined with minimum viable products probed the user needs in-depth, then confirmed them in fast "design-test" loops, which ensures the AR services concepts fulfill potential users' requirements and needs.

6.3. Conclusions

This chapter explored the research question: "*How can designers facilitate user experience via co-presence in remote collaboration?*"

Section 6.1 explored the influences of non-immersive and immersive XR interfaces on task load, intuitive use, presence, and situation awareness between local and remote users. The immersive XR interfaces showing both real-sized and miniature-sized workspaces to the remote user increase intuitiveness and situation awareness of local persons. The real-size immersive interface creates high perceived performance on the local user during the XR-based cooperation. The immersive interfaces need to switch between real-size and miniature-size to convey both spatial information and overview in the context.

Section 6.2 analyzed the workspace of non-immersive XR interfaces using the two-way video to assist local workers in accomplishing complicated tasks. Sharing the first-person view of the local worker and the virtual hands from the remote expert together with vocal instruction communicates contextual information adequately. Control of the virtual annotation (e.g., virtual hands), especially their proportions against the context determines the accuracy of the XR guidance. The adjustability of the view-sharing camera and display would reduce mental loads and improve performance.

For the *sensory* factor, the immersive interfaces communicate spatial and contextual information more efficiently. They facilitate situational awareness and reduce workload. Non-immersive interfaces can be enhanced by sharing first-person views and virtual objects. Regarding the *interaction* factor, sharing the gaze beams and hand postures on both sides might help to reduce the time pressure and, then consequently the frustration. Nevertheless, the interaction involving hand postures and vocal commands is unfamiliar to workers and is prone to errors, hence it doesn't support the goals of cooperative work sufficiently. Considering the *realism* factor, balancing the complexity of real-world tasks and the feasibility of implementation is critical in simulating collaboration effectively and efficiently. For *involvement*, scenarios matching the roles in real-world workflows challenge the skills of real-time communication during the collaboration.

The sense of co-location with high immersion affects communication efficiency between remotely located team members in cooperative working. However, novel interfaces (e.g., hand tracking, vocal commands, or virtual hands) would require a well-defined familiarization protocol to ensure users concentrate on cooperative tasks. For observing users' behaviors, XR systems would enhance situation awareness of the remote users to local contexts and increase their confidence in performance judgments.

CHAPTER 7

Extended Reality in Product-Service Design Practices

The first part of this chapter (7.1) reviews the conceptual process of XR-facilitated experience design (Ch3) based on the case studies on immersive design (Ch4), immersive training (Ch5), and immersive collaboration (Ch6). These case studies investigated the phenomena of *spatial presence*, *social presence*, and *co-presence* respectively. The outcomes of these studies show the interrelations between the components of this process: from *positive experiences* to *XR experiences* in both *immersion simulation cycles* of users and the *experience creation cycles* of designers. The interrelationships will reveal three underlying dimensions of immersion.

To understand the effects of immersion in design practices and design organizations, four co-creation sessions are conducted based on the key components in the conceptual process. These studies aim to answer the research question: "*What strategies do designers apply when introducing extended reality in product-service design practices?*" It connects to four questions to be answered in the corresponding co-creations.

In Section 7.2, co-creation sessions aim to survey the question "What knowledge do designers gain by piloting immersive experiences in their practices?" The sessions explore how the immersive cycles are integrated into design practices and what are the potentials, challenges, and expected improvements of the XR platforms.

Section 7.3 intends to discuss the question "How can designers translate general needs to design concepts via an immersive design protocol?" The co-creation sessions identify the effects of immersion on design processes. The four design teams apply a Double-Diamond Model-based protocol to solve design problems and demonstrate the design processes under immersion.

Section 7.4 aims to survey the question "Is an immersive experience suitable to prototype different design elements in product-service systems?" Two focus group sessions involved sixteen design professionals in discussing how suitable XR would be to prototype specific design elements of product-service systems. The immersive prototyping is then compared with physical prototyping based on various design elements and design activities.

In Section 7.5, a pilot study intends to investigate the question "How do design stakeholders coordinate with each other in an immersive co-design space?" It focuses on the ways that a shared immersive space might boost or block co-creating activities.

The last Section 7.6 aggregates the insights from the abovementioned co-creations based on the three dimensions of immersion. Finally, the author discusses the possibilities of integrating XR into product-service design practices.

The co-creation in Section 7.3 is adapted partly from the publication
Meng Li, Lorenzo Cecconi, Flora Gaetani, Federica Caruso, Zengyao Yang, Armagan Albayrak, Daan van Eijk. XR smart environments design and fruition: Personalizing shared spaces. *HCII24. Accepted*.

7.1. Reviewing the Conceptual Process

The case studies demonstrate the influences of immersion in specific topics, like conceptualization, cross-user group design, and collaborative work. The author analyses these cases according to the conceptual process (Section 3.2) and tries to integrate insights into three critical dimensions of immersion.

7.1.1. Understanding comfort via the spatial presence

The first set of case studies (Ch4) probed into positive experiences in long-haul flights in that they represent typical complex experiences influenced by various design elements (Figure 7.11). Positive experiences on flights are shaped by passengers' 'discomfort-comfort' perception that relates to various activities, like hygiene-related or privacy-related activities. The activities cover both physical and cognition domains, where VR technologies dominate. The case studies thus focused on comfort and satisfaction perception as key design qualities and explored the influences of types of experiences (active-immersive or passive-absorptive) on them.

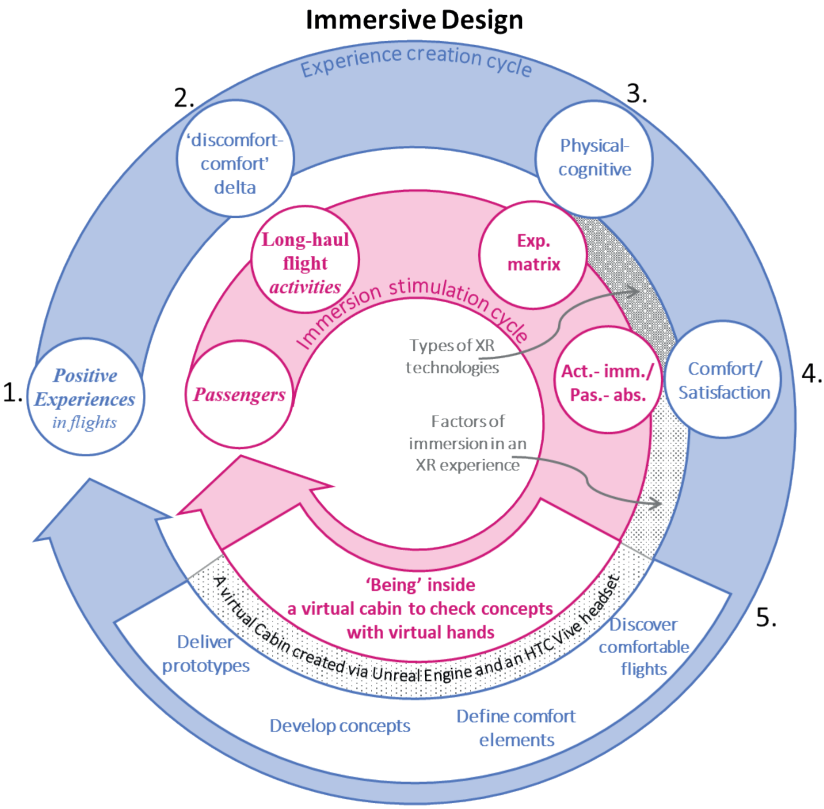


Figure 7.11 The conceptual process is adapted based on the case studies on immersive design.

To prototype the whole experience in immersion, the designers considered both the immersion stimulation cycle from the user's perspective and the experience creation cycle from the designer's angle. For the immersion cycle, the sensory factor was enhanced by the stereoscopic view and passive tactile feedback from physical parts; the realism factor depended on the real-size and textured context with interactive virtual hands; the interaction factor relied on active walk-through and direct manipulation of objects. When the headset blocked visual and auditory information from the physical environment, participants would have high involvement. Spatial presence was achieved by simulating cabin scenarios via the abovementioned factors.

For the experience creation, designers needed to understand the influence of each design element on comfort and then decide the parameters for these elements. The XR platform *Unreal Engine* enabled the designers to demonstrate each element separately to users and automated the sequences of different concepts in random order. To review the whole experience, animating functions helped users to focus on the concepts instead of the imprecision of prototypes. To investigate design elements, the designers applied various activities - mostly explorative - like generating comfort-related narratives, prototyping 3D solutions, and testing the prototypes.

The researchers found spatial experience, or *spatiality* as a key dimension in immersive experiences when designers started to explore solutions for design problems. The space-related aspects concerning human bodies are the first set of design elements to be examined to ensure well-being and comfort. This seems to be the first and foremost interest of designers to introduce immersion in design.

7.1.2. Understanding competence via the social presence

The second set of case studies (Ch5) investigated positive experiences in professional training, especially minimally invasive surgery (MIS) skills in that they are influenced by trainees' characteristics (Figure 7.12). Positive experiences in skills acquisition are associated with competence perceptions, like feeling a 'flow' state. During MIS procedures, trainees not only need to learn psychomotor and procedural skills but also gain self-management skills in chaotic, distracting surroundings (Mentis et al., 2016). Acquiring these skills relates to cognitive and organizational domains, where MR technologies could simulate 3D vision, precise haptic feedback, and team interactions together. The case studies focused on the influences of trainee characteristics on competence perception.

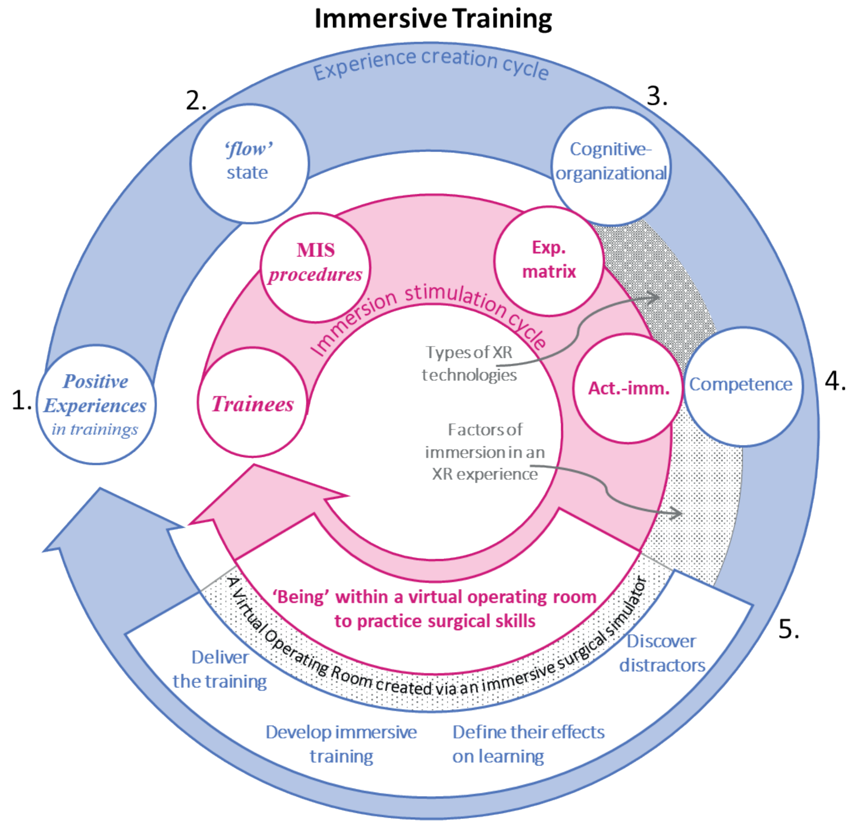


Figure 7.12 The conceptual process is revised based on case studies on immersive training.

To replicate a true-to-life operating room experience for users, the sensory factor, interaction factor, and involvement factor are critical in the immersion stimulation cycle. In the *sensory factor*, visual resolution and haptic fidelity contribute the most to learning psychomotor skills correctly. In the *interaction factor*, simulating maneuvers and procedures validly could convey the procedural skills matching the real-world experience. In the *involvement factor* simulating environmental factors, like noises and lighting, might isolate trainees from the physical world and trigger a "flow state" to accelerate the learning curve. Moreover, the realism factor is achieved by reproducing the layouts and setups of operating rooms. Social presence can be realized by simulating team communications and interactions in a virtual operating room.

In the experience creation cycle, designers gained a chance to observe the realistic reactions of the trainees towards different kinds of distractors, as well as their effects on cognitive well-being. The key potential of the XR surgical simulator is to replace the silent skills lab with a realistic clinical environment in a safe, repetitive, and controllable manner. Simulating the complete experience facilitated the observation of trainees across different professional levels and cultural backgrounds. Unlike immersive designing cases, the immersive training cases focused on evaluative activities, like observing behaviors and user testing.

The immersive training studies hence identified the second key dimension of immersion: personalization. Both individual differences and cultural differences were observed in the trainees, as individuals have diverse competencies and are always living and working under a specific cultural background.

Understanding remote teamwork via the co-presence

The last set of case studies (Ch6) examined positive experiences in teamwork, particularly remote teamwork which is affected by the setups of workspaces (Figure 7.13).

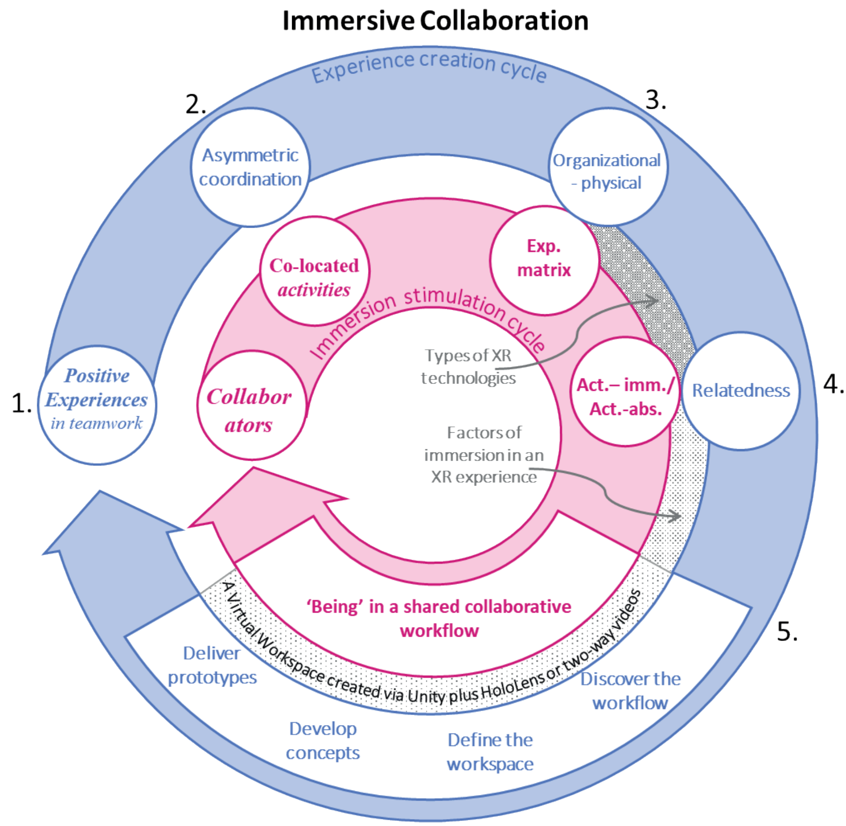


Figure 7.13 The conceptual process is adapted based on case studies on immersive collaboration.

Positive experiences of teamwork benefit from wide-ranging knowledge but are impeded by information asymmetry from diverting professional backgrounds. Asymmetric coordination relies on the perception of relatedness (Desmet & Fokkinga, 2020). This perceived relatedness emerges through co-located activities, like information sharing, function demonstration, and task guidance. These activities currently cover both physical and organizational domains of user experience. Rising global uncertainties are strengthening the motivation to bring the team together in a shared virtual workspace, especially in the sectors of manufacturing and healthcare. Co-presence happens when remote collaborators feel the workspace is blending both sites, where AR technologies are good at merging virtual artifacts into physical surroundings. The case studies thus investigated the effects of the immersive cooperative workspaces' setups on relatedness perceptions.

The first relevant design element is situation awareness, which indicates the awareness of elements and events in contexts as to time and/or space, to comprehend their meaning and to project their future status (Aschenbrenner et al., 2018). Moreover, task loads and intuitive use served as indicators of positive experiences as well.

To simulate the experience of a cooperative workflow, immersive interfaces (the sensory factor) played a critical role in communicating spatial and contextual information to enhance situation awareness. For the interaction factor, sharing the gaze direction and postures would reduce time pressure and frustration. Regarding the realism factor, streamlining real-world tasks is critical for simulating collaboration effectively and efficiently.

In experience creation cycles, designers found it valuable to compare the interfaces between the immersive version and the non-immersive version. Analyzing the original workflow also helped to pinpoint the potential values of XR platforms. The perception of being in a shared workplace from the collaborators allows them to understand the situation quickly and thoroughly. The design activities were generating concepts of workplaces, prototyping workplaces, and comparing concepts. In the immersive collaboration cases, co-location was spotted as the third key dimension of immersion.

The case studies demonstrated the main components of the conceptual process – immersion stimulation cycle, experience creation cycle, experience prototyping, and cooperative work. The researchers discovered three key dimensions of immersion: *spatiality*, *personalization*, and *co-location*. Co-creation sessions then were organized to scrutinize these components in design practices. Finally, the findings will be discussed regarding these dimensions.

7.2. Creating Immersion Cycles in Product-Service Designs

7.2.1. Introduction

Designing is viewed as an intentional, solution-driven action, which is composed of different phases including goal, approach, performing, and evaluation (Li, 1999). Designers are looking for methods to 'dive into' human needs in-depth and try to fulfill them with their solutions(Ball & Christensen, 2019). The attempts to integrate immersive experiences to enhance the empathy of users appeared when immersive technologies like virtual reality emerged in the early 1990s (Smets & Stappers, 1995). XR platforms are the technological ground to carry and deliver the immersive cycles, hence posting constraints on designers to create an immersive experience in the way they want (Lingan et al., 2021).

This study aims to understand the needs, motivations, actions, and constraints of design teams when they try to introduce XR into design practices. Thus, online co-creation sessions are organized with design teams to explore the research question, as well as its sub-questions:

What knowledge do designers gain by piloting immersive experiences in their practices?

1) How XR platforms are used in design practices, as well as their potential and challenges?
2) What are the needs of designers on these platforms?
3) What are the effects of first-person immersion on design practices?

7.2.2. Method

Participants

The participants were recruited via the network of designers and XR developers related to the Delft University of Technology, requiring both experiences in product-service development and XR platforms. As very few products and service development teams match this requirement, the researchers also include professionals from architecture design using XR platforms in the TU Delft network. Four design teams with seven design professionals joined in these sessions, which represent different types of designers including corporate designers, senior designers, junior designers, and part-time designers. Corporate designers and senior designers are design experts who have experience of around ten years to fifteen years, whereas junior designers and part-time designers are design novices who are involved in design cases for about one to three years. All participants have worked at least once with XR platforms in their design practices, and their familiarity with XR platforms diverged from several months to more than ten years as well. Their design focuses cover service design, product development, and building design.

Materials

Figure 7.21 shows a co-creation canvas that was developed according to the *Rubicon Model* which defines the mental process indicating how motivations are converted to actions (Li, 1999). This canvas aims to understand the mindsets of integrating immersive experiences into design practices. The canvas developed on an online collaborative whiteboard-miro.com[1], is composed of three sections: background, design activity, and reflection.

The background section at the top included information about the goals and the procedure of the sessions. The design elements and design activities as references are based on the studies that compare the effects of the types of prototyping on the design decision-making (Bennes et al., 2012) or discuss the suitability of different types of XR prototypes (Aromaa & Väänänen, 2016). The same set of elements and activities is shared in the experience prototyping study in 7.3. The design activity section in the middle contains four blocks that are related to the *goal*, *approach*, *perform*, and *evaluation* behaviors among design activities. The *goal* block surveyed the motivation to introduce XR platforms in design practices and the expected effects of using the system. The *approach* block investigated how the design teams plan for and prepare for the usage of XR platforms, especially at the stage of the design process. The *perform* block interrogated the actions design teams took to integrate the XR platforms into design practices and the problems they met. The *evaluation* block reflected the judgements from the design teams on integrating XR platforms in design practices and their empirical comparison between XR platforms and traditional design tools. The reflection section enclosed two questions: 1) the general comments on integrating immersive experiences in design practices; 2) a specific product or service the design team selected to simulate in a follow-up immersive design protocol.

1 https://miro.com/app/board/o9J_lDofsYg=/

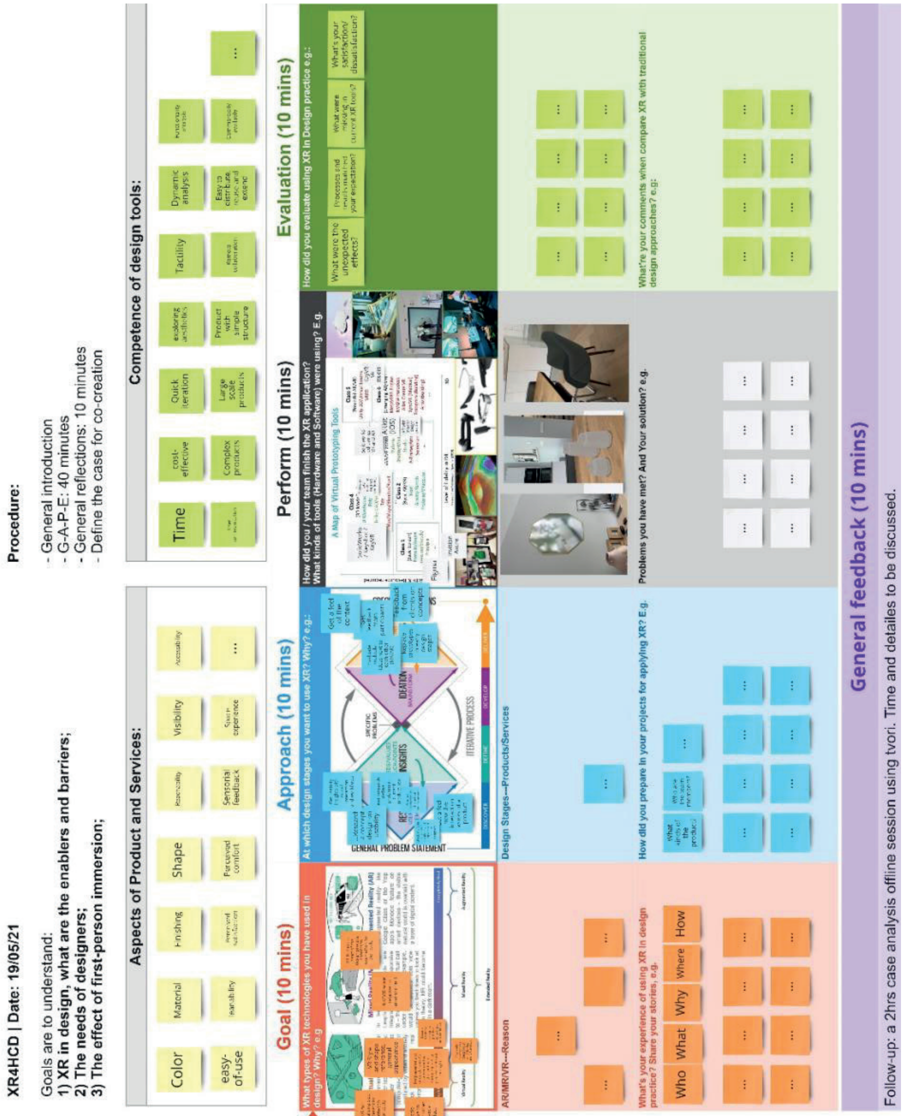


Figure 7.21 The canvas was developed to collect feedback during the co-creation sessions using the Miro board.

Procedure

The co-creation sessions were conducted in May and June 2021 including the following steps:

1. The researcher introduced the goals and the procedure of this session and then explained how to use this canvas. Afterward, participants could look at the whole canvas and try out the note function on the Miro board for about 5 minutes.
2. Participants spoke aloud about their experience related to the questions in each block together with the notes, starting from the "Goal" block. The researcher reminded them to move to the next block in about 10 minutes.
3. Participants gave a general reflection on how the first-person immersion might influence the design processes and defined a design task they thought would be explored in an immersive environment. In the end, the researcher thanked the participants for their support.

A full session lasts around 50 to 60 minutes. The informed consent was signed by the participants at least one day before the session. The study was approved by the ethical committee at the Delft University of Technology.

Data analysis

The sessions were fully video-recorded by Zoom. The researchers transcribed the video records while referring to the notes on the Miro boards. The transcript at first separated along with the *goal*, *approach*, *perform*, and *evaluation* blocks, and then labeled to connect to the four factors of immersive experience: *User*, *Experience*, *Presence*, and *Engagement* to indicate why and how designers use XR platforms to create immersive cycles on the user's world (Lingan et al., 2021). These factors represent the psychological phenomena users undergo within immersive cycles, and they link to the objective features of XR platforms, as mentioned in Section 3.1.

The factor "User" referred to the sensorial sensations involved in the design practices, while the factor "Experience" focused on the interaction aspects; the factor "Presence" collected the features that attributed to realism, whereas the factor "Engagement" referred to the features that involve people in the scenarios of using. In the end, the comments were tagged as "positive" or "negative". From the "positive" comments, the researchers generalized the potential, and from the "negative" comments the researchers aggregated the challenges of current XR platforms in terms of user experiences.

7.2.3. *Results*

The goals of applying immersive experiences

As shown in Figure 7.22, different designers have diverse purposes to integrate XR into design practices. For service designers, their focus is on VR to replicate true-to-life procedures in realistic surroundings (Figure 7.22a); while for product developers, VR is the reference to examine scales, or shapes and spatial interaction (Figure 7.22b-c); and for the architect, VR is an explorative tool for understanding the location (Figure 7.22d). Product design cases also used AR/MR to compare scales relative to the real environment.

The scale of designed objects also impacts the choice between VR and AR, while VR generally demonstrates large-scale objects in real size, like buildings, cabins, or streetlights, while AR usually shows smaller or down-scaled objects.

Design experience might alter the attitude toward the XR system as well. Design experts principally view VR as a presentation tool to show concepts to stakeholders, whereas design novices regard VR as an explorative tool for brainstorming, sketching, or ideating. Novice designers focus on limited projects using specific VR systems like Gravity Sketch (Figure 7.22c), while expert designers need VR for shape and scale validation, and AR/MR to check concepts relative to environments (Figure 7.22b). The novices think AR is convenient for specific design and co-creating with a group of people.

The approaches to involving immersive experiences

For design experts, XR is mainly applied at the start and end of a design process, to open the mind and to get quick feedback (Figure 7.23 a-b). Novice designers tend to apply a lean UX approach by involving XR in every stage (Figure 7.23 c-d).

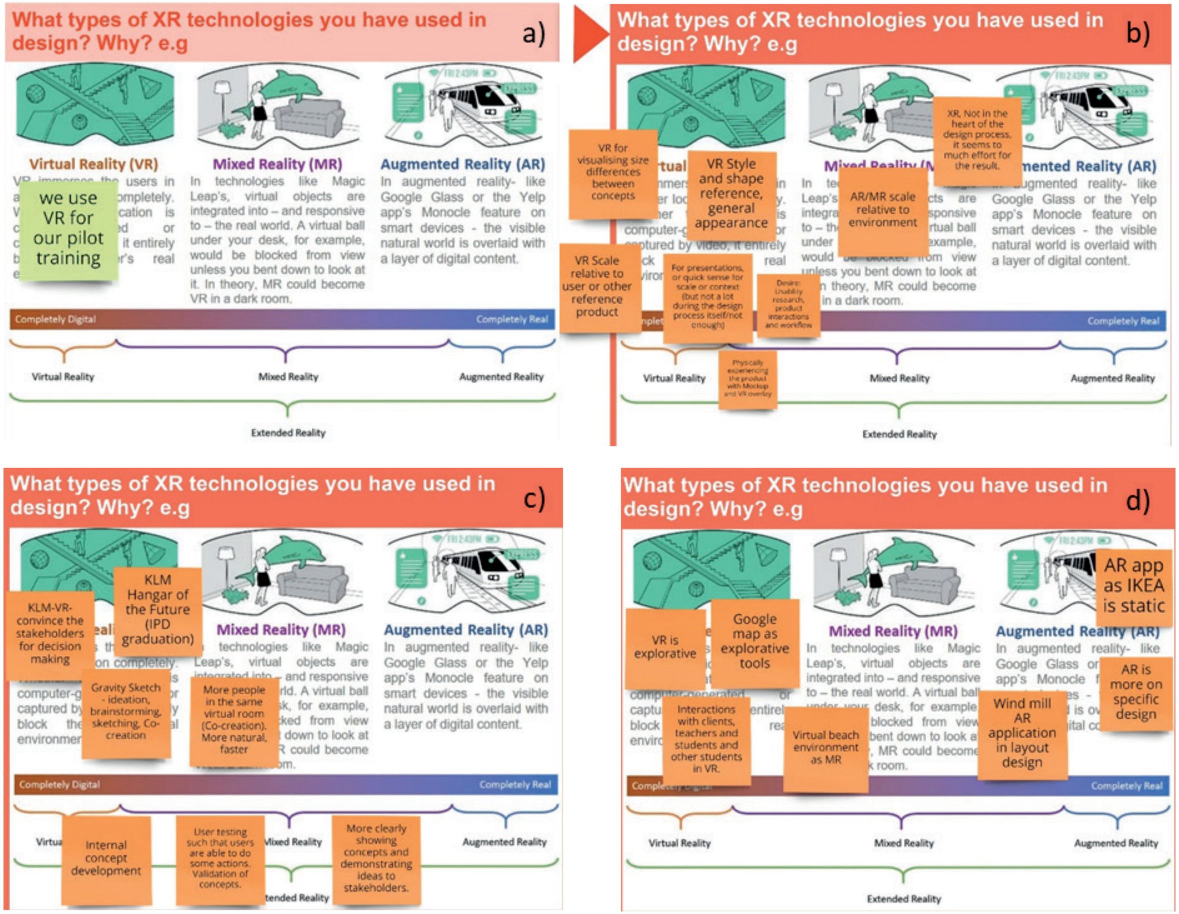


Figure 7.22 Different goals mentioned to involve XR in design practices: a) service design for aviation training. b) product design experts. c) product design novices. d) part-time designer with proficient XR experience.

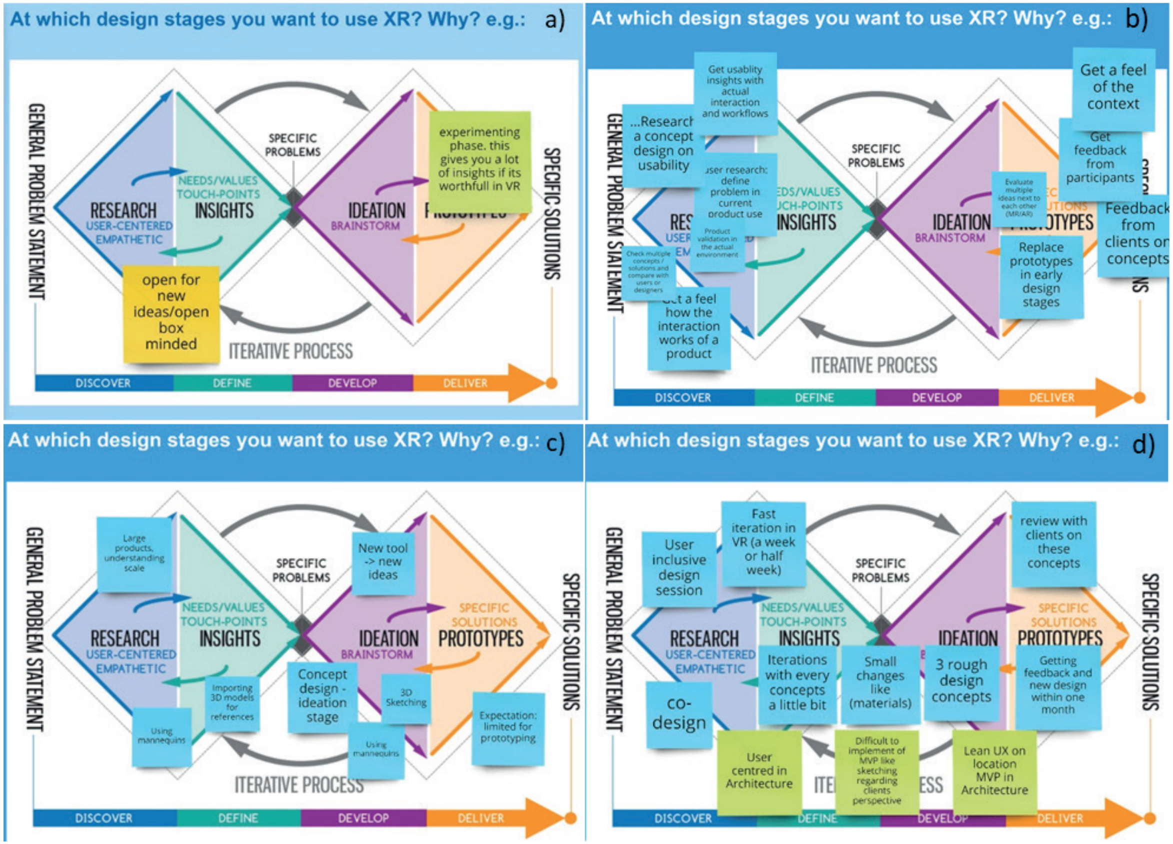


Figure 7.23 To integrate XR at different stages in the design process. a) Training design focuses on inspiring thinking and testing with trainees. b) Design experts agreed on the utility in discovery and delivery. c) Design novices who want to try XR in the whole process. d) Architecture designer intends to bring user-centeredness to building design.

The designers specify key functionalities at each stage. At the discovery stage, scale, usability, and interaction are the aspects designers want to explore to define problems in real usage or check multiple concepts. Using XR to see through the user's eyes, particularly under inaccessible circumstances such as ICU is also mentioned. Gaining empirical knowledge about the task procedures and actions is critical as well, thus product designers expect to use XR training programs to get insights into these procedures and actions. At the delivery stage, replacing physical prototypes and collecting stakeholders' feedback faster in contexts are the main goals. For junior designers and architects, XR experiences are expected to develop concepts in iterative loops with increased resolutions, among which digital humans, reference models, and 3D sketching are highlighted (Figure 7.23 c-d).

The actions to include immersive experiences

Various hardware and software are mentioned by the design professionals (Figure 7.24). The common setups are a headset tethered to a game computer (PC VR) or a standalone headset (e.g., Oculus Quest). The XR applications are developed via powerful game engines, like Unity and Unreal Engine. The service designer also uses 360 cameras (insta 360 pro2) to develop virtual environments (Figure 7.24 a). The senior designers use both 2D and 3D tools to model concepts but only focus on KeyVR for XR applications because it could integrate into the current modeling pipeline (Figure 7.24 b). The junior product developers tend to use open-source modeling software but try out different XR platforms (Figure 7.24 c). The architect who is proficient in XR application not only understands the tools spanning from 2D to 3D creation but also uses pre-defined assets (e.g., Unity templates) and specialized tools such as "one-click" XR solutions for architecture to increase productivity (Figure 7.24 d).

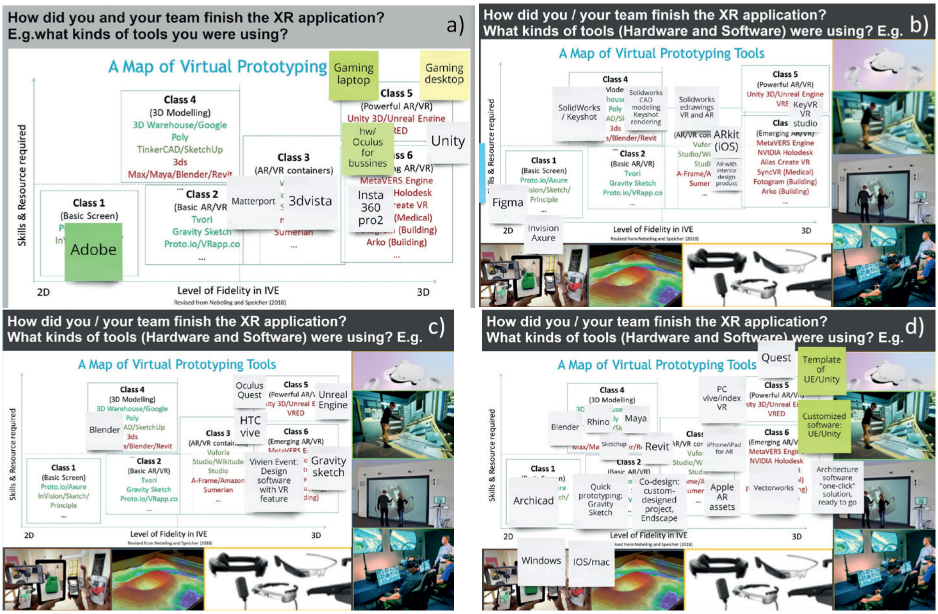


Figure 7.24 The tools to develop XR applications for design cases. a) service design for aviation training. b) product design experts. c) product design novices. d) the architect with rich XR experience.

This part indicates the thresholds of resources to utilize XR platforms. Learning a pipeline for XR applications requires many hours both on software and hardware, while "one-click" solutions now are only available in specific fields with very limited functions (Figure 7.25). The time to understand an XR pipeline is estimated at around 2500 to 3000, and sufficient computational power particularly on GPU requires extra monetary investment. Considering the rapid development of XR technologies, designers might need to invest forty hours per week to follow up with the advancements, even after they grasp the pipelines.

The feedback to improve immersive experiences

There are several surprising effects of applying XR platforms (Figure 7.26). For instance, the service designer benefits from XR to collect interaction data naturally. He immersed trainees into the target environment without instructions and saw what are their first reactions. The feedback is also useful to improve interfaces (a). Senior product developers appreciate the potential fast insights from XR prototyping as an alternative or combination with foam or carton prototypes (b). For this purpose, physical interactions and free model manipulation are fundamental. Using XR in sketching is physically demanding, but can be a good balance for long-time sitting postures (c). Affordable resources for research on large-scale products/services, such as buildings and transport interiors (d).

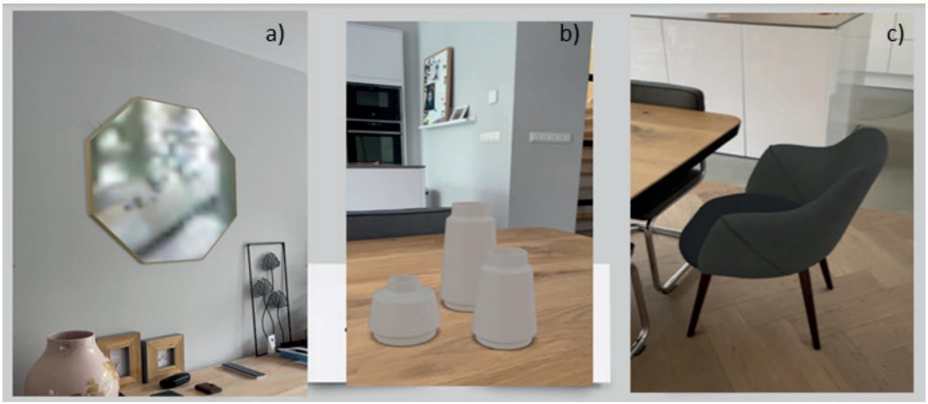


Figure 7.25 Design teams showed an AR shopping app to project furnishings in a real environment. The application rendered the light of the surroundings on the texture of virtual objects. a) a mirror b) a table and vases c) an armchair

The service designer empathizes with the trustworthiness of the procedures and the setups of the scenarios during the simulation. Control of the variety of procedures and involving challenging factors like distractors, and hazards are also mentioned. Product and building design requires fidelity to spatiality, i.e., space-relevant perception and interactions. A quick switch between concepts and control over the individual design is needed as well.

There are many improvements expected as a part of future XR platforms. First and foremost are the human factors of XR hardware and software, including simulation sickness, discomfort for long-time usage, concern for eyesight, inclusiveness, and quick change of setup. At the organizational level, acceptance of the team, the learning curve for the team, and extra computational power are also required. Several key functionalities are mentioned as well. Haptics is an important medium of tacit knowledge, hence the XR system shall allow us to feel the virtual objects at hand and shape them like foam, carton, or clay. Representing real interactive use instead of animations is key to understanding users' procedures and actions. Spatial validation is a fundamental design task in XR; thus, the fidelity of scale is also important.

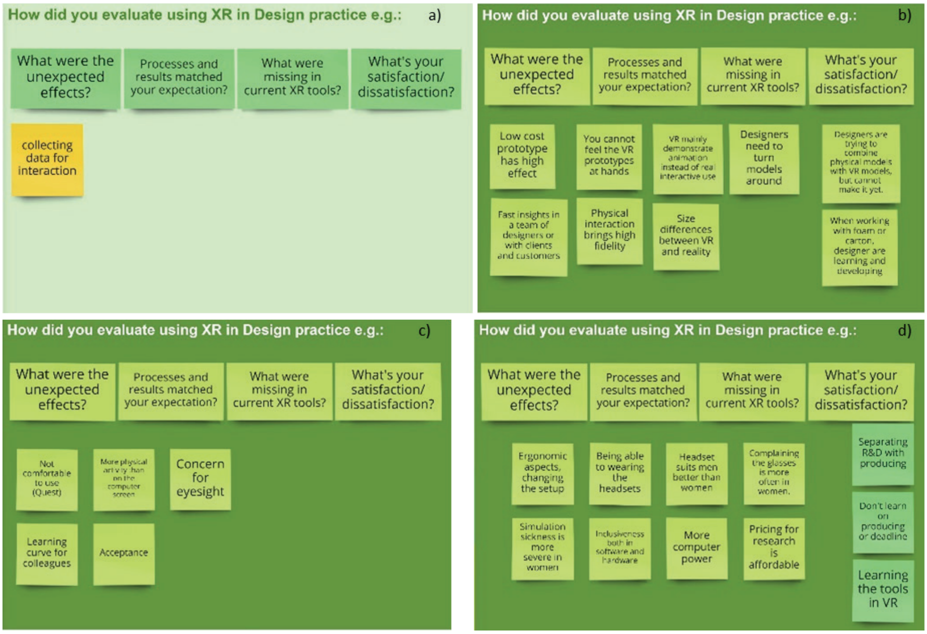


Figure 7.26 Designer's feedback on using XR in design processes. a) service design. b) product design experts. c) product design novices. d) the architect

The potentials and challenges

The co-creation sessions discovered the following potentials and challenges to integrating immersive experiences in design practices.

Factors	Potentials	Challenges
User	+ Present concepts to clients and stakeholders. + As a part of the shopping experience for the consumer. + Design team could try out VR products without training + For user validations or design evaluations, and professional training at the same time.	- Not seamlessly integrated into design workflows.
Sensory	+ Show clients what a design looks like in context. + Design teams judge the shape and the scale of the device relative to their own body. + The design team can see the end-user experience and the users, especially for medical-oriented products/services.	- The size differences between reality and virtual objects. - Concerns about eyesight. - Simulation sickness symptoms.

Factors	Potentials	Challenges
Experience	+ The value on the usability side. + To test concepts initially + To confirm that the scale is correct. + For physical ergonomics, evaluate the position in a realistic use setting, e.g., comfortable use or the squeeze points where the user cannot reach.	- It's a bit off the process. - VR misses a seamless experience for a quick space/shape check. - Not in the kind of small steps iteration processes. - Uncomfortable for long-time usage.
Interaction	+ Presentation tool + Interaction with the user, including reaching certain parts, overseeing the whole product and its functionalities, or opening and accessing something. + Mix in products that users already know or objects that are familiar to them. + To prototype concepts quickly in 3D.	- Designers have to set up each time on a separate PC. - To switch quickly between the XR demo and the main workflow. - To make makers see models through AR. - Changing and configuring texture takes quite some time. - People are afraid to walk around and try how to use the controls in VR.
Presence	+ The AR app is impressive, and you could have a very, very good idea of how it would fit in your spaces. + To see how products are used in user environments in VR. + Become more time-efficient by skipping the operation training for design. + Visiting 3D scans of real environments that are difficult to reach + To see through the eyes of someone via 360 videos.	- It's impossible to interact with XR prototypes like using a real device. - It's difficult to import a 3D scan into an XR tool, like KeyVR. - The choice between 360 video/image and 3D scan/models.
Realism	+ Designing really large objects. + Suitable for things that are difficult to evaluate on a screen. + VR works very well for products usually seen from a different viewpoint than what designers used to present them. + AR kit is quite good at integrating surrounding lights from the scene in the camera and projecting them on the object. + The XR training system can help the designer get real insights into the procedure and user actions.	- Much effort for the result. - Making an interactive model in VR requires a huge effort.
Engagement	+ The" Wow" effect on the clients	- The difficulties in involving stakeholders remotely.
Involvement	+ Having a VR application at the beginning of the process for design discovery.	- The difficulties of integrating challenging factors in contexts.

7.2.4. *Conclusion on immersion cycles in design practices*

Considering the question of how XR platforms are used in design practices and their potential and challenges, diverse purposes are identified:

- Design objects might determine the types of XR platforms. For example, in service design, VR is the replica of real procedures, while for products and buildings, VR is a tool for validating space-relevant requirements.
- The sensors involved in human-system interaction might determine the design elements to be tested in XR. Product developers focused on scales, shapes, and interactions, while architects used VR to check color, lighting, and materials as well. In addition, product developers were more concerned about touch perception in physical interactions.
- VR or AR fits different scales of product/service. VR usually suits large-scale products that are larger than human sizes, while MR/AR might be fitting for smaller objects.
- The designer's experience influences the way to use XR platforms. Design experts usually use XR at the beginning of the end of a process to present concepts to stakeholders, while junior designers tend to implement lean user experience throughout a process via XR platforms.

The typical ***potential*** proposed in this study is spatiality validation related to the body, the "wow" effect on stakeholders to increase their involvement, and prototyping of large-scale objects fast and cheap to test concepts initially.

The typical ***challenges*** proposed in this study are the hassled pipelines towards design processes, high thresholds both on monetary and man-hour resources, and human factors issues of XR platforms.

Considering the question on the needs of designers on XR platforms, several desires are found:

- Observing actual users and natural user experience from users' eyes, especially in inaccessible situations like ICU or emergencies.
- Examining multiple concepts via "one-click" functions with an interactive control on individual specifications.
- Confirming space-relevant design aspects initially, like scales, shapes, layouts, or physical interactions.
- Ideating concepts under small-step iterations with increased fidelity on multiple sensors.

- Prototyping design concepts faster and cheaper to 'learn' human needs from user feedback in contexts.

Considering the question on the effects of first-person immersion in design practices, the identified effects include:

- The "wow" effect engages stakeholders deeply, so designers can naturally collect users' data.
- The true perception of spatiality enables designers to judge relevant product requirements intuitively.
- The opportunity to check the concepts from the user's perspective under using procedures.
- The unlimited space where designers can explore concepts in real size at any scale.
- The chance to try immersive training to gain tacit knowledge of procedures and actions for complex products/services.

7.3. Experience Creation Cycles in Immersion

7.3.1. Introduction

The previous section discussed the motivations and the actions when design teams want to bring an immersive experience to the users and take advantage of the first-person immersion to check concepts from spatial experience and interaction aspects (Li et al., 2022). Designers need to translate human needs into targeted design qualities and design problems, define relevant design elements, and explore possible solutions to ensure these qualities, then fulfill the needs (Ball & Christensen, 2019). The design process model indicates the mind flow of designers across design processes (Cross, 2001). A well-acknowledged design process model is the *Double-Diamond Model (DDM)* which describes two circles of a divergent-convergent process (Design Council, 2007). In this model, the concentration of designers' minds gradually shifts from "problem discovery" to "solution verification" (Cross, 2006). This transformation plays a key role in ensuring the quality of the final design. Since designing is a "solution-driven" activity, the transformation is composed of iterative loops where the designer is continuously learning to understand the user's experience via "defining", "prototyping" and "testing" activities (Ball & Christensen, 2019; Buchenau & Suri, 2000; Norman, 2013). In this section, the focus is thus on the effects of immersion to support the designer's thinking among specific design processes.

In Section 7.2, designers showed a divergent way of thinking about the approaches to integrating XR experiences throughout their design processes. Understanding how high-level immersion influences a designer's thinking in design processes is also of significance for design communities. As a follow-up section, this study will analyze the thinking styles of designers under immersion as well. A pre-defined protocol simulates realistic design processes following the *DDM*. This study focuses on the following research question and sub-questions:

How can designers translate general needs to design concepts via an immersive design protocol?

1) What are the effects of immersion on design processes?
2) What are the limitations of the current immersive process?
3) What are the key factors of an immersive design protocol?

7.3.2. Methods

Participants

The same design teams as in section 7.2 were invited to this study at the VR Zone lab on the campus of the Delft University of Technology from June to July 2021. None of them has used the XR platform previously and nobody reported the sensitivity of simulation sickness symptoms.

Materials

As shown in Figure 7.31, an immersive design protocol including nine docks was developed following the *Immersive Cycle* aligning with the *DDM* (Lingan et al., 2021). The protocol starts with the "User" dock to brainstorm the needs of a specific product-service system. The "Involvement" dock requires reflection on the sensors and experiences involved. The "Participation & Connection" dock checks whether the experience is active and immersive. The "Nature of Experience" dock maps the experience to understand its nature. The "Engagement" dock requires discussing the way to engage users, especially via challenges in the storyline. The "Immersion" dock needs reflections on the coherence and meaningfulness when prototyping the experience. The "Presence" dock reflects on the narrative and interactions, as well as predicted users' responses. The "Being There" dock checks which imagination and memory can be triggered with the experience. Every two docks link to a stage in the DDM subsequently.

The protocol was developed on an XR platform -*Tvori.co*[2], which supports immersive prototyping and animating scenarios by using the Google Poly library or importing external files, like videos, audio, or 3D models. An HTC VIVE headset (1080 x 1200 pixels per eye with 6 Degree-of-freedom) was used to support navigating in the

2 https://tvori.co/tvori

immersive environment and uses hand controllers to interact with virtual objects. The immersive environment was synchronized to a 19-inch LED display in front of the researcher and a 50-inch screen for the other team members. The sessions were screen recorded and video recorded (using a Logitech webcam) together using OBS studio™.

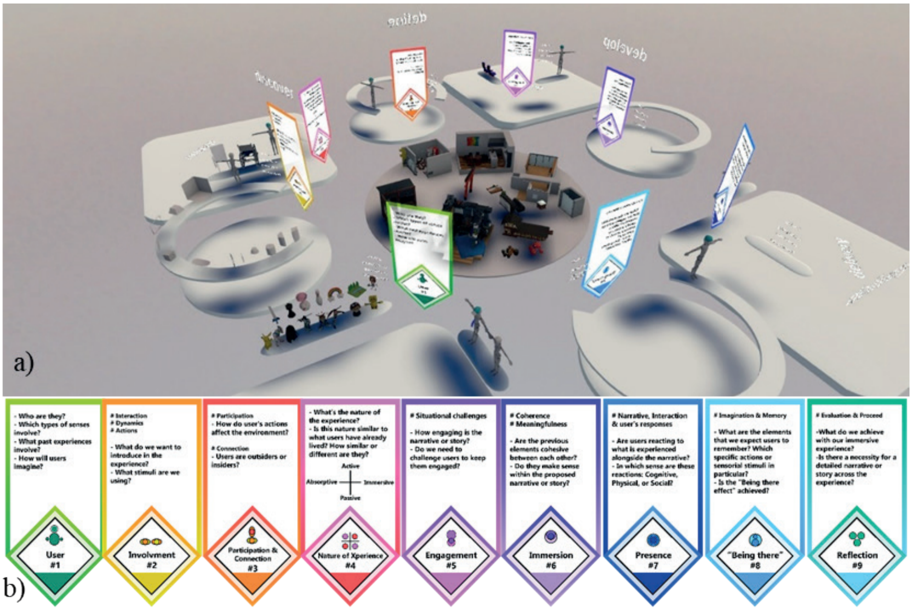


Figure 7.31 The immersive design protocol is developed with the XR platform – Tvori. co. a) a bird's view of the immersive protocol that guides the sessions. b) the protocol is composed of nine phases.

Procedure

Before the session, several preparations have been made to replicate true-to-life design processes:

– A specific design task was defined together with the teams and the researcher asked what they wanted to explore in the immersive session.
– The protocol (Figure 7.31) was customized to include texts, videos, or models that could be used for a particular design task.
– The start point was set at the "User" dock in the Tvori protocol.

Each immersive design session lasted about two hours including the following steps:

1. The researcher introduced the goal and the procedure of the session and then gave a demonstration on how to move around and interact with the objects.

7

2. One participant from each team put on the headset to try out the immersive protocol till he or she felt confident enough to interact with it.
3. The participant with the headset guided the team throughout the protocol to complete a concept of the design task within two hours. The team could decide whether to switch between different members to guide through the protocol. When a team couldn't complete the protocol in 140 minutes, the researcher asked the team to leave the design process and move to the final part.
4. The last part was a briefing where the team could give general comments, recommendations, or expectations on future XR design platforms. Then the researcher thanked the participants for their contribution to the study.

The informed consent was signed by the participants at least one day before the session. The study was approved by the ethical committee at the Delft University of Technology.

Data analysis
The researchers transcribed the records and then tagged the designer's comments as "positive", "neutral", or "negative" to reflect the potential and challenges of the immersive design protocol. The comments were then categorized into four categories according to the Double-Diamond Model: *Discover*, *Define*, *Develop*, and *Deliver*.

7.3.3. Results
The four teams created a concept within 120 to 150 minutes respectively (Figure 7.32). The service designer created a cabin to check the layout of seats (a). The senior product designer team checked the configuration of the dialysis machine and reviewed reachability both from the patient's view and the nurse's view (b). The junior designer team built a 3D persona for youth and ideated an outdoor wheelchair in context (c). The architect generated a container house for a middle-aged couple (d).

Each team acknowledged the immersive session as engaging and creative. Learning basic interactions like navigation and object manipulation took 30 minutes to more than an hour, whereas junior designers took a shorter time to learn, and senior designers needed a longer duration to understand basic functions. The senior designers viewed the immersive protocol as a replacement for cardboard prototypes to explore different layouts and examine ergonomics; while junior designers appreciated creating personas with 3D polygons and showed interest in simulating interactions with animation. Both senior and junior designers naturally put digital humans in the scenes they created either to represent the human sizes or to indicate the target users.

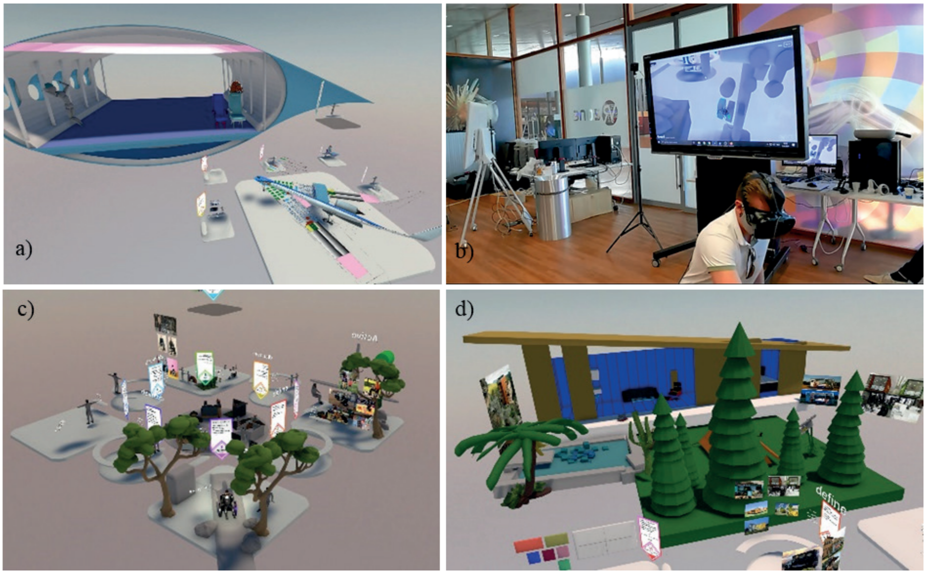


Figure 7.32 The examples of the outcome of the immersive design sessions. a) conceptual safety training setup for Dutch crews; b) the configuration of a dialysis machine for Chinese hospitals; c) a conceptual scenario of a wheelchair for Dutch youths; c) a concept of a container house for a middle-aged Dutch couple.

7

The potentials and barrier

Stages	Potentials	Challenges
Discover	+ Prototyping is the key to discovering users' needs. Testing and observing (recording) are the key design activities. + Creating personas in 3D is creative and fun, especially for young designers. + Working with low polygon models is nice. + The opportunity to share design proposals across mobile and PC.	- Feel floating and nauseous. - Collaboration would be nice with two players. - Designers need to search for pictures inside the environment. - Teleport within the environment is difficult.
Define	+ The Environment has the function of being an experience. + Designers could work in the real size. + Posturing digital humans freely in the scene is useful and fun. + By simulating realistic experience, it's a tool to observe users from different angles. + Simulating scenes with people (like a crowd in a cabin). + Zoom in and out to check the layouts and scales.	- Designers would be careful if they have real sizes. - Introducing eye-tracking could help to understand the designer's thinking processes. - Sketching is difficult. - Missing a whiteboard in the environment. - Similar functions with different controls in various XR platforms.

Stages	Potentials	Challenges
Develop	+ Opportunities for participatory design: people understand VR and concepts better if they create a bit of it themselves. + Exploring the stories behind the use scenarios. + The experience simulation can be both immersive or absorptive depending on use cases.	- The difficult control of resizing objects. - Various challenges should be brought to the scene to build up the purposes and goals of XR applications. - An XR system should provide intuitive sketching while including different possibilities to explore user experience.
Deliver	+ Users feel better acceptance and ownership when designing together in XR. + The opportunity to personalize user experience.	- The heavy weight of the headset makes the neck discomfort. - Using a virtual camera is difficult.

7.3.4. Conclusion on experience creation via XR experiences

Regarding the question on the effects of immersion on design processes, the findings are listed as follows:

- Discover: Sketching and prototyping, then testing and observing are the key activities to discover user experience both in product and service development. Pooling and sharing design materials from different sources (mobile, PC, or direct online searching) is useful.
- Define: Real-size perception of the experience is a key benefit. Prototyping experience with digital humans is an interesting tool to observe users' behaviors from different angles. Zoom in and out viewpoints in 3D helps to check both overview and details.
- Develop: The immersion brings opportunities to explore storylines to understand the purposes and goals within the user experience. Involving users in immersive design processes helps to understand XR platforms and design concepts better.
- Deliver: Users might feel higher acceptance and ownership via participatory design in immersion. This brings an opportunity to personalize the user experience for future products and services.

Considering the question of the limitations of the current immersive process, the main focuses are the human factors and the openness of the XR system.

- Simulation sickness and discomfort of headsets are still the main challenges.
- Difficult and unstandardized controls for basic interactions, like navigating in space, resizing objects, and zooming in/out.
- To provide open spaces that enable the pooling of various sources including mobile, desktop, as well as online databases and search engines.

- To support design teams in a remote coordination setup that enables multi-collaborators to work in a shared design space.

Consider the question on the key factors of an immersive design protocol - *user*, *experience*, *engagement*, and *presence* are highlighted including the following contents:

- Considering the user factor, 3D vision is the influential modality together with audio.
- For the experience factor, free walk-through and object manipulation with 3D controllers are the key features.
- For the engagement factor, the designer is fully immersed in the virtual environment that isolates him/her from the physical location.
- Regarding the presence factor, virtual objects and digital humans with basic textures are the basic components to simulate tasks and contexts. The human-system interaction might be demonstrated by animating virtual objects.

7.4. Experience Prototyping for Product-Service Systems

7.4.1. Introduction

Experience is a unique asset in our memory, which is very dynamic, complex, and subjective (Hassenzahl, 2010). Experience-driven design by its nature is human-centered in that it depends upon the human perception of multiple sensorial qualities of a design proposition (Xue & Desmet, 2019). In this sense, product-service systems can be viewed as a medium to deliver a specific experience to users (Hassenzahl, 2010; Hassenzahl et al., 2015). Hence not only representing the appearances and functions but also representing the whole experience becomes a useful tool to promote innovation (Buchenau & Suri, 2000).

As the researchers discovered in the previous section, designers are mostly interested in prototyping-related design activities within immersive environments, especially in the early design stage. This study hence aims to show how suitable prototyping with XR can be for user experience research, as well as how it can influence various design elements and design activities. Considering that panoramic immersion is the key characteristic differentiating XR prototypes from other prototypes, the researchers name it *Immersive Prototyping* (IP) in this study. Prototypes with tangible perceptions are named *Physical Prototyping* (PP) in this study.

In this study, a conceptual airplane cabin provides an appropriate example of immersive prototyping (IP), as it not only represents a typical large-scale product/service but also closely serves as a context of complex user experience. In addition, an immersive and a physical prototype of the cabin are available from the same CAD models. It offers a perfect chance to study how can immersive prototypes substitute physical prototypes for various design elements and different design activities. Two focus group sessions were organized with design professionals to explore the following research question and sub-questions:

Is an immersive experience suitable to prototype different design elements in product-service systems?

1) Is immersive prototyping maturing enough to be useful for user experience evaluation?
2) Can immersive prototyping replace physical prototyping in the early stage of design?

7.4.2. Method

Participants

Two groups of design professionals (16 in total) took part in the session in the Applied Lab of Industrial Design Engineering faculty at the campus of the Delft University of Technology between September and November 2019. There are four females and twelve males with an average age of 41.2 years. The professions of the participants covered diverse stakeholders in design cases, including product developers, project managers, design researchers, interior designers, and managers. Their design experience varied from one year to twenty-three years with an average of 13.9 years. 62.5% of the participants have used XR platforms in their design practices.

Materials

Two prototypes representing the same concept design of the Flying-V interior were included in this study (Figure 7.41 a). Figure 7.41b shows the IP - a section of real size cabin with twelve PRIVA seats (featured with a privacy shelter) as in Section 4.3 (Torkashvanda et al., 2021). The PP is the same section of the cabin with normal flight seats and other resting facilities (Figure 7.41 c).

Figure 7.41 The cabin a) and the immersive prototype b) and physical prototype c). The XR and physical prototype share the same cabin segment, while the XR prototype uses the PRIVA seats and the physical prototype includes both seats and the other resting facilities.

The layouts of seats in the immersive and physical prototypes both replicate the same interior. In a demo of IP, some participants could walk within the virtual cabin when wearing an HTC VIVE headset (1080 × 1200 resolution per eye) and interact with one of the PRIVA seats with virtual hands, while the others took the role of the observer. A physical chair was aligned with the interactive PRIVA seat so participants could check the functionalities while sitting inside the shelter.

A questionnaire (Table 7.41 and Table 7.42) was developed based on the research questions (Section 7.4.1) about the suitability of the IP for user experience studies. The questionnaire started with informed consent to be agreed upon by the participants. Then it contained two sections: the first section assesses the ease-of-use, usefulness, natural interaction, and physical/mental stresses of the IP via a 7-point Likert scale ("1" means "not at all", and "7" means "completely"). A rate less than "4" indicates the item is "unsuitable".

Table 7.41 A sample of the Likert scale in the questionnaire

How would you rate the ease-of-use of the immersive prototype regarding the interaction and navigation?

Not at all						Completely
1	2	3	4	5	6	7

The second section used the Pugh Matrix to compare the IP with the PP on different designable elements that were collected in the co-creations about immersion cycles in product-service designs (Section 7.2.2). The Pugh matrixes set the values of the PP as baseline "0". When participants thought that on one item the IP was better than the PP, its rate was "+1"; when the IP was worse than the PP on the other aspect, its rate was "-1"; when they were viewed as the same, the IP's rate was "0". Additionally, the participants' first impressions, short reflections, and general comments on the IP were collected when they were watching the IP demo and their comparisons with the PP. The full sessions were video recorded by an assistant researcher using a video camera.

Table 7.42 A sample of the Pugh matrix in the questionnaire

Please fill in the Pugh Matrixes after the discussion: Consider physical prototype as the baseline and rate VR prototype.
+1 - better than baseline; 0 - equal to it; -1 - worse than baseline.

Aspects of products	Physical prototype	XR prototype	Competences	Physical prototype	VR prototype
Colour	0		Time	0	
Material	0		Cost-effective	0	
Finishing	0		Iteration of options	0	
Shape	0		Exploring aesthetics	0	
…			…		

Procedure

The 45-minute focus group sessions were composed of three parts (Figure 7.42):

1) Introduction and demo (5 minutes): the researchers welcomed the participants and introduced the goals and process of this study. She then put on the headset and demonstrated how to navigate within the virtual cabin and interact with the virtual seat.
2) Immersive prototype assessment (20 minutes): One or two participants of each group played the role of the user interacting with the IP while walking around and sitting on the physical seat (Figure 7-4-2a). The participant who has the role of user needs to think aloud while interacting with the IP. The rest of the group plays the role of observers watching the user's actions on-site and the user's viewpoint real-time streamed on a desktop. They were asked to write down their first impressions with three to five keywords and then fill in the first section of the questionnaire while watching the demo. After the demo session, each participant gave a general comment in one or two sentences.
3) Immersive and physical prototypes comparison (20 minutes): the group was asked to move to the physical prototype and find a seat to sit. They were encouraged to discuss the differences in the perception between the IP and the PP and in which aspects the IP might replace or even surpass the physical one (Section 7.4.1 part 2). The participants needed to fill in the Pugh Matrix and their general feedback on the IP.

Data analysis

The mean and standard deviation were calculated via SPSS v.15. The participants with more than average years of design experience (13.9 years) were labeled as "experts" while the ones who had less than 13.9 years of experience were as "novices". They were classified as "designer", "manager", and "researcher" regarding their professions in design cases as well. The differences between design experience (novices and experts) and XR experiences (with or without) were compared using a two-tail independent sample t-test, while different groups of professions (designer, manager, and researcher) and the roles in the XR demo (user, observer with XR experience, an observer without XR experiences) were compared using one-way ANOVA test. If the comparison resulted in findings with $p < 0.01$, $p < 0.05$, or $p < 0.1$ (merely viewed as an indication), the researchers would report the corresponding p-values. The first impression keywords were categorized as "positive", "neutral", and "negative" to conduct semantic analysis, e.g., "innovation" as positive, "sound" as neutral, and "strange" as negative.

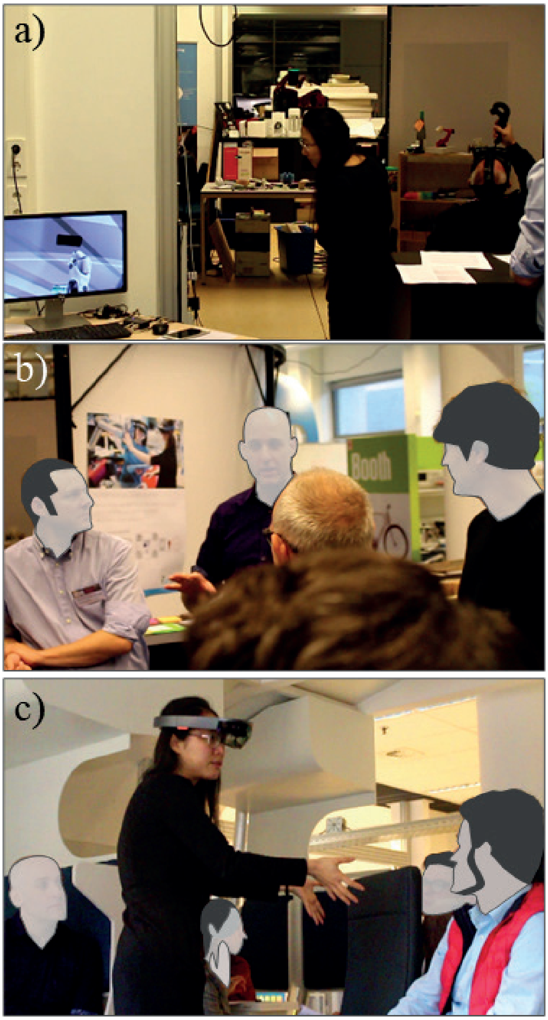


Figure 7.42 The procedure and the setup of the focus groups: a) a researcher helped a participant to interact with the XR prototype; b) the group discussed the XR prototype after watching the interaction; c) the discussion on the physical prototype.

7.4.3. Results

The number of design “experts” and “novices” was equal to eight. The average year of design experience is 13.9, whereas the average year of experts in design practices was 19.3 and the number of novices was 8.6. Detailed information about the participants is shown in *Table 7.43*.

Table 7.43 The participants' information on their experiences and roles in design, as well as their roles in the XR demo.

Role	XR experience		Design roles			XR demo roles		
	Yes	No	designer	manager	researcher	User	Observer with XR	observer without XR
Experts	5	3	3	4	1	3	2	3
Novices	5	3	3	1	4	1	5	2

First Impressions of the Immersive Prototype

The participants had more positive and neutral comments on the XR prototype, whereas those who had previous experience working on XR platforms gave no negative impressions (Table 7.44). The novices and experts seemed to have a similar attitude towards XR prototyping. Detailed information about the comments can be found in the Appendix as Table A.41.

Table 7.44 The semantic analysis of the first impression of the Immersive Prototype from design professionals with different design and XR experiences

First impressions	Total (n=16)	Novice (n=8)	Expert (n=8)	Without XR (n=6)	With XR (n=10)
Positive	15	8	7	3	12
Neutral	11	8	3	5	6
Negative	3	1	2	3	0

Considering the roles in a design team, managers and researchers seemed to be more positive than designers on the XR prototype, e.g., designers gave all three negative comments. When designers have previous experience (observer with XR) or current experience (user) on XR platforms, they both show positive attitudes toward the XR prototype.

The Suitability of Immersive Prototyping

The participants agreed that the IP is easy-to-use and useful for user experience studies (Table 7.45).

However, the *natural interaction* and the *mental-physical stresses* are rated as unsuitable. These judgments are not influenced by design and XR experience except for *ease of use*, that is both design experts and designers who had used XR showed positive attitudes toward the ease of use of IP. Different roles in design cases as well as in the demo do not influence the judgements.

Table 7.45 Design professionals with different design and XR experiences rated the suitability of the Immersive Prototype

Suitability	Total		Novice		Expert		Without XR		With XR	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ease-of-use ††	5.00	1.10	4.50	1.31	5.50	0.53	4.33	1.21	5.40	0.84
Usefulness	5.38	0.81	5.50	0.76	5.25	0.89	5.00	0.89	5.60	0.70
Natural interaction	3.50	0.82	3.50	0.76	3.50	0.93	3.33	0.82	3.60	0.84
Mental & physical stress	3.25	1.00	3.50	1.20	3.00	0.76	3.67	0.82	3.00	1.05

† indicates the $p < 0.1$.

The Comparison between the Immersive and Physical Prototyping

On the thirteen design elements, IP appears to receive lower rates than the physical one, especially on *Material*, *Finishing*, *Sensorial feedback*, and *Comfort*. Design experience or XR experience does not change their judgments except for *satisfaction*, that is both design experts and designer who has applied XR showed a positive attitude toward evaluating satisfaction-relevant user experience via IP (Table 7.46). Both design and XR experience indicated a positive influence on *satisfaction*. Considering the roles in design cases and the demo, "managers" seem to show a more positive attitude towards *space/layout*, *ease of use*, and *learnability*, while the "user" role with an immersive view also seems to be more positive on *space/layout* and *learnability*, as well as *satisfaction*.

Table 7.46 Design professionals with different roles in design cases and the demo compared the IP and PP by different system elements.

Design elements	Total (n=16)	Novice (n=8)	Expert (n=8)	Without XR (n=6)	With XR (n=10)
Color	-0.53	-0.43	-0.63	-0.67	-0.44
Material	-1.00	-1.00	-1.00	-1.00	-1.00
Finishing	-0.87	-0.86	-0.88	-0.83	-0.89
Shape	-0.47	-0.43	-0.50	-0.67	-0.33
Space/layout	-0.07	-0.17	0.00	0.00	-0.11
Reachability	-0.57	-0.33	-0.75	-0.40	-0.67
Visibility	-0.36	-0.17	-0.50	-0.60	-0.22
Accessibility	-0.62	-0.60	-0.63	-0.80	-0.50
Ease-of-use	-0.15	-0.60	0.13	-0.20	-0.13
Learnability	-0.08	-0.20	0.00	-0.20	0.00
Satisfaction ††	-0.31	-0.80	0.00	-0.80	0.00
Sensorial feedback	-1.00	-1.00	-1.00	-1.00	-1.00
Comfort	-0.85	-0.80	-0.88	-1.00	-0.75

† indicates the $p < 0.1$

The participants are positive towards IP on seven design-relevant activities out of the thirteen items, especially on the *Time, Cost-effective,* and *Iteration of options* (Table 7.47). The weak points of IP are *Tactility*, *Functionality test,* and *User communication*. Experts seem to be more positive than the novices on the *Time* item. Design and XR experience both have a significantly positive effect on the judgments of *Easy to distribute, reuse, and extend*, that is both design experts and designers who used XR believed in the value of IP in this aspect.

Table 7.47 Design professionals with different roles in design cases and the demo compared the IP and PP by different design activities.

Design competences	Total (n=16)	Novice (n=8)	Expert (n=8)	Without XR (n=6)	With XR (n=10)
Time †	0.85	0.60	1.00	0.80	0.88
Cost-effective	0.92	1.00	0.88	1.00	0.88
Iteration of options	0.85	1.00	0.75	0.60	1.00
Exploring aesthetics	0.31	0.20	0.38	0.20	0.38
Tactility	-0.77	-0.80	-0.75	-1.00	-0.63
Dynamic analysis	-0.38	-0.60	-0.25	-0.60	-0.25
Functionality test	-0.46	-0.40	-0.50	-0.60	-0.38
User communication	-0.42	-0.40	-0.43	-0.60	-0.29
Complex product	-0.23	0.00	-0.38	-0.60	0.00
Product with simple structure	-0.15	0.00	-0.25	-0.20	-0.13
Remote collaboration	0.54	0.60	0.50	0.20	0.75
Easy to distribute, reuse and extend***	0.29	0.00	0.50	-0.67	1.00
Commercally available tech.	0.08	-0.20	0.25	0.00	0.13

***indicates the p <0.01; † indicates the p <0.1.

The role in design cases has a significant influence on the judgments on design activities, e.g., *Time*, where the designers and managers have more positive feedback than the researchers (Table 7.48). Current and past XR experience play a significant role in positive rates on *Easy to distribute, reuse, and extend*.

Table 7.48 The comparison of design activities between the IP and PP with different roles in design cases and the demo.

Design competences	Designer (n=6)	Manager (n=5)	Researcher (n=5)	User (n=4)	Observer with XR (n=6)	Observer without XR (n=6)
Time***	1.00	1.00	0.33	1.00	0.75	0.80
Cost-effective	1.00	1.00	0.67	1.00	0.75	1.00
Iteration of options	0.67	1.00	1.00	1.00	1.00	0.60
Exploring aesthetics	0.33	0.25	0.33	0.25	0.50	0.20
Tactility	-0.50	-1.00	-1.00	-1.00	-0.25	-1.00
Dynamic analysis	-0.50	0.00	-0.67	-0.50	0.00	-0.60
Functionality test	-0.83	0.00	-0.33	-0.25	-0.50	-0.60
User communication	-0.50	0.00	-0.67	-0.67	0.00	-0.60
Complex product	-0.33	0.00	-0.33	-0.25	0.25	-0.60
Product with simple structure	0.00	-0.25	-0.33	-0.25	0.00	-0.20
Remote collaboration	0.67	0.50	0.33	0.75	0.75	0.20
Easy to distribute, reuse and extend***	0.33	0.20	0.33	1.00	1.00	-0.67
Commercally available tech. †	-0.33	0.50	0.33	0.00	0.25	0.00

***indicates the $p<0.01$; † indicates the $p<0.1$.

7.4.4. *Conclusion on experience prototyping using XR*

Considering the question of whether immersive prototyping is mature for user experience research, it gains the following results:

- For design professionals, immersive prototyping has mostly positive comments, including "reduce prototyping", "innovative", "immersive", "flexible system", and "fast implementation".
- Design professionals think current immersive prototyping is ease-of-use and useful for user experience evaluation. However, it brings mental and physical stresses, as well as unnatural interactions.

Considering the question of whether immersive prototypes can replace physical ones, the researchers have the following outcomes:

- For design elements, immersive prototyping is mainly sufficient for evaluating "space/layout", "ease-of-use", "learnability", and "satisfaction".
- Design professionals who have higher design and XR experience tend to show more interest in replacing PP with IP on satisfaction assessments.
- Regarding design activities, design professionals agreed on the benefits of immersive prototyping compared to the physical ones, including "time", "cost-

effective", "iteration of options", "exploring aesthetics", "remote collaboration", and "easy to distribute, reuse and extend".
- Design experts seem to be more positive on "time", while XR experts had a significantly higher acknowledgment of "easy to distribute, reuse and extend".
- Considering different roles in design cases, designers and managers are significantly more positive on 'time', while professionals with XR experience have significantly higher rates on "easy to distribute, reuse and extend".

7.5. Immersive Co-design Space

7.5.1. Introduction

Remote collaboration was mentioned as a key functionality of XR platforms in Section 2.1, and design professionals showed a positive expectation of this aspect in the previous section. Hence, the researchers need to investigate the designer's needs for an immersive space for co-design. This study aims to conduct a simulated co-design session using an XR collaboration platform – *spatial.io*[3], which is reviewed as a *conference room* in Section 2.1. Spatial allows a maximum of 50 collaborators to join a session simultaneously, and attendees can join via a VR headset, a mobile app, or a web app. It's important to know how designers would view this hybrid experience in human-centered design practices. Hence, this study aims to understand how co-design activities in immersion can facilitate human well-being.

The research question in this study is: "***How do design stakeholders coordinate with each other in an immersive co-design space?***"

7.5.2. Methods

Participants

Three participants joined this pilot study including a corporate designer, a design educator, and a senior design student. The corporate designer has more than ten years of experience in XR and training program development for an airline. The design educator has over fifteen years of teaching undergraduate and postgraduate design courses and is coordinating an association of Dutch design agencies. The design student is a Master of Design who has done several design cases. All participants have had experience with XR platforms previously.

Materials

An immersive design space (Figure 7.51) was developed using the online platform spatial.io where a design team can meet in a virtual meeting room with avatars of their

[3] Spatial.io is an online virtual gallery that support people create their own design space from desktop, mobile and XR headsets.

faces. Two participants attended this session via the desktop interface where they can move around with the keyboard, manipulate virtual objects with a mouse, and share videos via webcams (Figure 7-5-2). The other participant and the researcher attended it via VR interfaces where they could walk around or teleport, and grab and scale the objects with controllers.

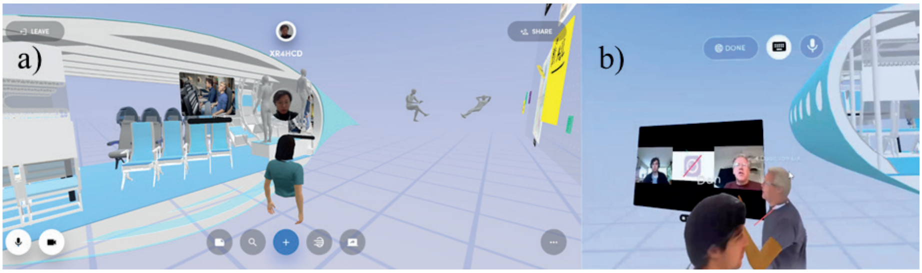


Figure 7.51 The immersive workspace during the session in Spatial.io: a) The immersive space included an immersive prototype and a virtual board; b) The participants joined the session via a desktop app both with their avatars and live videos.

The immersive design space included a real-size immersive prototype with digital manikins and a virtual board to share 2D materials, like images, videos, texts, notes, and screens (Figure 7.52). The same interior of Flying-V as in Section 7.4.2 was used as an example of immersive prototypes in this study.

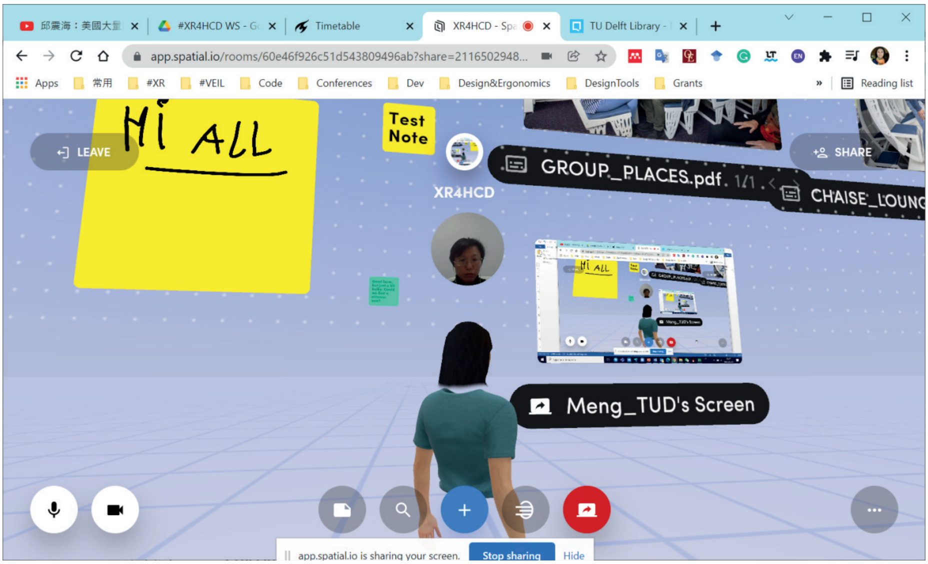


Figure 7.52 A virtual board was used for immersive co-design

The SolidWorks model of the cabin section and the various resting facilities were assigned basic textures and converted into .obj files separately using the Rhino v 6.0, and then they were converted into .glb files using the CAD Exchanger application. The PRIVA seat together with its animation was converted into the. glb format from Unreal Engine v 4.02. In the end, all .glb files were imported into Spatial.io and reassembled to their original layout. A digital human model (. stl format) represented the 95-percentile height and the 50-percentile shoulder breadth of Dutch male adults generated from the DINED database[4]. The .stl file then was converted into a .obj file via Rhino v 6.0 and imported into Spatial.io as well.

Procedure

The immersive co-design session lasted around 60 minutes, including the following steps:

1) General introduction (5 minutes): the researcher first introduced the goals and the procedure of the session, and then demonstrated how to navigate the environment and how to manipulate the immersive prototype.
2) Free try-out (10 minutes): The participants could walk around and interact with the prototype freely and the research helped them when they had problems with navigation or manipulation.
3) Immersive prototype review (10 minutes): The researcher asked the participant to come to the interior of the prototype and check its different parts.
4) Brainstorming (25 minutes): The participants were asked to work on the virtual board and take notes, and then they needed to think aloud about the shared design space.
5) General reflection (10 minutes): The researcher asked the participants to reflect both on the advantages and disadvantages of the immersive design space, as well as their expectations of a future design space.

The immersive co-design was held online in August 2021. All the participants voluntarily joined the session by receiving and signing the informed consent. The study was approved by the ethical committee of the Delft University of Technology.

Data analysis

The full session is video recorded via Zoom and then transcribed into texts. The questions were marked to indicate the designer's needs for the immersive co-design space. The comments are classified as "positive" and "negative" which refers to the potential and challenges of the immersive design space. Moreover, the potential and

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[4] https://dined.io.tudelft.nl/en/mannequin/tool

challenges are further classified according to the HCD principles "bring designers to the world of users", "bring users to the world of designers", "explore the solutions", and "evaluate solutions with users".

7.5.3. Results

Designers paid attention to the types of information that could be shared in the immersive space, and how the information is useful for co-design. They were interested in the feedback from peer designers on the immersive design space. Regarding the immersive prototype, they are concerned about the real scale of the 3D models owning to the desire to inspect the objects in 1:1 scale regardless of product or service design. Designers asked about the way to zoom in and – out of the space. They wanted to understand the workflow of importing external resources, e.g., digital humans, as well as the learning curve for organizing a co-design session. In the end, they were also interested in how to automate the import workflow.

The potentials and challenges

Potentials	Challenges
User's world	
+ Designers can easily see how the end-user will experience the product/service. + Immersive review helps to both consider fundamental requirements (like security) and critical needs (like comfort).	- Beginner had a problem navigating inside the space using a keyboard or mouse. - It's a bit confusing to review a large-scale product like a cabin on a desktop app. - The web app has different functions than the VR app, thus it limited desktop reviewers' involvement.
Designer's world	
+ It's beneficial to bring people together so they can imagine together. + The platform brings 2D and 3D together making it more creative. + The platform mixed both absorptive (desktop/ mobile) and immersive (headset) experiences and provided direct manipulations with objects.	- Some shared information looks very small from the web app, like a browser window. - Typing with a VR app is not efficient. - The platform requires extra hours to understand functions on interactions or navigation. - Beginners had the problem of putting notes in a place they wanted.
Exploring solutions	
+ For designers, designing with XR brings more fun and intuition like working with physical parts. + It's fast to do a design review with the platform. + The interaction function is useful.	- It's impossible to "undo" the model changes. - Format conversion distorts the original scales of models. - The platform could not control the sizes of models precisely.
Evaluating with users	
+ Even on the desktop, actively navigating the prototype is more useful than demonstrating on 2D media like PPT or Zoom meetings.	- Video recording function is missing. - There are technological bugs like the headset connection during the session.

7.5.4. Conclusion on immersive co-design spaces

Regarding the question of how co-design activities in immersion can facilitate coordination in a team, the following opportunities are identified:

- In connecting the "user's world" and the "designer's world", the first-person immersion enables designers to see how end users will experience their solutions. To inspect the whole experience via various criteria, immersive spaces could be beneficial to bring stakeholders together so their imagination has a common ground. The immersive design space combines 2D tools (e.g., whiteboard and notes) with 3D tools (e.g., interactive models) to check concepts from different levels of abstraction, hence designers become more creative.
- On prototyping and testing solutions, navigating, and manipulating actively with prototypes bring a better understanding than the 2D presentation. Designer stakeholders can "play" with immersive prototypes as they do with physical objectives, which brings more fun and intuition to designing. It helps to conduct design reviews fast.

7.6. Discussion on Immersion for and in Product-Service Designs

In section 7.1, the author reviewed the case studies from Chapters 4 to 6 and then identified three key dimensions of immersion supporting well-being-driven experience design: spatiality, personalization, and co-location. To align the findings with design professionals in Chapter 7, the author will discuss the outcomes from the studies in Sections 7.2 to 7.5 following these dimensions.

7.6.1. Spatiality

To introduce immersive cycles in design practices, the types and scales of design objects influence the choice of technological settings. Service and large-scale products tend to apply VR systems, while AR/MR is used to place objects within a real environment (Peruzzini, Grandi, et al., 2019). The real-size perception is also viewed as important in design processes and co-design studies. The spatial experience could be a fundamental characteristic of perception-action coupling identified in an early study of designing in virtual reality (Smets & Stappers, 1995).

To enhance design processes in immersion, a real-size perception of the experience is a key benefit. Sketching and prototyping, then testing and observing are the key activities involved in design processes. 3D vision is the influential sensor together with audio in creating a spatial experience. Zoom in and out of viewpoints in 3D helps designers to switch between different levels of abstraction.

For experience prototyping, designers acknowledged that immersive prototyping is suitable for *space* and *layout* inspection. Regarding personalization, designers found the value of immersive prototyping in *ease of use*, *learnability*, and *satisfaction*.

In the sense of co-design, design teams might gain tacit knowledge easily like working on physical objects via interaction function. The design work becomes engaging and pleasant in an immersive space. Active navigation and direct manipulation are more useful in perceiving and communicating concepts than showing them in 2D images.

Designers need to confirm space-relevant design aspects initially, like scales, shapes, layouts, or physical interactions. Thus, the main potential of XR platforms is also spatiality-relevant: space/layout validation related to the body and prototyping of large-scale objects fast and cheap to test concepts initially. The true perception of spatiality enables designers to judge relevant design elements intuitively.

7.6.2. Personalization

Different design professionals tend to prototype experiences involving diverse design elements. For instance, product developers acknowledge space- and usability-related items, like space, layout, scales, shapes, and satisfaction, while architects tend to examine color, materials, and lighting on top of these items. The explanation from the design professionals was people usually interact with a product via visual, auditory, and haptic sensors, while mainly using vision to check buildings. Hence, the sensors involved in daily human-system interaction might determine the design elements to be investigated in immersion as well.

In integrating immersive experience, designers desire to observe actual users and natural user experience from users' eyes, especially in inaccessible situations like ICUs or emergencies. In addition, designers benefit from the "wow" effect on stakeholders to increase their involvement. It makes XR platforms a natural way to collect users' data. XR platforms bring the opportunity to check the concepts from the user's perspective during using procedures. Free walk-throughs and direct object manipulation are identified as key factors for the experience, as their importance is also proposed in an early study of VR-facilitated designing (Smets & Stappers, 1995).

Users might feel higher acceptance and ownership via participatory design in immersion. To replicate the experience fast and cheaply, virtual objects and digital humans with basic textures could be used to simulate tasks and contexts. The human-product interaction can be simulated by animating virtual objects. Digital human is important in creating relevant narratives and contexts. For instance, the behaviors of digital humans can represent both distractions in a context or triggers of the storyline.

Prototyping experience via XR platforms is an interesting tool to observe users' behaviors from different angles. The immersion brings opportunities to explore storylines to understand the purposes and goals within the user experience. Involving users in immersive design processes helps to understand XR platforms and design concepts better.

7.6.3. Co-location

To gain an immersive experience from the user's perspective, designers want to view the product through the user's eyes. They need a chance to try immersive training to gain tacit knowledge of procedures and actions for complex products/services. XR platforms also provide unlimited spaces where designer teams can explore concepts in real size at any scale. This need is also mentioned in the design process and co-design study. In addition, designers showed positive comments on remote collaboration and the convenience of distributing, reusing, and extending immersive prototyping.

Prototyping in an immersive space together showed the potential to co-locate stakeholders virtually to share their imagination about an experience. This would provide a common ground for establishing a shared point of view (Buchenau & Suri, 2000). Thus, a design team could make decisions on design proposals fast. To facilitate co-design, a mixture of absorptive and immersive experiences helps stakeholders to "jump in" and "jump out" of the experience from the user's perspective. It supports the consideration of various design elements at the same time, such as security and comfort.

7.7. Conclusions

When returning to the question "*What strategies do designers apply when introducing extended reality in product-service design practices?*", the author could identify the possibilities of integrating XR in product-service design practices following the three dimensions of immersion, as well as the main challenges:

1) **Spatiality**: as also acknowledged in early studies on designing with VR, the immersive experiences provide a vivid spatial experience link to people's senses of their own body – the "perception-action" coupling, which is an intuitive and natural way to judge space and size related design elements, like visibility, reachability, sizes, layouts. Thus, representing designs in true sizes and scales is a key enabler of XR systems.

Large-scale products and service developers would prefer VR as the way to prototype experiences, while AR/MR would be suitable to check if objects match their environment. In addition, this in-situ-like experience could easily trigger the recall of relevant past experiences from the users. The first-person immersion helps designers observe their concepts from the user's perspective.

2) **Personalization**: designers are eager to observe actual users and user experiences via XR, e.g., panoramic video streams of real user scenarios, especially those difficult to access like ICU. In turn, when participating in design processes via XR, users might find it easier to accept a design and gain ownership of the design. Moreover, different design professionals focus on various elements of an experience, for instance, product developers like the space- and usability-related items, while architects prefer to check color, materials, and lighting in XR. Thus, clearly defining the target users and corresponding sensorial stimulus of a particular experience is the starting point of crafting experiences in XR.
3) **Co-location**: to gain the empathy of a particular user group, designers desire to see the system through the user's eyes. Co-location also means designers want to take a virtual hands-on to gain tacit knowledge of the system by themselves, and they expect that interacting with digital twins of the system via XR would help to skip the mandatory security procedures and thus accelerate design projects. Putting design stakeholders virtually together in a shared design space aligns their envision of a future system easier and faster. Sharing spatial information about the system across the team is also critical for smooth coordination.
4) Several limitations in these co-creations might indicate directions for future studies: 1) a larger population of designers is needed. The sessions invited in total of 24 designers with various types and experience levels of design professionals, like service designers, product developers, and architects, including senior designers, junior designers, and design students alike. We included design managers and design researchers as well. Several types only have one person as a representative, thus the result can be biased by personal opinions. 2) Systematic analysis is required. The sessions collected mostly qualitative data, and only reported according to general topics. Further studies are required to apply systematic approaches like thematic analysis or protocol analysis to understand the designer's thinking under immersion. 3) The designer's attitudes towards XR prototypes need further investigation. Though section 7.4 did a survey about XR prototyping, its statistical relevance requires verification from a larger design population.

In general, the main challenges of XR technologies are mostly bound to human factors and their interface design. The most prominent ones are the simulation sickness symptoms and the comfort of long-term use (e.g., longer than 1 hour daily). The secondary issues are the ways to navigate and manipulate objects in XR, which currently require a guided familiar session before the formal studies. It limits the capability to conduct remote user research via XR and requires to development of a new design protocol. The last issue is related to the openness of XR platforms and the unification of data formats. Leading companies and consortiums put continuous efforts into regulating the transplantable formats, like the Open XR (a set of royal-free and open standards for XR) are now supported by mainstream XR platforms (e.g., Unity 3D, Unreal Engine, and HTC Vive).

CHAPTER 8

General Discussion and Conclusion

In the field of design, using a virtual environment to simulate inaccessible situations was initiated in the mid-1990s. However, the immersive technologies were at their infantry. The interest is accelerated by the soaring need for digitalization, especially during global crises (IDC, 2020b). Extended Reality (XR), an immersive virtual world that could interact with the physical world - has become the center of world attention recently (Shaw, 2021). What emerged from previous chapters, is that a smooth integration of immersive experience in design practices requires deep optimizations on human, technology, and organizational aspects, such as human factors of immersive technological systems, resources allocation on design teams, and systematic configurations of production pipelines. The main argumentation of this dissertation was when viewing products, services, and systems as mediators of human experiences, extended reality (XR) technologies, such as virtual reality, mixed reality, or augmented reality provide a new horizon to prototype these experiences for better well-being.

This dissertation presented the models of immersive experience and a conceptual process in which the factors of immersive experiences were described via reviewing design cases from the literature. This process has served as a structure for a series of case studies (immersive design, immersive training, and immersive collaboration) on how to integrate immersive experiences to fulfill the fundamental needs of humans. The insights from these case studies proposed three dimensions of immersion in designing: spatiality, personalization, and co-location, as designing is a way to develop positive experiences for product-service systems. The last work focused on exploring immersive experiences in design practices. The insights of these cases will be used as input for the recommendations to support designers and researchers to involve extended reality systems for user experience design.

How this dissertation contributes to the integration of immersive experiences in designing to enhance human well-being is discussed below.

8.1. Discussions on Main Conclusions

sRQ1: What are the key factors of immersive experiences in product-service systems both from the user's and designer's perspectives?
Chapter 2 discussed this research question by reviewing immersive technological systems as well as literature centering around the perception of "immersion".

From the user's perspective, the Immersion Cycle (IC) model describes how an immersive experience is generated. It starts with sensorial and cognitive memories in relevant user experiences in the real world, and ends with new memories from "virtual places". By recognizing the steps involved in this cycle, a guideline was proposed to dive deeply into the immersive characteristics of design proposals. Designers or developers can view the IC as a mapping tool of processes towards immersion, or as a starting point to ideate or conceptualize a user-centered immersive experience. The effectiveness of these guidelines was reviewed later (Chapter 7) with design teams in immersive design protocols during a pilot study.

From a designer's perspective, immersive technological systems serve as methods and tools to regenerate experiences. Their effectiveness often takes priority in implementation. Eighty-eight immersive technological platforms (namely XR platforms) were collected and mapped in the sense of design assisting and experience inspiring. As tools for design assisting, nearly half of these platforms concentrate on creating XR experiences, simulating real-life actions, modeling for collective review, and remotely assisting with augmented annotations. Various platforms can support design activities throughout the *Double-Diamond Model*, where *discover* and *define* stages contain XR platforms that are generally unfamiliar in the design circle.

Current XR platforms are scattered across the four quarters of Pine and Gilmore's experience matrix, which mostly focuses on the active experience. For creating XR applications, team meetings, and collaboration, XR platforms usually apply absorptive experience with 2D interfaces. For simulating, modeling, and exploring, XR platforms mainly involve immersive experiences in a virtual environment.

sRQ2: What are the roles of state-of-the-art extended reality technologies in developing user experience for product-service systems?
Chapter 3 focused on this research question via a scoping review to analyze the UX studies applying immersive experiences for performance and/or well-being. The top three sectors of implementing immersive technologies are mobility, control room, and workstation, as well as manufacturing. Two scales of products and services are

focused on, *elbow-height* and *beyond human heights*. Products at the first scale have a lot of physical interaction with human bodies, while the second scale is often beyond the scope of rapidly producing full-scale physical prototypes. As confirmed by early studies on VR-facilitated designing, the "spatiality" within an immersive virtual environment "gave the best possible impression of three-dimensionality" (Smets & Stappers, 1995).

XR systems are good at collecting quantitative and hybrid data, whose attention is on triangulating subjective and objective feedback from users. These systems are usually combined with conventional ergonomic tools for better design qualities, including RULA, NASA-TLX, or psychological scales, as confirmed by Di Gironimo et al. (2006). Particularly for large-scale products, XR systems allow involving a larger user sample with time-cost efficiency than traditional HCD methods.

XR Technologies for User Experience

Along with the realistic scale representation, an immersive experience usually involves information like texture, lighting, horizon references, and motion parallax. This information from XR systems allows people to actively navigate and manipulate, as indicated by the mapping of XR platforms in Chapter 2. In addition to fully digital systems as the mainstream, more and more XR systems choose to create a blend of sensorial sensation by aligning virtual artifacts with physical parts. Introducing physical parts provides proprioception in immersive experiences. It substantially benefits designing scales in product-service systems in that spatial perception can be enhanced via the sense of embodiment (the feeling of having a body inside the virtual world) (Scharff, 2021). This tendency indicates the attempts of designers to create a true-to-life experience that is relevant to users.

Immersive experiences depend on technological specifications such as visual resolution and tracking technologies (e.g., 2K to 4K resolution, or head-tracking). The advancements in XR technologies are mainly concentrated on headset-based systems, as they lower the threshold of introducing immersive experiences to explore human-system interaction. The other technological options are custom-developed platforms, combining projectors, large- or multi-wall screens, stereoscopic glasses, 3D controllers (e.g., Wii controller or gamepad), or simplified full-scale simulators. Such systems often bond with specific use case which is more expensive, more complex, and less flexible.

As XR technical systems are progressing rapidly, this study thus defined the objective characteristics of technological systems as immersive factors, including *Sensory*, *Interaction*, *Realism*, and *Involvement*. An immersive experience in UX mainly requires a medium level of each factor, while the *realism* factor usuallyneeds a high level. The key characteristics that contribute to immersion include stereoscopic vision plus another sensorial feedback for *sensory*, active navigation and direct object handling for *interaction*, and invisible interfaces with challenges for *involvement*. To reach a high level of *realism*, XR systems need to encompass the following characteristics: real-size virtual and/or physical objects, task simulation, texture rendering, environment simulation, and digital humans. To engage users, XR experiences usually involve challenges like emergencies, high workload tasks, distractors, or teamwork.

Immersion is not only influenced by the objective aspects of XR systems but also determined by user characteristics. The case studies in Chapter 5 hence investigated how the user's characteristics will influence their perception of an immersive experience.

A conceptual process of experience prototyping via XR
This chapter then combined the insights from Chapters 2 and 3 to form a conceptual process for "translating" daily positive experiences to humans' needs and desires, and then into immersive experiences. To integrate immersive experience in user experience design, this research thus proposed a conceptual framework containing four pillars: positive experiences, experience prototyping, design processes, and immersion cycles. This process indicated a way to design for experience via immersive technologies focusing on human well-being. The XR-based experience prototypes could bridge the immersion stimulation cycles of users with the experience creation cycles of designers. The experience prototyped via XR technologies generates immersion cycles inside users. When the users are under immersion cycles, designers can collect their data beyond real environments. They can precisely observe natural behaviors, automatically control variables, collect real-time multi-modality data, enable post-hoc simulation, and reuse assets with cost efficiency.

Among the domains of UX, a combination of different domains can form compound design qualities that anchor different needs inside humans. Currently, immersive experiences are mostly applied in physical and cognitive domains, where the sense of scales helps to review design proposals intuitively. The organizational aspect is limited by the complexity of simulating collaborative behaviors. XR systems showed the potential to study design qualities that link different domains in UX, such as comfort for physical perception and cognition, competence for skill acquisition, or relatedness in remote teamwork.

The experience prototyping converts target design qualities into immersive experiences provided by the above-mentioned XR systems. In current XR cases, the design qualities related to effectiveness gain the most attention, followed by efficiency. Satisfaction seemed to be out of the focus, especially during the stages to *develop* and *deliver* design proposals. This phenomenon implies that the current implementation of immersive experiences in design practices is explorative instead of daily utilization. The imperfections of current immersive technologies seem to surpass the benefits; hence the designers are concerned that these glitches would affect users' judgments of products. The enablers and barriers of XR systems will be further discussed in section 8.3.

sRQ3: How can designers efficiently ideate user experience via spatial presence in conceptualization?

Chapter 4 highlighted the research questions via three case studies to probe the processes that introduce immersive experiences to improve satisfaction-related designs. These case studies concentrated on inviting end-users during the early design stages, in which designers are most interested. Comfort is a compound design quality discussed in this chapter, representing one of the fundamental needs that influence both in-situ satisfaction and long-term well-being. It thus serves as a central topic in the field of ergonomics. The sense of comfort involves multiple sensory perceptions intertwining both physical and cognitive domains.

Like the cases in Chapter 3, Case One combined classic HCD methods with VR prototyping in the context of long-haul traveling. In a design process, the problem-solution co-evolution plays a key role, this study hence focused on the concept selection and verification. A key point is observing how these processes help designers surpass the fixation on initial concepts and evaluate alternatives. The results showed that VR prototyping helps designers to converge initial concepts with alternatives, and users provided concrete feedback backed by their past life experiences during their immersion cycles. The perception of space-related design elements (like space, height, storage, and facilities) is particularly built on immersion cycles. The "being there" effect seemed to activate memories of the history of relevant experience, the 'truth' behind a specific experience (Gadamer, 2004). The participant's comfort perception hence was different when the same design elements were presented with narratives or were viewed against the spatial context. Subsequently, the preferences between user groups seemed to become more obvious with the XR prototypes than with the narrative version.

Case Two probed the feasibility of an interactive VR prototype with animated functions to evaluate the comfort and satisfaction of a new concept compared with the current one. The frequent flyers acknowledged the advantage of the XR prototype as a "high fidelity simulation of an existing experience" enhanced by spatial experience and intuitive interaction. The vivid perception of the enclosure from the 'virtual shelter' was enhanced by intuitive interaction using stereoscopic vision and embedded motion-tracking technology. A new point of inflight comfort was discovered, as group flyers seemed to be more aware of privacy than individual flyers.

Sharing immersive viewpoints helps to transfer the awareness of local situations to remote members, and thus has been applied in the security and maintenance sectors. However, cases in the design field are rare. Case three thus investigated a setup of sharing the immersive viewpoint of a VR prototype with a desktop viewer for a comfort-relevant design review. This setup combined two functionalities of XR platforms mentioned in Chapter 2: the exploration in immersion and the remote review. The results indicated that the comfort perception of size-related design elements was different between the VR review (active-immersive mode) and the desktop review (passive-absorptive mode). With adequate scales compared to the desktop review, the VR review enables the inspection of details at first glance. It thus resulted in a more diverse perception among reviewers. The desktop review triggered higher simulation sickness symptoms due to passive navigations. To reduce the simulation sickness, the novice members shall share their immersive viewpoints with the experts instead of vice versa, and the viewpoint shall be separated from the head motions of the XR viewer (like in Case Eight).

Spatial Presence and Spatiality

The spatial presence from XR experiences influences the comfort perception of space-relevant design elements. Experience in daily life always happens in a specific place, where spatial and contextual information is a critical part of the history of the experience. The immersion from a first-person view is of paramount importance to understand the spatial and contextual information cost-efficiently or enable true-to-life exploration/evaluation of design proposals under impossible conditions. XR systems showed great potential as a designer's virtual playground for ideating and prototyping not only the product but also the contexts. To further human well-being in physical and cognitive domains, different design elements might require different fidelity in immersive prototyping.

Regarding the immersive factors for spatiality, the stereoscopic interactive review (sensory), interactive embodiment (realism), and active navigation (interaction) are critical to perceiving the nuances between concepts that facilitate the problem-solution co-evolution. The VR headset can create isolation from the real environment which increases the involvement during the sessions.

sRQ4: How can designers effectively assess user experience via social presence across different user groups?

Chapter 5 investigated the research question via three case studies to indicate the influences of user characteristics on immersive experiences to promote professional skill acquisition. Competence in a profession, such as laparoscopy, is a compound design quality. It spontaneously involves different layers of skills, such as psychomotor skills, descriptive knowledge, procedural knowledge, as well as self-management. Training competence thus requires long learning curves plus many resources. Besides, the tediousness of long-term training demotivates trainees. This chapter hence took competence as an example to represent the needs for performances that mainly cover the cognitive and organizational aspects of UX. As engagement plays a key role in a learning process, these case studies observed the *involvement* factor of immersion, i.e., the interfaces and distractions, as discovered in the review (Chapter 3).

Case four concentrated on the influences of proficiency on competence perception. Immersive training would reduce the task load (except for *performance* and *frustration*) of an expert but increase the *perceived effort of learning*. The simulated audio distractors enhanced the perception of immersion and, at the same time might increase the mental effort of novices. The resemblance of a virtual world to the real world seemed to release stress. High *mental demand* plus low *frustration* of novices implied that the simulated distractors brought challenges to engaging trainees throughout the session.

Case five analyzed the responses of a group of trainees from different cultural backgrounds toward the same set of immersive contexts and distractions. The professional experience played a similar role in reducing the task load on the *mental demand*, but also on a *low subjective mental workload* and a *high achievement of goals*.

Case six cross-examined the proficiency, cultural background, and XR familiarity, as well as their interactive effects. The occupational experience could affect the *mental demand* in the general task load. Cultural background is differentiated in every aspect, especially on *match with the real world, uses users' language, user control,* as well as *self-evaluation of performance, subjective mental workload,* and *perceived achievement of goals*. The familiarity with XR systems mainly reduced the rates of *quality of interfaces*. Cultural background significantly influenced the perception of mental workload, intuitiveness, and realism, whereas occupational experience altered mental workload perception.

Social presence and personalization

Social presence influences the competence perception of users with different characteristics, particularly from different cultures. The distractors, especially the social distractors like team interactions, have different effects on learning behaviors under different cultural contexts. The case studies identify the variation of users' responses from different cultural backgrounds towards the same XR content. This would effectively facilitate the cross-culture design. The personalized/localized simulation of visual and auditory distractions, such as the sound of pagers, phone calls, music, conversations, and team interactions, would easily trigger autobiographical memory - the vivid, visual-auditory, emotional accounts of relevant procedures. Hence it leads to a high level of involvement and creates emotional engagement that activates the "flow state" for better learning efficiency.

The most salient issue of immersive training is associated with the interfaces, especially the haptic and visual interfaces. The interface designs that disrupt the manipulations in real life might cause discomfort and even physical traumas for long-term use. Considering both the interaction and realism factor, the real challenge is replicating true-to-life maneuvers and procedures that convey tacit knowledge matching the real-world experience. The improper interfaces inside a virtual environment would disturb the learning flow and impoverish the perception of immersion.

sRQ5: How can designers facilitate user experience via co-presence in remote collaboration?

Chapter 6 examined this research question via two case studies to assess the visual interfaces in immersive experiences to facilitate relatedness in tele-cooperation. Tele-cooperation is related to the need to 'be related' in teamwork - coordinating work with team members with various knowledge. It is the compound design quality scrutinized in this chapter. In teamwork, information alignment throughout the team is of paramount importance, which is supported at its best by putting the team in a shared space. The relatedness in remote teamwork thus encompasses the organizational as well as the physical and cognitive domains. These cases required generating a shared experience with continuous information exchanges to create common situational awareness within a team.

The spatial information of large-scale products and services is of interest in UX, as mentioned in Chapter 3. Case seven thus compared non-immersive and immersive interfaces for a factory planning task regarding situation awareness, as well as task load, intuitive use, and presence for both local and remote workers. The immersive interfaces showing both real-size and miniature scenarios to the remote worker increased the intuitiveness and situation awareness of the local worker. The real-size immersive interface could increase the perceived performance of local workers during tele-cooperation. A quick switch between real-size and miniature views is needed to convey both spatial information and the overview of the contexts.

Social presence has a positive effect on competence perception, as discussed in Chapter 5. Case eight, therefore, explored an immersive workspace with semi-immersive interfaces to guide procedural and detail operations during remote assistance. Offering the co-presence of experts via an XR experience largely increased the confidence of a non-expert toward complex tasks. Sharing a near first-person view and virtual annotations plus vocal instructions could communicate detailed and procedural information accurately. Controlling virtual annotation (e.g., virtual hands), especially their proportions against the context might determine the accuracy of the guidance. The stability (independent of body motions) and adjustability (changing angles and zoom-in/-out) of the shared view would improve the performance of the coordination.

Co-presence and co-location

The co-presence affects the sense of co-location and consequently the communication efficiency between the remote and local team members. However, novel interfaces (e.g., hand tracking, vocal commands, or virtual hands) are unfamiliar to users and are prone to errors, hence would require a well-defined training protocol to ensure smooth collaboration. For observing users' behaviors, XR systems would enhance the situation awareness of the remote designers in local contexts and increase their confidence in performance judgments.

For the *sensory* factor, the immersive interfaces communicate spatial and contextual information more efficiently, thus facilitating situation awareness and reducing workload. Non-immersive interfaces can accurately communicate detailed and procedural information by sharing the first-person view and virtual annotations. Regarding the *interaction* factor, sharing the gaze beams and hand postures on both sides might help to reduce the time pressure and, then consequently the frustration. Considering the *realism* factor, balancing the complexity of real-world tasks and the feasibility of implementation is critical in simulating collaboration effectively and efficiently. For *involvement*, scenarios matching the roles in real-world workflows challenge the skills of real-time communication during the collaboration.

sRQ6: What strategies do designers apply when introducing extended reality in product-service design practices?

Chapter 7 explored this research question via four pilot studies to explore the way of introducing XR in design practices to enhance user experience. Combining the analyses of the case studies and pilot studies, three dimensions of immersive experiences appeared that facilitate user experience design - *spatiality*, *personalization*, and *co-location*. Considering *spatiality*, representing designs in true sizes and scales is a key enabler for physical well-being. Considering *personalization*, clearly defining target users and the corresponding sensorial stimulus of an experience is the starting point. Considering *co-location*, putting design stakeholders together in a virtual co-design space can align their visions of a future system.

Design expertise is a key factor influencing the way to involve XR in design practices. Design experts focus on specific design activities like presenting, while design novices are open to exploring XR throughout the design process. This finding is in line with the outcomes of the XR platform mapping. Designers generally agree that fully immersive design protocols are engaging and creative because they can easily externalize their imagination about the experience. Designers with different design expertise focused on different activities. The senior designers focused on sketching prototypes and body-storming about the ergonomics of these prototypes; while junior designers appreciated the immersive protocol as a whole and showed interest in learning different functions in the protocol. Both senior and junior designers naturally put digital humans in the protocol either to represent human sizes or to indicate target users.

Both design expertise and XR familiarity significantly influenced designers' attitudes toward the substitution between immersive and physical prototypes. Design experts focus on the time-saving features and XR experts agreed on the convenience of reusing assets. The designers who were familiar with XR technologies or interacted with the immersive prototype were significantly more positive towards immersive prototypes. This is in line with the findings about spatial experiences in immersive design (Chapter 4). The object of design professionals alters their attitudes toward design elements, for example, product developers emphasize the real-size perception but are unsatisfied with haptic fidelity, while service designers focus on the truthfulness of procedure simulation, whereas architects intend to check space, light, materials, and color in immersion. The suitability of XR to simulate design elements depends on intertwining perception, cognition, action, and emotion in relevant real-world experiences.

Designers expect the supremacy of immersive prototyping to increase design advantages such as remote assistance, time efficiency, cost-effectiveness, and iteration of options. It matches the improvements of XR systems mentioned in the case studies. Some designers want to explore aesthetics with immersive experiences, which might focus on shape and scale. An obvious imperfection in immersive prototyping is the perception of materials, composed of color, texture, and finishing (Di Cicco, 2021).

The limitations of current XR systems are mainly bound to human factors and system openness, as also partly mentioned in the mapping of XR platforms in Chapter 2:

- For sketching or ideating activities, simulation sickness and discomfort of headsets limit the duration of use to one hour.
- Difficult and unstandardized controls for basic interactions, like navigating in large spaces, resizing objects, and zooming in/out.
- The learning threshold of an XR workflow could reach 2500 to 3000 hours.
- The openness of XR systems is expected to support design processes by combining 2D and 3D tools.

8.2. Implications of this dissertation

Immersive Experience Prototyping for Human Well-being

The main research question of this dissertation is: ***How can designers use extended reality to develop the user experience for product-service systems?***

The challenge in user experience design is to bridge the gap or, at least, to allow for shorter leaps from needs to technology. Before determining the functionalities of a product-service system and ways to operate these functionalities, designers should first create the story of the system. To craft the story, the process in Chapter 3 provides a possibility that generalizes design qualities from positive experiences and specifies them in an immersive experience via XR technologies.

From a designer's perspective, immersive experiences provide safe conditions to stimulate realistic postural, cognitive, emotional, and collaborative responses at affordable monetary and time expenses. XR enables them to study natural behaviors under any conditions that are too dangerous, expensive, or complex to carry out. The possibility to automate design protocols by reusing virtual objects or coding empowers designers to run studies with a vast number of variables. Furthermore, emerging XR systems are embedding more and more tracking techniques at low costs, such as head-, hands-, and sometimes eye-tracking or face-tracking, which collect abundant user data that is missing in real-world studies due to expenses or feasibility (Apple, 2023;

Oculus, 2020). During immersive usages, future systems might enable seamless data collection and faster feedback loops that support design iteration better.

From a user's perspective, people are emotionally involved with high engagement and concentration under immersive experiences. XR systems show the potential of being a more personalized, distributed, and on-demand medium both for design and education. The first and foremost concerns of introducing XR in UX design are the ergonomics and human factors of these systems, including but not limited to simulation sickness, discomfort and high effort in usage, low usability, and even negative effects on performances. Improvements on sensorial fidelities are needed, for instance, limited field-of-view and graphic resolution, depth perception, haptic fidelity, mismatched sensory, and missing virtual bodies/avatars. Despite natural interactions, it is still unfamiliar to most people how to use XR systems, hence it requires a new design protocol with well-defined training sessions. Finally, virtual environments are confounding factors themselves, and the author calls for more studies to discuss the differences between XR and the real world regarding different aspects of UX.

Implementing XR systems usually involves the resources to configure both hardware and software, stream data via protocols, process models into compatible formats, program interaction/visualization, and debug the system. These skills currently are not included in educational or training curriculums for design professionals. Though dazzling technological advances in XR are opening new horizons for UX practices, the socio-technological concerns of implementing XR are worth paying more attention to. These concerns include but are not limited to steep learning curves of coding, streamlining the workflow from sketches to interactions, the validation of XR experiences compared to real-world scenarios, and so forth.

Recommendations for Creating an Immersive Experience Prototype

At the design organization level

- Considering the threshold of required resources, integrating immersion in design practices should be viewed as a long-term strategy instead of an independent tool to implement in the short term.
- Design professionals who want to realize this strategy should put R&D budgets on it, particularly on man-hour resources.
- Considering the ergonomics of XR systems, such as discomfort, simulation sickness, and physical demands, planning a mixture of both XR and desktop work might improve the well-being of the team by increasing physical activities.

- The acceptance of XR among a team can be very different, while junior designers are more willing to learn XR development as a part of personal competencies, senior designers usually expect "one-click" solutions for specific functions like scale check or projecting in a real environment.
- The main concerns about immersive prototyping are abstractness, unfamiliarity, and suitability. Immersive prototyping is easy to use and useful for getting feedback, however, these technologies might bring about mental and physical stress.
- Design professionals expect benefits from design activities like *time*, *cost-efficiency*, *design iterations,* and *remote collaboration*, as well as *exploring aesthetics* and *ease-to-distribute, -reuse, and -extend*.
- Professionals who are familiar with immersive technologies often show a positive attitude toward implementing immersive experiences in design work. The designers who have no XR experience might show reluctance in trying out immersive prototyping.
- Design experts expected XR prototyping to be more efficient on tasks such as *time* and *easy to distribute, reuse, and extend*.

At the design team's level

- Immersive experience prototyping shall provide an open space that collects and shares design materials across different sources, such as desktop, mobile, and online databases.
- Designers shall prototype an experience, including real-size objects, digital humans, storylines, environments, as well as challenges.
- A set of basic controls shall be shared across different XR systems, including navigating and teleporting, resizing, and zooming in/out.
- There should be a "one-click" function to help designers to display XR scenes in real size.
- Different creation tools shall be integrated into one environment like whiteboard, sketching, and polygons.
- A cross-system template of XR applications is needed to set up universal reference points and units to eliminate the distortion of the original scales.
- Co-locating design teams within the same virtual scene is necessary for teamwork.
- Designers could start immersive prototyping that might replace the physical ones in the designable elements like *space/layout*, *easy-of-use*, *learnability*, and *satisfaction*.
- *Color*, *material*, and *finishing*,as well as *reachability, accessibility, sensorial feedback,* and *comfort,* could be evaluated by combining physical parts to enhance the haptic fidelity.

At the design stakeholder's level

- The protocol should be developed to set up the co-design processes and make sure the prototype is unchangeable during the review. A clear workflow should indicate when to interact and when to make comments.
- A guided tour instead of a completely free exploration helps design stakeholders who join the immersive co-design for the first time to focus on the review.
- By involving users, the experience can be more personal, e.g., participatory design of the seats or the interior. The personalized experience will increase immersion as well.
- To be more active and immersive is the direction of future technological trends.

Design Metaverse(s)

The term "Metaverse(s)" was originally invented by Neal Stephenson in the science fiction novel "Snow Crash". It depicts the immersive virtual world(s) that metaphorizes the real world while following different rules, so people can do what's impossible in the real world, and have plenty of space to expand, thus creating value through their activities. People goggle into Metaverse(s) with their audio-visual avatars as a place where experiences are hard to forget. The avatars not only give people a different identity but can reflect the changes and emotions in real life. This digital graphic world is "a fictional structure made out of codes where magic is possible" (Stephenson, 2000). Programming these codes is connecting pre-defined code units, like building LEGOs. The visitors of Metaverse(s) could make the goggles transparent to see the reality, then turn on the view of the Metaverse(s) and return to it. All these features of 'Metaverse(s)" would endow design communities with many opportunities to open new horizons that accentuate user experience design in immersion. In terms of technology, recent advancements in extended reality will make these features commercially affordable (Apple, 2023; VARJO, 2021). When envisioning the future possibility of designing in immersion, the author would like to propose the concept of *Design Metaverse(s)* – an immersive co-design community.

As a collection of design communities, the Design Metaverse offers an infinite, co-located virtual "playground" where designers team up with users to learn about human needs and desires via iterative and fast loops in immersive experience prototyping. Design Metaverse shows possibilities to expand in three dimensions – *Spatiality*, *Personality*, and *Co-location* to cover the physical, cognitive, and organizational aspects of the human-system interaction. Design cases with shared design qualities and elements could compose a sub-space to share assets like models, materials, storyboards, and codes (Figure 8.31). Moreover, artificial intelligence (AI) has recently attracted much attention in graphic designer communities to generate 2D artworks at very low cost and high efficiency, like stylized paintings (Jining, et al., 2019). In terms of 3D creation, AI-driven design also drew attention in the field of game and environmental design, where most XR technologies are also applied (Li, 2021; Spronck et al., 2018). Considering the complexity of manually generating assets for immersive experiences, researchers attempt to introduce AI to accelerate the creation work for XR applications, particularly in the domain of medical training and mobility design (Reiners et al., 2021).

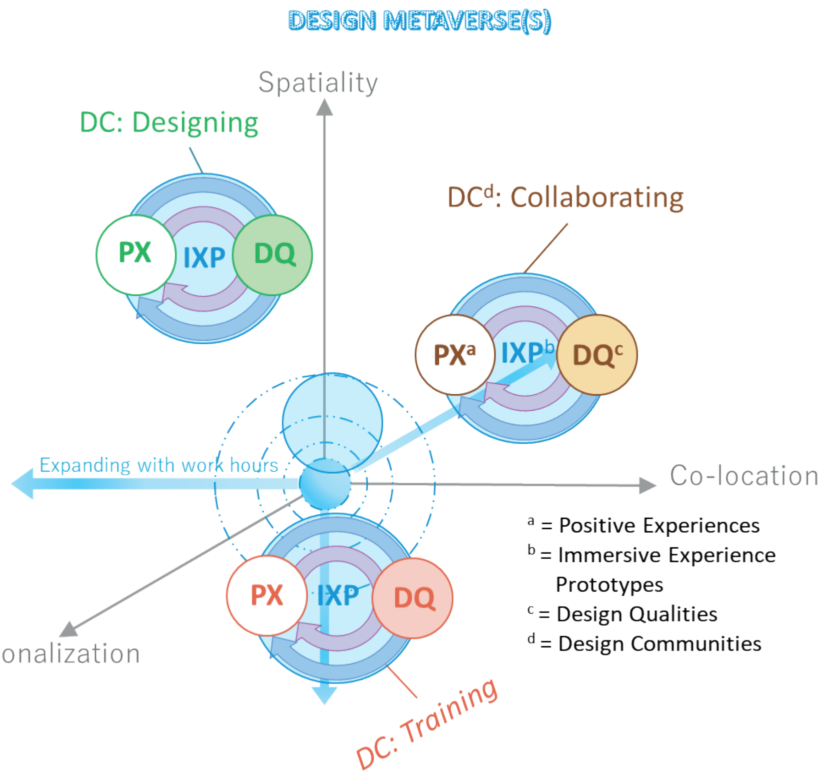

Figure 8.31 A conceptual diagram of immersive design communities - Design Metaverse(s).

The potential directions of Design Metaverse(s) are projected in:

- "One-click" prototyping: comparing multiple design concepts via interactive controls on individual design elements.
- Participatory design: design stakeholders interact with immersive prototypes together in fast loops with different levels of fidelity.

- Smooth pipelines: towards design processes with low monetary and man-hour costs.
- Natural UIs: the improvements in hardware and software regarding human factors and interfaces.
- Trans-platform space: to provide open spaces that enable the pooling of various sources including mobile, desktop, as well as online databases and search engines.
- Smart creation: AI engines that create assets (e.g., models, materials, scenes, and codes) for immersive experiences based on textual descriptions.
- Assets markets and warehouses: though current mainstream engines currently provide online stores to purchase assets, the available sources are still very limited. Trans-platform asset management and exchange systems might be needed when more and more design teams join the community.

8.3. Limitations and Future Works

This dissertation discussed the way to integrate immersive experiences into design practices to enhance design qualities in the sense of human well-being. This dissertation calls up further studies to develop tools to facilitate the transformation from utility-focused design toward experience-focused design: at the user level, designer level, and organization level to authorize experience design. Some results from this research might be debatable, but the urgency of this transformation is not. However, there are critical themes that need further research:

Avatars

As a core component in the Metaverse, an avatar usually portrays an alter ego who performs a social role or persona in the virtual world (Park et al., 2021). Avatar studies is a central topic in social VR that focuses on social behaviors in a virtual world, generally out of the scope of this research. However, the case studies and pilot design studies (Chapter 4 and Chapter 7) demonstrated twofold values of avatars both as anthropometric references and as user personas. On one hand, first-person and third-person views of anthropometric avatars provide an intuitive reference to judge space-related design elements; on the other hand, the effect, when embedding designers in user avatars to literally "see through their eyes", is rarely studied. Further studies shall first put effort into understanding how avatars facilitate design teams to gain empathy in perception, cognition, emotion, and social meanings. Second, how the appearances of avatars might influence design-relevant communication that requires scrutiny. Moreover, the appearance styles of avatars might also influence the perception of the user persona.

Emotion

Though there were no deliberate studies on the emotional effects of immersive experience, most case studies denoted the influences of emotion in immersion on designated design qualities. For instance, participants reported refreshed feelings after using the VR hygiene space. Most surgical trainees experienced a hilarious sensation when they stepped into the virtual operating room. Additionally, the simulated auditory environment of the virtual operating room engaged people deeply in the context, hence releasing frustration during the training. The virtual co-presence of experts decreases the anxiety and stress of novice co-workers. McCarthy and Wright (2004) noted in "Technology as Experience" that "emotions are qualities of particular experiences". High-order cognitive functions like learning, decision-making, and coordination, crucially depend on emotion. A critical question that needs further research is the emotional effects of immersive technology as a mediator of experience. A secondary question is whether this emotional effect truly reflects the user's emotion under the corresponding situation in real life. Finally, the stability of this emotional effect shall be measured as it is related to maintaining learning motivations.

Methodology

To propose a possible way to integrate XR into design practices, this dissertation developed the main research question and divided it into sRQs. Considering the explorative nature of this doctoral research, its roadmap consists of three phases: the descriptive studies in the theoretical field explored and defined the scope; the prescriptive studies on specific design cases demonstrated the influences of XR in the user experience; the explorative studies in design practices indicated the empirical knowledge from the design community. Regarding feasibility, this research separated the conceptual design method into different case studies and co-creations instead of one main project and assumed that a summary of their conclusions would contribute to the main question. Considering the various populations and methods applied in these studies, the researcher hence generalized the "common sense" that resonates across these studies, which largely depends on the researcher's interpretation. Therefore, further studies are needed to integrate XR into a full design process at a deeper level in the long run. Additionally, the design cases are selected in that they represent the aspects that are less studied according to the scoping review. They are fragments from the spectrum of the design field. There is plenty of room to apply XR in various design cases across different design stages.

Potential Risks

Though the interest in integrating immersive experiences in design can be traced back to the early 1990s, applying immersive technologies is still far from the daily routines in design practices. Hence, the insights in this dissertation are primitively based on the XR applications focused on exemplar design qualities and limited samples that can oversimplify the immersive experience. Though this research targets designing experience, the studies contained can only take the angle of manipulating a single element to craft the experience. The framework thus attempted to provide an approach toward the topic of designing in immersion, however, design guidelines, protocols, and tools are still needed.

A key benefit of XR is the abundance of data sources that surpass the most known smart devices. This might impose a serious issue on data security and privacy, as Stephenson also warned in the fictional narrative of "Snow Crash". The studies on the ethical protocol of collecting, processing, publishing, and reusing human data with immersive technologies are of paramount significance for the field of designing in immersion.

An experience is subjective, holistic, and dynamic, thus becoming unique and irreducible to be truly replicated, particularly in showing real emotion. Being aware that there are human experiences that cannot be regenerated in immersion. Furthermore, despite the vivid visualization, the immersive virtual world might distort the natural way of human communication as we experienced on other digital information platforms, like Zoom, Facebook, and Instagram. Hence, the question about the proper extent to which design teams shall involve immersive experiences requires further examination as well.

8.4. Concluding Remarks

Originating from a long-last interest, immersive experiences generated by emerging XR technologies make an alternative approach to shaping experience. This dissertation scrutinizes the efficacy of extended reality in improving the user experience for product-service systems. This work could serve as a gateway toward a field where design activities and processes can be conducted fully in a highly immersive virtual environment. This, soon, shows potential to form a new type of design community - *Design Metaverse(s).*

One should bear in mind that immersion is only one way among the thousands of routes toward understanding and creating experiences. For example, the pivotal figure in classical philosophical Daoism, Zhuangzi had a famous dialogue with his friend Hui Shi on fish pleasure.

> *"Zhuangzi and Hui Shi wandered over the Hao River bridge. Zhuangzi said, "Those mini-fish coming from there and cruising around, relaxed and unhurried, are fish at leisure." Hui Shi said, "You are not a fish; from whence do you know the leisure of fish?" Zhuangzi retorted, "You are not me, from what perspective do you know my not knowing fish at leisure?" Hui Shi responds, "I'm not you, of course, I don't know about you; You are not a fish and that's enough to count as you're not knowing fish's leisure." Zhuangzi concludes, "Let's return to where we started. When you said 'From what perspective do you know fish at leisure', you clearly knew my knowing it as you asked me. I knew it here above the Hao. (Ibid., HY 45/17/87–91)"*

Human beings may apply different concepts of knowing in different situations, among which there is a right way to grasp the essence of truth (Hansen, 2021).

BIBLIOGRAPHY

Abdi, H. (2007). Bonferroni and Šidák corrections for multiple comparisons. *Encyclopedia of measurement and statistics*, *3*, 103--107.

Ahlers, K. H., Kramer, A., Breen, D. E., Chevalier, P.-Y., Crampton, C., Rose, E., Tuceryan, M., Whitaker, R. T., & Greer, D. (1995). Distributed augmented reality for collaborative design applications. *Computer Graphics Forum*, *14*(3), 3--14. https://doi.org/10.1111/j.1467-8659.1995.cgf143_0003.x

Ahmadpour, N., Lindgaard, G., Robert, J.-M., & Pownall, B. (2014). The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. *Ergonomics*, *57*(6), 801-815. https://doi.org/10.1080/00140139.2014.899632

Ahmed, S., Zhang, J., & Demirel, O. (2018). Assessment of Types of Prototyping in Human-Centered Product Design. In *Digital Human Modeling. Applications in Health, Safety, Ergonomics, and Risk Management* (pp. 3-18). https://doi.org/10.1007/978-3-319-91397-1_1

Alatta, R. A., & Freewan, A. (2017). Investigating the effect of employing immersive virtual environment on enhancing spatial perception within design process. *Archnet-IJAR: International Journal of Architectural Research*, *11*(2), 219.

Almeida, A., Rebelo, F., & Noriega, P. (2016). Development of a Virtual Environment for Safety Warnings Behavior Compliance Evaluation. In R. F. & S. M. (Eds.), *Advances in Ergonomics in Design* (Vol. 485, pp. 35-42). Springer. https://link.springer.com/chapter/10.1007/978-3-319-41983-1_4

Althoff, T., White, R. W., & Horvitz, E. (2016). Influence of Pokemon Go on Physical Activity: Study and Implications. *J Med Internet Res*, *18*(12), e315. https://doi.org/10.2196/jmir.6759

Anjani, S., Li, W., Ruiter, I. A., & Vink, P. (2020). The effect of aircraft seat pitch on comfort. *Applied Ergonomics*, *88*, 103132. https://doi.org/10.1016/j.apergo.2020.103132

Apple. (2023). *Introducing Apple Vision Pro: Apple's first spatial computer*. Apple Newsroom. Retrieved June 25, 2023 from https://www.apple.com/newsroom/2023/06/introducing-apple-vision-pro/

Arastehfar, S., Liu, Y., & Lu, W. F. (2013). On design concept validation through prototyping: Challenges and opportunities. DS 75-6: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 6: Design Information and Knowledge, Seoul, Korea, 19-22.08. 2013.

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International Journal of Social Research Methodology*, *8*(1), 19-32. https://doi.org/10.1080/1364557032000119616

Armstrong, S. (2018, November 29). *Extended reality: what's stopping businesses from adoption? Raconteur Publishing*. Raconteur. Retrieved January 17, 2022 from https://www.raconteur.net/technology/vr-ar/extended-reality-barriers-adoption/

Aromaa, S., & Väänänen, K. (2016). Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design. *Applied Ergonomics*, *56*, 11-18. https://doi.org/10.1016/j.apergo.2016.02.015

Arora, R., Habib Kazi, R., Grossman, T., Fitzmaurice, G., & Singh, K. (2018, 2018-April). SymbiosisSketch. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, Montreal; Canada.

Arroyave-Tobon, S., & Osorio-Gomez, G. (2017). Ergonomic analysis in conceptual design stage using a gesture-based modelling tool. *International Journal of Interactive Design and Manufacturing*, *11*(3), 481-488. https://doi.org/10.1007/s12008-015-0289-9

Aschenbrenner, D., Leutert, F., enen, A., Verlinden, J., Schilling, K., Latoschik, M., & Lukosch, S. (2019). Comparing human factors for augmented reality supported single-user and collaborative repair operations of industrial robots. *Frontiers in Robotics and AI*, *6*, 37.

Aschenbrenner, D., Li, M., Dukalski, R., Verlinden, J., & Lukosch, S. (2018). Exploration of different Augmented Reality Visualizations for Enhancing Situation Awareness for Remote Factory Planning Assistance. Fourth IEEE VR International Workshop on 3D Collaborative Virtual Environments (3DCVE 2018),

Aschenbrenner, D., Sittner, F., Fritscher, M., Krauß, M., & Schilling, K. (2016). Cooperative remote repair task in an active production line for industrial internet telemaintenance. *IFAC-PapersOnLine*, *49*(30), 18-23.

Ashbrook, D., Guo, S. S., & Lambie, A. (2016). *Towards Augmented Fabrication: Combining Fabricated and Existing Objects* Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems, San Jose, California, USA. https://doi.org/10.1145/2851581.2892509

Aukstakalnis, S. (2016). *Practical augmented reality: A guide to the technologies, applications, and human factors for AR and VR*. Addison-Wesley Professional. https://books.google.de/books/about/Practical_Augmented_Reality.html?id=4oz_DAAAQBAJ&redir_esc=y

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355-385.

Badash, I., Burtt, K., Solorzano, C. A., & Carey, J. N. (2016). Innovations in surgery simulation: a review of past, current and future techniques. *Annals of translational medicine*, *4*(23), 453. https://doi.org/10.21037/atm.2016.12.24

Bai, H., Sasikumar, P., Yang, J., & Billinghurst, M. (2020, apr). *A User Study on Mixed Reality Remote Collaboration with Eye Gaze and Hand Gesture Sharing* Conference on Human Factors in Computing Systems - Proceedings, https://dl.acm.org/doi/10.1145/3313831.3376550

Ball, L. J., & Christensen, B. T. (2019). Advancing an understanding of design cognition and design metacognition: Progress and prospects. *Design Studies*, *65*, 35-59.

Barfield, W., Baird, K. M., & Bjorneseth, O. J. (1998). Presence in virtual environments as a function of type of input device and display update rate. *Displays*, *19*(2), 91-98.

Barr, A. H., Hitchcock, H.-R., Gropius, W., Nelson, G., Ralph, T. W., Tunnard, C., Gutheim, F., Marcel, B., Blake, P., Kallmann, G., Hamlin, T., Mumford, L., & Koch, C. (1948). What Is Happening to Modern Architecture? *The Bulletin of the Museum of Modern Art*, *15*(3), 4-20. https://doi.org/10.2307/4058109

Barton, J. D., Cybyk, B., Drewry, D. G., Frey, T. M., Funk, B. K., Hawthorne, R. C., & Keane, J. F. (2011). Use of a High-Fidelity UAS Simulation for Design, Testing, Training, and Mission Planning for Operation in Complex Environments. *Wiley Encyclopedia of Operations Research and Management Science*. https://doi.org/10. 1002/9780470400531.eorms0154

Benford, S., Greenhalgh, C., Reynard, G., Brown, C., & Koleva, B. (1998). Understanding and Constructing Shared Spaces with Mixed-Reality Boundaries. *ACM Transactions on Computer-Human Interaction*, *5*(3), 185-223. https://doi.org/10.1145/292834.292836

Bennes, L., Bazzaro, F., & Sagot, J. C. (2012). Virtual reality as a support tool for ergonomic-style convergence: Multidisciplinary interaction design methodology and case study. 2012 Virtual Reality International Conference, VRIC'12, Laval; France.

Berg, L. P., & Vance, J. M. (2017). An Industry Case Study: Investigating Early Design Decision Making in Virtual Reality. *Journal of Computing and Information Science in Engineering*, *17*(1), 011001. https://doi.org/10.1115/1.4034267

Berg, L. P., & Vance, J. M. (2017). Industry use of virtual reality in product design and manufacturing: a survey. *Virtual Reality*, *21*(1), 1-17.

Berghman, M., & Hekkert, P. (2017). Towards a unified model of aesthetic pleasure in design. *New Ideas in Psychology*, *47*, 136-144. https://doi.org/https://doi.org/10.1016/j.newideapsych.2017.03.004

Bergroth, J. D., Koskinen, H. M. K., & Laarni, J. O. (2018). Use of Immersive 3-D Virtual Reality Environments in Control Room Validations. *Nuclear Technology*, 202(2-3), 278-289. https://doi.org/10.1080/00295450.2017.1420335

Berguer, R., Chen, J., & Smith, W. D. (2003). A Comparison of the Physical Effort Required for Laparoscopic and Open Surgical Techniques. *Archives of Surgery*, *138*(9), 967-970. https://doi.org/10.1001/archsurg.138.9.967

Berguer, R., Smith, W. D., & Chung, Y. H. (2001). Performing laparoscopic surgery is significantly more stressful for the surgeon than open surgery. *Surgical Endoscopy*, *15*(10), 1204-1207. https://doi.org/10.1007/s004640080030

Bernard, F., Zare, M., Sagot, J. C., & Paquin, R. (2019). Virtual reality simulation and ergonomics assessment in aviation maintainability. 20th Congress of the International Ergonomics Association, IEA 2018, Florence; Italy.

Bhagat, K. K., Liou, W.-K., & Chang, C.-Y. (2016). A cost-effective interactive 3D virtual reality system applied to military live firing training. *Virtual Reality*, *20*(2), 127-140. https://doi.org/10.1007/s10055-016-0284-x

Billinghurst, M., Weghorst, S., & Furness, T. (1998). Shared space: An augmented reality approach for computer supported collaborative work. *Virtual Reality*, *3*(1), 25-36. https://doi.org/10.1007/BF01409795

Biocca, F., Harms, C., & Burgoon, J. K. (2003). Toward a More Robust Theory and Measure of Social Presence: Review and Suggested Criteria. *Presence*, *12*(5), 456-480. https://doi.org/10.1162/105474603322761270

Boess, S. U. (2009, 18/10/09 → 22/10/09). Designing in research: characteristics and criteria: research method, questions and programme. IASDR2009 "Design Rigor & Relevance", Seoul.

Bokharaei, S., & Nasar, J. L. (2016). Perceived Spaciousness and Preference in Sequential Experience. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *58*(7), 1069-1081. https://doi.org/10.1177/0018720816650068

Bordegoni, M., Colombo, G., & Formentini, L. (2006). Haptic technologies for the conceptual and validation phases of product design. *Computers & Graphics*, *30*(3), 377-390. https://doi.org/10.1016/j.cag.2006.02.012

Bordegoni, M., Cugini, U., Caruso, G., & Polistina, S. (2009). Mixed prototyping for product assessment: a reference framework. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *3*(3), 177-187. https://doi.org/10.1007/s12008-009-0073-9

Bordegoni, M., & Ferrise, F. (2013). Designing interaction with consumer products in a multisensory virtual reality environment This paper shows how Virtual Reality technology can be used instead of physical artifacts or mock-ups for the new product and evaluation of its usage. *Virtual and Physical Prototyping*, *8*(1), 51-64. https://doi.org/10.1080/17452759.2012.762612

Bordegoni, M., Ferrise, F., & Cugini, U. (2013). Development of virtual prototypes based on visuo/tactile interaction for the preliminary evaluation of consumer products usage. CIRP Design 2012 - Sustainable Product Development, Bangalore; India.

Boven, v. L., & Gilovich, T. (2003). To Do or to Have? That Is the Question. *Journal of personality and social psychology*, *85*(6), 1193-1202. https://doi.org/10.1037/0022-3514.85.6.1193

Bowman, D. A., Gabbard, J. L., & Hix, D. (2002). A survey of usability evaluation in virtual environments: Classification and comparison of methods. *Presence-Teleoperators and Virtual Environments*, *11*(4), 404-424. https://doi.org/Doi 10.1162/105474602760204309

Bowman, D. A., & McMahan, R. P. (2007). Virtual Reality: How Much Immersion Is Enough? *Computer*, *40*(7), 36-43. https://doi.org/10.1109/mc.2007.257

Brooks, K. (2003). There is nothing virtual about immersion: Narrative immersion for VR and other interfaces. *Motorola Labs/Human Interface Labs*.

Brown, B., MacColl, I., Chalmers, M., Galani, A., Randell, C., & Steed, A. (2003). *Lessons from the Lighthouse: Collaboration in a Shared Mixed Reality System* Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, https://doi.org/10.1145/642611.642711

Bruno, F., & Muzzupappa, M. (2010). Product interface design: A participatory approach based on virtual reality. *International Journal of Human-Computer Studies*, *68*(5), 254-269. https://doi.org/10.1016/j.ijhcs.2009.12.004

Brynjolfsson, E., & McAfee, A. (2014). *The second machine age: Work, progress, and prosperity in a time of brilliant technologies*.

Buchanan, R., & Csikszentmihalyi, M. (1991). Flow: The Psychology of Optimal Experience. *Design Issues*, *8*(1), 80-81. https://doi.org/10.2307/1511458

Buchenau, M., & Suri, J. F. (2000, August 01). Experience prototyping. DIS '00: Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques, Brooklyn, New York.

Bulu, S. T. (2012). Place presence, social presence, co-presence, and satisfaction in virtual worlds. *Computers & Education*, *58*(1), 154-161. https://doi.org/https://doi.org/10.1016/j.compedu.2011.08.024

Burdea, G. C., & Coiffet, P. (2003). *Virtual reality technology*. John Wiley & Sons.

Buzink, S., Soltes, M., Radonak, J., Fingerhut, A., Hanna, G., & Jakimowicz, J. (2012). Laparoscopic Surgical Skills programme: preliminary evaluation of Grade I Level 1 courses by trainees. *Wideochirurgia i inne techniki maloinwazyjne = Videosurgery and other miniinvasive techniques*, *7*(3), 188-192. https://doi.org/10.5114/wiitm.2011.28895

Cai, M., & Luo, J. (2020). Influence of COVID-19 on manufacturing industry and corresponding countermeasures from supply chain perspective. *Journal of Shanghai Jiaotong University (Science)*, *25*(4), 409--416.

Cappetti, N., Naddeo, A., Califano, R., & Vallone, M. (2017). Using axiomatic design to identify the elements that affect the evaluation of comfort/discomfort perception. In *Advances in Social & Occupational Ergonomics* (pp. 235-248). Springer.

Carlson, N. R. (2010). *Psychology: The science of behaviour*. Pearson Education.

Carroll, J. M., Singley, M. K., & Rosson, M. B. (1992). Integrating theory development with design evaluation. *Behaviour & information technology*, *11*(5), 247-255. https://doi.org/10.1080/01449299208924345

Carswell, C. M., Clarke, D., & Seales, W. B. (2005). Assessing mental workload during laparoscopic surgery. *Surg Innov*, *12*(1), 80-90. https://doi.org/10.1177/155335060501200112

Caruso, G., Polistina, S., Bordegoni, M., & Aliverti, M. (2011). Collaborative mixed-reality platform for the design assessment of cars interior. 4th International Conference on Virtual and Mixed Reality, Held as Part of HCI International 2011, Orlando, FL; United States.

Caruso, G., & Re, G. M. (2010). Interactive Augmented Reality System for product design review. In *Engineering Reality of Virtual Reality 2010* (Vol. 7525, pp. 75250H). Spie-Int Soc Optical Engineering.

Carver, C. S., Scheier, Michael F. (1990). Origins and Functions of Positive and Negative Affect: A Control-Process View. *Psychological Review*, *97*(1), 19-35.

Castelan, E., Vinnikov, M., & Alex Zhou, X. (2021, July 5). Augmented Reality Anatomy Visualization for Surgery Assistance with HoloLens. International Conference on Interactive Media Experiences (ACM IMX'21), New York City, US.

Catalano, G. (2011). Virtual Reality In Interactive Environments: A Comparative Analysis Of Spatial Audio Engines. *SAE Institute Oxford*.

Cater, J. P., & Huffman, S. D. (1995). Use of the Remote Access Virtual Environment Network (RAVEN) for Coordinated IVA—EVA Astronaut Training and Evaluation. *Presence: Teleoperators \& Virtual Environments*, *4*(2), 103--109.

Cencen, A., Verlinden, J., & Geraedts, J. (2016). Qualifying the performance of Human Robot coproduction at a relabling station. *Tools and Methods for Concurrent Engineering*, 1--10.

Ceruti, A., Marzocca, P., Liverani, A., & Bil, C. (2019). Maintenance in aeronautics in an Industry 4.0 context: The role of Augmented Reality and Additive Manufacturing. *Journal of Computational Design and Engineering*, *6*(4), 516-526. https://doi.org/10.1016/J.JCDE.2019.02.001

Chen, W., Shidujaman, M., & Xuelin, T. (2020). *AiArt: Towards Artificial Intelligence Art* ThinkMind // MMEDIA 2020, The Twelfth International Conference on Advances in Multimedia, Lisbon.

Chintamani, & Rastogi, S. (2019). Tool or the Teacher?—Mentoring and Mastering Using Simulation in Surgery. *Indian Journal of Surgery*, *81*(3), 207-210. https://doi.org/10.1007/s12262-019-01909-0

Coburn, J. Q., Freeman, I., & Salmon, J. L. (2017). A review of the capabilities of current low-cost virtual reality technology and its potential to enhance the design process. *Journal of Computing and Information Science in Engineering*, *17*(3).

Cooper, J. B., & Taqueti, V. R. (2004). A brief history of the development of mannequin simulators for clinical education and training. *Postgraduate Medical Journal*, *84*(997), 563-570. https://doi.org/10.1136/qshc.2004.009886

Corbusier, L. (2004). *The Modulor and Modulor 2* (Vol. 1). Springer Science & Business Media.

Corbusier, L. (2014). *Towards a New Architecture* (Reprint ed.). Martino Fine Books.

Cowgill, J. L., Gilkey, R. H., & Simpson, B. D. (2013). The VERITAS facility: A virtual environment platform for human performance research. 12th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human - Machine Systems, HMS 2013, Las Vegas, NV; United States.

Cross, N. (2001). Design Cognition: Results from Protocol and other Empirical Studies of Design Activity. *Design Knowing and Learning: Cognition in Design Education*, 79-103. https://doi.org/10.1016/B978-008043868-9/50005-X

Cross, N. (2006). *Designerly Ways of Knowing*. Springer. https://doi.org/ https://doi.org/10.1007/1-84628-301-9.

Cross, N. (2018). Developing design as a discipline. *Journal of Engineering Design*, *29*(12), 691-708. https://doi.org/https://doi.org/10.1080/09544828.2018.1537481

Csikszentmihalyi, M. (2000). *Beyond boredom and anxiety*. Jossey-Bass.

Csikszentmihalyi, M. (2008). *Flow: The Psychology of Optimal Experience* (1st ed.). Harper Perennial Modern Classics.

Cummings, J. J., & Bailenson, J. N. (2015). How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence. *Media Psychology*, *19*(2), 272-309. https://doi.org/10.1080/15213269.2015.1015740

Davenport, T. H., & Kirby, J. (2016). *Only Humans Need Apply: Winners and Losers in the Age of Smart Machines*.

Dawe, S. R., Pena, G. N., Windsor, J. A., Broeders, J. A., Cregan, P. C., Hewett, P. J., & Maddern, G. J. (2014). Systematic review of skills transfer after surgical simulation-based training. *Br J Surg*, *101*(9), 1063-1076. https://doi.org/10.1002/bjs.9482

De Crescenzio, F., Bagassi, S., Asfaux, S., & Lawson, N. (2019). Human centred design and evaluation of cabin interiors for business jet aircraft in virtual reality. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *13*(2), 761-772. https://doi.org/10.1007/s12008-019-00565-8

de Giorgio, A., Romero, M., Onori, M., & Wang, L. (2017). Human-machine Collaboration in Virtual Reality for Adaptive Production Engineering. *Procedia Manufacturing*, *11*, 1279-1287. https://doi.org/10.1016/j.promfg.2017.07.255

Deb, S., Carruth, D. W., Sween, R., Strawderman, L., & Garrison, T. M. (2017). Efficacy of virtual reality in pedestrian safety research. *Applied Ergonomics*, *65*, 449-460. https://doi.org/10.1016/j.apergo.2017.03.007

B

Deci, E. L., & Ryan, R. M. (2000). The "What" and "Why" of Goal Pursuits: Human Needs and the Self-Determination of Behavior. *Psychological Inquiry*, *11*(4), 227-268. https://doi.org/10.1207/S15327965PLI1104_01

Delangle, M., Petiot, J. F., & Poirson, E. (2017). Using motion capture to study human standing accessibility: comparison between physical experiment, static model and virtual ergonomic evaluations. *International Journal of Interactive Design and Manufacturing - Ijidem*, *11*(3), 515-524. https://doi.org/10.1007/s12008-016-0304-9.

Demirel, H. O., & Duffy, V. G. (2017). Incorporating Tactile Cues into Human-Centered Virtual Product Design. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *27*(1), 5-16. https://doi.org/10.1002/hfm.20402

Design Council. (2007). *Eleven lessons: Managing design in eleven global companies-desk research report*. D. Council. www.designcouncil.org.uk

Design Council. (2021). *Design methods*. Design Council. Retrieved May 01, 2021 from www.designcouncil.org.uk/news-opinion/design-methods-step-1-discover

Desmet, P., & Fokkinga, S. (2020). Beyond Maslow's pyramid: introducing a typology of thirteen fundamental needs for human-centered design. *Multimodal Technologies and Interaction*, *4*(3), 38. https://www.mdpi.com/2414-4088/4/3/38

Desmet, P., & Hekkert, P. (2007). Framework of Product Experience. *International Journal of Design*, *1*(1). http://www.ijdesign.org/index.php/IJDesign/article/view/66

Dey, A., Billinghurst, M., Lindeman, R. W., & Swan, J. E. (2018). A systematic review of 10 Years of Augmented Reality usability studies: 2005 to 2014. *Frontiers Robotics AI*, *5*(APR). https://doi.org/10.3389/frobt.2018.00037

Di Cicco, F. (2021). *Convincing stuff: Disclosing perceptually-relevant cues for the depiction of materials in 17th century paintings* [Dissertation, Delft University of Technology]. Delft.

Di Gironimo, G., Guida, M., Lanzotti, A., & Vanacore, A. (2012). Improving quality of train interiors through a VR-based participative design approach. *1*, 383-393. https://doi.org/10.1115/ESDA2012-82946

Di Gironimo, G., Lanzotti, A., & Vanacore, A. (2006). Concept design for quality in virtual environment. *Computers & Graphics*, *30*(6), 1011-1019. https://doi.org/10.1016/J.CAG.2006.08.002

dos Santos, I. J. A. L., dos Santos Grecco, C. H., Mol, A. C. A., & Carvalho, P. V. R. (2009). The use of questionnaire and virtual reality in the verification of the human factors issues in the design of nuclear control desk. *International Journal of Industrial Ergonomics*, *39*(1), 159-166. https://doi.org/10.1016/j.ergon.2008.08.005

Douglas, Y., & Hargadon, A. (2000). The pleasure principle: immersion, engagement, flow. Proceedings of the eleventh ACM on Hypertext and hypermedia,

Duarte, E., Rebelo, F., Teles, J., & Wogalter, M. S. (2014). Behavioral compliance for dynamic versus static signs in an immersive virtual environment. *Applied Ergonomics*, *45*(5), 1367-1375. https://doi.org/10.1016/j.apergo.2013.10.004

Duarte, E., Rebelo, F., & Wogalter, M. S. (2010). Virtual Reality and its potential for evaluating warning compliance. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *20*(6), 526-537. https://doi.org/10.1002/hfm.20242

Dukalski, R., Çençen, A., Aschenbrenner, D., & Verlinden, J. (2017). Portable Rapid Visual Workflow Simulation Tool for Human Robot Coproduction. *Procedia Manufacturing*, *11*, 185-197. https://doi.org/10.1016/J.PROMFG.2017.07.223

Dul, J., Bruder, R., Buckle, P., Carayon, P., Falzon, P., Marras, W. S., Wilson, J. R., & van der Doelen, B. (2012). A strategy for human factors/ergonomics: developing the discipline and profession. *Ergonomics*, *55*(4), 377-395.

Dyer, R. F., Matthews, J. J., Wright, C. E., & Yudowitch, K. L. (1976). *Questionnaire construction manual* https://apps.dtic.mil/dtic/tr/fulltext/u2/a037815.pdf

Endsley, M. R. (2013). Situation awareness. In *The Oxford handbook of cognitive engineering.* (pp. 88-108). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199757183.001.0001

Ens, B., Lanir, J., Tang, A., Bateman, S., Lee, G., Piumsomboon, T., & Billinghurst, M. (2019). Revisiting collaboration through mixed reality: The evolution of groupware. *International Journal of Human Computer Studies*, *131*, 81-98. https://doi.org/10.1016/j.ijhcs.2019.05.011

Ermi, L., & Mäyrä, F. (2005). Fundamental Components of the Gameplay Experience: Analysing Immersion. Changing Views: Worlds in Play-Selected Papers of the 2005 Digital Games Research Association's Second International Conference,

Eyal, R., & Tendick, F. (2001). Spatial ability and learning the use of an angled laparoscope in a virtual environment. Medicine Meets Virtual Reality 2001, JD Westwood et al, Editors. In: IOS Press, Amsterdam.

Faisal, A. (2017). Computer science: Visionary of virtual reality. *Nature*, *551*(7680), 298-299. https://doi.org/10.1038/551298a

Favi, C., Moroni, F., Manieri, S., Germani, M., & Marconi, M. (2018). Virtual Reality-Enhanced Configuration Design of Customized Workplaces: a Case Study of Ship Bridge System. *Computer-Aided Design and Applications*, *16*(2), 345-357. https://doi.org/10.14733/cadaps.2019.345-357

Femia, J. (2006). *Pareto and Political Theory*. Routledge. https://doi.org/10.4324/9780203508626

Fite-Georgel, P. (2011). *Is there a reality in industrial augmented reality?*

Flin, R., O'Connor, P., & Mearns, K. (2002). Crew resource management: improving team work in high reliability industries. *Team Performance Management: An International Journal*, *8*(3/4), 68-78. https://doi.org/10.1108/13527590210433366

Forbes, T., Kinnell, P., & Goh, M. (2018). A study into the influence of visual prototyping methods and immersive technologies on the perception of abstract product properties. 13th Biennial Norddesign Conference, NordDesign 2018, Linkoping; Sweden.

Forlizzi, J., & Battarbee, K. (2004). *Understanding experience in interactive systems* Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques, Cambridge, MA, USA. https://doi.org/10.1145/1013115.1013152

Freina, L., & Ott, M. (2015). A literature review on immersive virtual reality in education: state of the art and perspectives. The international scientific conference elearning and software for education,

Friemert, D., Saala, F., Hartmann, U., & Ellegast, R. (2018). Similarities and Differences in Posture During Simulated Order Picking in Real Life and Virtual Reality. *Digital Human Modeling: Applications in Health, Safety, Ergonomics, and Risk Management*, *10917*, 41-53. https://doi.org/10.1007/978-3-319-91397-1_4

Gadamer, H.-G. (2004). *Truth and method*. Continuum.

Ganni, S., Botden, S. M. B. I., Chmarra, M., Li, M., Goossens, R. H. M., & Jakimowicz, J. J. (2020). Validation of Motion Tracking Software for Evaluation of Surgical Performance in Laparoscopic Cholecystectomy. *Journal of Medical Systems*, *44*(3). https://doi.org/10.1007/s10916-020-1525-9

Ganni, S., Chmarra, M. K., Goossens, R. H. M., & Jakimowicz, J. J. (2017). Self-assessment in laparoscopic surgical skills training: Is it reliable? [journal article]. *Surg Endosc*, *31*(6), 2451-2456. https://doi.org/10.1007/s00464-016-5246-6

Ganni, S., Li, M., Botden, S. M. B. I., Nayak, S. R., Ganni, B. R., Rutkowski, A.-F., Goossens, R. H. M., & Jakimowicz, J. (2020). Virtual Operating Room Simulation Setup (VORSS) for Procedural Training in Minimally Invasive Surgery – a Pilot Study. *Indian Journal of Surgery*, *82*(5), 810-816. https://doi.org/10.1007/s12262-020-02131-z

Gaver, W. (2002). Designing for Homo Ludens. *I3 Magazine*, *12*.

Gero, J. S., & Mc Neill, T. (1998). An approach to the analysis of design protocols. *Design Studies*, *19*(1), 21-61. https://doi.org/10.1016/s0142-694x(97)00015-x

Giunta, L., O'Hare, J., Gopsill, J., & Dekoninck, E. (2018). A review of augmented reality research for design practice: looking to the future. DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th-17th August 2018.

Goedicke, D., Li, J., Evers, V., & Ju, W. (2018). Vr-oom: Virtual reality on-road driving simulation. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.

Gordon, S., Ryan, A., & Loughlin, S. (2018). Meeting the Needs of Industry in Smart Manufacture - The Definition of a New Profession and a Case Study in Providing the Required Skillset. Procedia Manufacturing.

Gothelf, J., & Seiden, J. (2013). *Lean UX: Applying lean principles to improve user experience*. O'Reilly Media Inc.

Gould, J. D., & Lewis, C. (1985). Designing for usability: key principles and what designers think. *Communications of the ACM*, *28*(3), 300-311. https://doi.org/10.1145/3166.3170

Grajewski, D., Górski, F., Zawadzki, P., & Hamrol, A. (2013). Application of Virtual Reality Techniques in Design of Ergonomic Manufacturing Workplaces. *Procedia Computer Science*, *25*, 289-301. https://doi.org/10.1016/J.PROCS.2013.11.035

Gregoriades, A., Hadjicosti, J., Florides, C., & Pamapaka, M. (2015). Human Requirements Validation for Complex Systems Design. *Procedia Manufacturing*, *3*, 3033-3040. https://doi.org/10.1016/j.promfg.2015.07.848

Guo, Z., Zhou, D., Zhou, Q., Zhang, X., Geng, J., Zeng, S., Lv, C., & Hao, A. (2020). Applications of virtual reality in maintenance during the industrial product lifecycle: A systematic review. *Journal of Manufacturing Systems*, *56*, 525-538.

Haeling, J., Winkler, C., Leenders, S., Kebelheim, D., Hildebrand, A., & Necker, M. (2018). In-Car 6-DoF Mixed Reality for Rear-Seat and Co-Driver Entertainment. 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Tuebingen/Reutlingen, Germany.

Halabi, O., & Halwani, Y. (2018). Design and implementation of haptic virtual fixtures for preoperative surgical planning. *Displays*, *54*, 9-19.

Hamberg-van Reenen, H. H., van der Beek, A. J., Blatter, B. M., van der Grinten, M. P., van Mechelen, W., & Bongers, P. M. (2008). Does musculoskeletal discomfort at work predict future musculoskeletal pain? *Ergonomics*, *51*(5), 637-648. https://doi.org/10.1080/00140130701743433

Hamilton, M. F. (2019). Virtual reality: can it improve the PICU experience? *Pediatric Critical Care Medicine*, 20(6), 587-588.

Hansen, C. (2021). 'Zhuangzi'. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Fall 2021 ed.): Metaphysics Research Lab, Stanford University.

Hao, C. (2019). *Cultura: Achieving intercultural empathy through contextual user research in design* [Dissertation, Delft University of Technology]. Delft.

Hart, S. G. (2006). Nasa-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *50*(9), 904-908. https://doi.org/10.1177/154193120605000909

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology* (Vol. 52, pp. 139-183). Elsevier.

Hassenzahl, M. (2010). *Experience Design: Technology for All the Right Reasons* (Vol. 3). Morgan & Claypool Publishers LLC. https://doi.org/10.2200/s00261ed1v01y201003hci008

Hassenzahl, M., Eckoldt, K., Diefenbach, S., Laschke, M., Lenz, E., & Kim, J. (2013). Designing Moments of Meaning and Pleasure. Experience Design and Happiness [Online]. *International Journal of Design*, 7(3). http://www.ijdesign.org/index.php/IJDesign/article/view/1480

Hassenzahl, M., & Tractinsky, N. (2006). User experience - a research agenda. *Behaviour & information technology*, *25*(2), 91-97. https://doi.org/10.1080/01449290500330331

Hassenzahl, M., Wiklund-Engblom, A., Bengs, A., Hägglund, S., & Diefenbach, S. (2015). Experience-Oriented and Product-Oriented Evaluation: Psychological Need Fulfillment, Positive Affect, and Product Perception. *International Journal of Human–Computer Interaction*, *31*(8), 530-544. https://doi.org/10.1080/10447318.2015.1064664

Hekkert, P. (2006). Design aesthetics: Principles of pleasure in design. *Psychology Science*, *48*(2), 157-172.

Hekkert, P., Snelders, D., & Van Wieringen, P. C. (2003). 'Most advanced, yet acceptable': Typicality and novelty as joint predictors of aesthetic preference in industrial design. *British journal of Psychology*, *94*(1), 111-124.

Held, R. M., & Durlach, N. I. (1992). Telepresence. *Presence: Teleoperators & Virtual Environments*, *1*(1), 109-112.

Henrich, J. (2020). *The WEIRDest people in the world: How the West became psychologically peculiar and particularly prosperous*. Farrar, Straus and Giroux.

Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Sciences*, *33*(2-3), 61-83. https://doi.org/10.1017/s0140525x0999152x

Henry, D., & Furmess, T. (1993). Spatial perception in virtual environments: evaluating an architectural application. 1993 IEEE Annual Virtual Reality International Symposium,

Hillmann, C. (2019). Comparing the Gear VR, Oculus Go, and Oculus Quest. *Unreal for Mobile and Standalone VR*, 141-167. https://doi.org/10.1007/978-1-4842-4360-2_5

Hornbæk, K., & Law, E. L.-C. (2007). *Meta-analysis of correlations among usability measures* Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, San Jose, California, USA. https://doi.org/10.1145/1240624.1240722

Hornbeck, R. G., & Barrett, J. L. (2013). Refining and Testing "Counterintuitiveness" in Virtual Reality: Cross-Cultural Evidence for Recall of Counterintuitive Representations. *International Journal for the Psychology of Religion*, *23*(1), 15-28. https://doi.org/10.1080/10508619.2013.735192

Huang, S.-H., Yang, Y.-I., & Chu, C.-H. (2012). Human-centric design personalization of 3D glasses frame in markerless augmented reality. *Advanced Engineering Informatics*, *26*(1), 35-45. https://doi.org/10.1016/j.aei.2011.07.008

Huang, Z., Li, T., Chen, W., Zhao, Y., Xing, J., LeGendre, C., Luo, L., Ma, C., & Li, H. (2018). Deep Volumetric Video From Very Sparse Multi-view Performance Capture. Computer Vision – ECCV 2018, Cham.

Huber, T., Paschold, M., Hansen, C., Lang, H., & Kneist, W. (2018). Artificial Versus Video-Based Immersive Virtual Surroundings: Analysis of Performance and User's Preference. *Surgical Innovation*, *25*(3), 280-285. https://doi.org/10.1177/1553350618761756

Huber, T., Paschold, M., Hansen, C., Wunderling, T., Lang, H., & Kneist, W. (2017). New dimensions in surgical training: immersive virtual reality laparoscopic simulation exhilarates surgical staff. *Surgical Endoscopy*, *31*(11), 4472-4477. https://doi.org/10.1007/s00464-017-5500-6

Huber, T., Wunderling, T., Paschold, M., Lang, H., Kneist, W., & Hansen, C. (2018). Highly immersive virtual reality laparoscopy simulation: development and future aspects. *International Journal of Computer Assisted Radiology and Surgery*, *13*(2), 281-290. https://doi.org/10.1007/s11548-017-1686-2

IATA. (2018, 24 October). *IATA Forecast Predicts 8.2 billion Air Travelers in 2037* https://www.iata.org/en/pressroom/pressroom-archive/2018-press-releases/2018-10-24-02/

IDC. (2020a). *IDC Reveals 2021 Worldwide Digital Transformation Predictions; 65% of Global GDP Digitalized by 2022, Driving Over $6.8 Trillion of Direct DX Investments from 2020 to 2023*. International Data Corporation. Retrieved January 17, 2022 from https://www.idc.com/getdoc.jsp?containerId=prUS46967420

IDC. (2020b). *Worldwide Spending on Augmented and Virtual Reality Forecast to Deliver Strong Growth Through 2024*. International Data Corporation. Retrieved January 17, 2022 from https://www.idc.com/getdoc.jsp?containerId=prUS47012020

IEA. (2021). *Core Competencies in Human Factors and Ergonomics*. The International Ergonomics Association Press.

Ihemedu-Steinke, Q. C., Rangelova, S., Weber, M., Erbach, R., Meixner, G., & Marsden, N. (2017). Simulation Sickness Related to Virtual Reality Driving Simulation. In (pp. 521-532). Springer International Publishing. https://doi.org/10.1007/978-3-319-57987-0_42

IJsselsteijn, W., & Riva, G. (2003). *Being there: Concepts, effects and measurements of user presence in synthetic environments*. IOS Press.

IMO. (2018). *About IMO*. International Maritime Organization. Retrieved March 25 from

ISO. (2000). ISO/FDIS 11226: Ergonomics–Evaluation of static working postures. In *Ergonomics* (pp. 19). Geneva: International Organization for Standardization.

ISO. (2018). ISO 9241-11: Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts. In *Ergonomics of human-system interaction* (Vol. 13.180, pp. 29): International Organization for Standardization.

ISO. (2019). ISO 9241-210: Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems. In *Ergonomics of human-system interaction* (pp. 33): International Standard Organization.

ISO. (2020). ISO 9241-110: 2020–Ergonomics of human-system interaction–Part 110: Dialogue principles. In *Ergonomics of human-system interaction* (Vol. 9241-110, pp. 32): International Standard Organization.

Jakimowicz, J. J., & Buzink, S. (2015). Training Curriculum in Minimal Access Surgery. In N. Francis, A. Fingerhut, R. Bergamaschi, & R. Motson (Eds.), *Training in Minimal Access Surgery* (pp. 15-34). Springer London. https://doi.org/10.1007/978-1-4471-6494-4_2

Johansen, R. (1988). *Groupware: Computer support for business teams*. The Free Press. https://dl.acm.org/citation.cfm?id=542298

Kahneman, D., & Miller, D. T. (1986). Norm theory: Comparing reality to its alternatives. *Psychological Review*, *93*(2), 136-153. https://doi.org/10.1037/0033-295X.93.2.136

Kano, N. (1984). Attractive quality and must-be quality. *Hinshitsu (Quality, the Journal of Japanese Society for Quality Control)*, *14*, 39-48. https://ci.nii.ac.jp/naid/10025070768

Karwowski, W. (2005). Ergonomics and human factors: the paradigms for science, engineering, design, technology and management of human-compatible systems. *Ergonomics*, *48*(5), 436-463. https://doi.org/10.1080/00140130400029167

Kavanagh, S., Kavanagh, S., Luxton-Reilly, A., Wuensche, B., & Plimmer, B. (2017). A systematic review of Virtual Reality in education. *Themes in Science and Technology Education*, *10*(2), 85-119.

Keefe, D. F. (2009, April 3-9, 2009). Creative 3d form-making in visual art and visual design for science. CHI 2009 Workshop on Computational Creativity Support: Using Algorithms and Machine Learning to Help People Be More Creative, Boston, MA, USA.

Kefalidou, G., D'Cruz, M., Castro, A., & Marcelino, R. (2019). Designing airport interiors with 3D visualizations. Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, Glasgow, Scotland UK.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*(3), 203-220. https://doi.org/10.1207/s15327108ijap0303_3

Kent, L., Snider, C., Gopsill, J., & Hicks, B. (2021). Mixed reality in design prototyping: A systematic review. *Design Studies*, *77*, 101046. https://doi.org/https://doi.org/10.1016/j.destud.2021.101046

Kim, C., Lee, C., Lehto, M. R., & Yun, M. H. (2011). Affective evaluation of user impressions using virtual product prototyping. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *21*(1), 1-13. https://doi.org/10.1002/hfm.20210

Kim, D. B., & Lee, K. H. (2011). Computer-aided appearance design based on BRDF measurements. *Computer-Aided Design*, *43*(9), 1181-1193. https://doi.org/10.1016/j.cad.2011.04.015

Kim, H.-J., Kim, J.-W., & Nam, T.-J. (2016). *miniStudio: Designers' Tool for Prototyping Ubicomp Space with Interactive Miniature* Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, San Jose, California, USA. https://dl.acm.org/citation.cfm?doid=2858036.2858180

Kim, H. J., Lim, H. Y., & You, Y. W. (2018). A study on the optimization of manufacturing process through motion analysis and virtual reality. *Journal of Advanced Research in Dynamical and Control Systems*, *10*(1), 78-82.

Kim, K., Billinghurst, M., Bruder, G., Duh, H. B., & Welch, G. F. (2018). Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008-2017). *IEEE Trans Vis Comput Graph*, *24*(11), 2947-2962. https://doi.org/10.1109/TVCG.2018.2868591

Kim, K., Rosenthal, M. Z., Zielinski, D., & Brady, R. (2012, 4-8 March 2012). Comparison of desktop, head mounted display, and six wall fully immersive systems using a stressful task. 2012 IEEE Virtual Reality Workshops (VRW), Costa Mesa, CA, USA.

Kim, K. G., Oertel, C., Dobricki, M., Olsen, J. K., Coppi, A. E., Cattaneo, A., & Dillenbourg, P. (2020). Using immersive virtual reality to support designing skills in vocational education. *British Journal of Educational Technology*, *51*(6), 2199-2213. https://doi.org/10.1111/bjet.13026

Kim, M., Wang, X., Love, P., Li, H., & Kang, S.-C. (2013). Virtual reality for the built environment: a critical review of recent advances. *Journal of Information Technology in Construction*, *18*(2013), 279-305.

Kim, S., Billinghurst, M., & Lee, G. (2018). The effect of collaboration styles and view independence on video-mediated remote collaboration. *Computer Supported Cooperative Work (CSCW)*, *27*(3-6), 569--607. https://doi.org/10.1007/s10606-018-9324-2

Kim, S., Nussbaum, M. A., & Gabbard, J. L. (2019). Influences of augmented reality head-worn display type and user interface design on performance and usability in simulated warehouse order picking. *Appl Ergon*, *74*, 186-193. https://doi.org/10.1016/j.apergo.2018.08.026

Klahr, D., Triona, L. M., & Williams, C. (2007). Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science teaching*, *44*(1), 183-203.

KLM. (2019). *Kijk nu (zonder ticket) rond in alle KLM-vliegtuigen*. KLM Blog. Retrieved January 18, 2022 from https://blog.klm.com/nl/kijk-zonder-ticket-rond-alle-klm-vliegtuigen/

Koch, A., Pfandler, M., Stefan, P., Wucherer, P., Lazarovici, M., Navab, N., Stumpf, U., Schmidmaier, R., Glaser, J., & Weigl, M. (2019). Say, What Is on Your Mind? Surgeons' Evaluations of Realism and Usability of a Virtual Reality Vertebroplasty Simulator. *Surg Innov*, *26*(2), 234-243. https://doi.org/10.1177/1553350618822869

Kokorikou, A., Vink, P., De Pauw, I., & Braca, A. (2016). Exploring the design of a lightweight, sustainable and comfortable aircraft seat. *Work*, *54*(4), 941-954.

Koppenborg, M., Nickel, P., Naber, B., Lungfiel, A., & Huelke, M. (2017). Effects of movement speed and predictability in human-robot collaboration. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *27*(4), 197-209. https://doi.org/10.1002/hfm.20703

B

Kruizinga, C. P., Delleman, N. J., & Schellekens, J. M. (1998). Prediction of Musculoskeletal Discomfort in a Pick and Place Task (A pilot study). *Int J Occup Saf Ergon*, *4*(3), 271-286. https://doi.org/10.1080/10803548.1998.11076394

Kuhn, S., & Muller, M. J. (1993). Participatory design. *Communications of the ACM*, *36*(6), 24-29.

Kuzuoka, H. (1992). *Spatial workspace collaboration: a SharedView video support system for remote collaboration capability* Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Monterey, California, USA. https://doi.org/10.1145/142750.142980

Langlois, S., Nguyen That, T., & Mermillod, P. (2016). Virtual head-up displays for augmented reality in cars: A user testing to validate the congruence. *06-08-September-2016*, Article a15. https://doi.org/10.1145/2970930.2970946

Lawson, G., Herriotts, P., Malcolm, L., Gabrecht, K., & Hermawati, S. (2015). The use of virtual reality and physical tools in the development and validation of ease of entry and exit in passenger vehicles. *Appl Ergon*, *48*, 240-251. https://doi.org/10.1016/j.apergo.2014.12.007

Lawson, G., Salanitri, D., & Waterfield, B. (2016). Future directions for the development of virtual reality within an automotive manufacturer. *Applied Ergonomics*, *53*, 323-330. https://doi.org/10.1016/j.apergo.2015.06.024

Lee, G. I., Lee, M. R., Clanton, T., Sutton, E., Park, A. E., & Marohn, M. R. (2014). Comparative assessment of physical and cognitive ergonomics associated with robotic and traditional laparoscopic surgeries [journal article]. *Surgical Endoscopy*, *28*(2), 456-465. https://doi.org/10.1007/s00464-013-3213-z

Lee, Y. G., Park, H., Woo, W., Ryu, J., Kim, H. K., Baik, S. W., Ko, K. H., Choi, H. K., Hwang, S. U., Kim, D. B., Kim, H., & Lee, K. H. (2010). Immersive modeling system (IMMS) for personal electronic products using a multi-modal interface [Article]. *Computer-Aided Design*, *42*(5), 387-401. https://doi.org/10.1016/j.cad.2009.11.003

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The ITC-Sense of Presence Inventory. *Presence: Teleoperators & Virtual Environments*, *10*(3), 282-297.

Levac, D., Colquhoun, H., & O'Brien, K. K. (2010). Scoping studies: advancing the methodology. *Implementation Science*, *5*(1), 69. https://doi.org/10.1186/1748-5908-5-69

Li, B., Segonds, F., Mateev, C., Lou, R., & Merienne, F. (2018). Design in context of use: An experiment with a multi-view and multi-representation system for collaborative design. *Computers in Industry*, *103*, 28-37. https://doi.org/10.1016/j.compind.2018.09.006

Li, H., Daugherty, T., & Biocca, F. (2003). The Role of Virtual Experience in Consumer Learning. *Journal of Consumer Psychology*, *13*(4), 395-407. https://doi.org/10.1207/s15327663jcp1304_07

Li, L. (1999). *Action theory and cognitive psychology in industrial design: user models and user interfaces* [Dissertation, Braunschweig, Hochsch. für Bildende Künste].

Li, M., Albayrak, A., Zhang, Y., & van Eijk, D. (2019). Multiple Factors Mental Load Evaluation on Smartphone User Interface. In S. Bagnara, R. Tartaglia, S. Albolino, T. Alexander, & Y. Fujita (Eds.), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* (pp. 302-315). Springer International Publishing. https://doi.org/10.1007/978-3-319-96059-3_33

Li, M., Ganni, S., Albayrak, A., Rutkowski, A. F., Van Eijk, D., & Jakimowicz, J. (2021). Proficiency from Immersion---A User-Centered Design in Cross-Cultural Surgical Training. *Frontiers in Virtual Reality*, *2*, 65.

Li, M., Ganni, S., Ponten, J., Albayrak, A., Rutkowski, A.-F., & Jakimowicz, J. (2020). Analysing usability and presence of a virtual reality operating room (VOR) simulator during laparoscopic surgery training. 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Atlanta, GA, USA.

Li, M., Houwing, D., Albayrak, A., Shidujaman, M., & van Eijk, D. (2023). Mapping XR Platforms: Analyzing Immersion from the Designer's Perspective.*Human-Computer Interaction* HCII2023, Copenhagen, Danmark.

Li, M., Yao, X., Aschenbrenner, D., van Eijk, D., & Vink, P. (2022). *Ergonomics 4.0: Human-Centered Procedure for Ergonomic Design Using Virtual Reality Prototyping* INCOSE International Symposium, Virtual event.

Li, W., Nee, A., & Ong, S. (2017). A state-of-the-art review of augmented reality in engineering analysis and simulation. *Multimodal Technologies and Interaction*, *1*(3), 17.

Li, Y. (2021). Intelligent Environmental Art Design Combining Big Data and Artificial Intelligence. *Complexity*, *2021*, 1-11.

Lim, L. (2017, OCT 27). *Are We Ready For Smart Manufacturing?* leaderonomics.com. Retrieved April 28, 2021 from https://www.leaderonomics.com/articles/business/ready-smart-manufacturing

Lim, Y.-K., Stolterman, E., & Tenenberg, J. (2008). The anatomy of prototypes. *ACM Transactions on Computer-Human Interaction*, *15*(2), 1-27. https://doi.org/10.1145/1375761.1375762

Lin, J., Zhu, R., Li, N., & Becerik-Gerber, B. (2020). Do people follow the crowd in building emergency evacuation? A cross-cultural immersive virtual reality-based study. *Advanced Engineering Informatics*, *43*, 101040. https://doi.org/https://doi.org/10.1016/j.aei.2020.101040

Lindebaum, D. (2015). Book review: Sapiens: A brief history of humankind. *Management Learning*, *46*(5), 636-638. https://doi.org/10.1177/1350507615602981

Lindgaard, G., & Dudek, C. (2003). What is this evasive beast we call user satisfaction? *Interacting with Computers*, *15*(3), 429-452. https://doi.org/10.1016/S0953-5438(02)00063-2

Ling, Y., Nefs, H. T., Morina, N., Heynderickx, I., & Brinkman, W.-P. (2014). A Meta-Analysis on the Relationship between Self-Reported Presence and Anxiety in Virtual Reality Exposure Therapy for Anxiety Disorders. *PLoS ONE*, *9*(5), e96144. https://doi.org/10.1371/journal.pone.0096144

Lingan, C. L., Li, M., & Vermeeren, A. P. (2021). The immersion cycle: Understanding immersive experiences through a cyclical model. *Proceedings of the Design Society*, *1*, 3011-3020.

Liu, Y., Castronovo, F., Asce, A. M., Messner, J., Asce, M., & Leicht, R. (2019). Evaluating the Impact of Virtual Reality on Design Review Meetings. *Journal of Computing in Civil Engineering*, *34*(1), 04019045-04019045. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000856

Liu, Z., Rotte, T., Anjani, S., & Vink, P. (2021). Seat pitch and comfort of a staggered seat configuration. *Work*, *68*, S151-S159. https://doi.org/10.3233/WOR-208014

Loth, M., van Eijk, D., & Molenbroek, J. (2014). Mock-up test of two train toilet modules. The 5th international conference on applied human factors and Ergonomics AHFE 2014, Krakow, Poland.

Lukosch, S., Billinghurst, M., Alem, L., & Kiyokawa, K. (2015). Collaboration in augmented reality. *Computer Supported Cooperative Work (CSCW)*, *24*(6), 515--525.

Lukosch, S., Lukosch, H., Datcu, D., & Cidota, M. (2015a). *On the Spot Information in Augmented Reality for Teams in the Security Domain* Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems, New York, NY, USA.

Lukosch, S., Lukosch, H., Datcu, D., & Cidota, M. (2015b). Providing Information on the Spot: Using Augmented Reality for Situational Awareness in the Security Domain. *Computer Supported Cooperative Work: CSCW: An International Journal*, *24*(6), 613-664. https://doi.org/10.1007/s10606-015-9235-4

Mallam, S. C., Nazir, S., Renganayagalu, S. K., Ernstsen, J., Veie, S., & Edwinson, A. E. (2019). Design of experiment comparing users of virtual reality head-mounted displays and desktop computers. 20th Congress of the International Ergonomics Association, IEA 2018, Florence; Italy.

Manetta, C., & Blade, R. A. (1995). Glossary of Virtual Reality Terminology. *International Journal of Virtual Reality*, *1*(2), 35-39. https://doi.org/10.20870/ijvr.1995.1.2.2604

Mansfield, N., Naddeo, A., Frohriep, S., & Vink, P. (2020). Integrating and applying models of comfort. *Applied Ergonomics*, *82*, 102917-102917. https://doi.org/10.1016/J.APERGO.2019.102917

Marc, J., Belkacem, N., & Marsot, J. (2007). Virtual reality: A design tool for enhanced consideration of usability "validation elements". *Safety Science*, *45*(5), 589-601. https://doi.org/10.1016/J.SSCI.2007.01.004

Mbaabu, O. (2020, November 5, 2020). *Introduction to Extended Reality*. Section.io. Retrieved January 20 from https://www.section.io/engineering-education/introduction-to-extended-reality/

McCarthy, J., & Wright, P. (2004). Technology as experience. *Interactions*, *11*(5), 42-43.

McCreery, G. L., El-Beheiry, M., & Schlachta, C. M. (2017). Local and national laparoscopic skill competitions: residents' opinions and impact on adoption of simulation-based training [journal article]. *Surg Endosc*, *31*(11), 4711-4716. https://doi.org/10.1007/s00464-017-5546-5

McGloin, R., Farrar, K., & Krcmar, M. (2013). Video games, immersion, and cognitive aggression: does the controller matter? *Media Psychology*, *16*(1), 65-87.

McGrenere, J. (2000). *"Bloat": the objective and subject dimensions* CHI '00 Extended Abstracts on Human Factors in Computing Systems, The Hague, The Netherlands. https://doi.org/10.1145/633292.633495

Mengoni, M., Peruzzini, M., Mandorli, F., Bordegoni, M., & Caruso, G. (2008). Performing Ergonomic Analysis in Virtual Environments: A Structured Protocol to Assess Humans Interaction. *Proceedings of the ASME Design Engineering Technical Conference*, *3*(PARTS A AND B), 1461-1472. https://doi.org/10.1115/DETC2008-49160

Mentis, H. M., Chellali, A., Manser, K., Cao, C. G., & Schwaitzberg, S. D. (2016). A systematic review of the effect of distraction on surgeon performance: directions for operating room policy and surgical training [journal article]. *Surg Endosc*, *30*(5), 1713-1724. https://doi.org/10.1007/s00464-015-4443-z

Merriam-Webster. (2021). *Comfort*. Merriam-Webster Website. Retrieved February 08 from https://www.merriam-webster.com/dictionary/comfort

Merriam-Webster. (2023). *Well-being* https://www.merriam-webster.com/dictionary/well-being

Mestre, D., Fuchs, P., Berthoz, A., & Vercher, J. (2006). Immersion et présence. *Le traité de la réalité virtuelle. Paris: Ecole des Mines de Paris*, 309-338.

Miaskiewicz, T., & Kozar, K. A. (2011). Personas and user-centered design: How can personas benefit product design processes? *Design Studies*, *32*(5), 417-430. https://doi.org/https://doi.org/10.1016/j.destud.2011.03.003

Microsoft. (2023). *Business-ready solutions for HoloLens 2*. Retrieved July 01 from www.microsoft.com/en-gb/hololens/apps

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: A class of displays on the reality-virtuality continuum. Proc. SPIE 2351, Telemanipulator and Telepresence Technologies, Boston, MA, United States.

Mims, C. (2020, September 19, 2020). Huang's Law Is the New Moore's Law, and Explains Why Nvidia Wants Arm. *The Wall Street Journal*. https://www.wsj.com/articles/huangs-law-is-the-new-moores-law-and-explains-why-nvidia-wants-arm-11600488001

Moes, N. C. C. M., & Horváth, I. (2016). Editorial: Virtual reality and ergonomics enablers for product development. *International Journal of Computer Aided Engineering and Technology*, *8*(1/2), 7.

Molenbroek, J. M. F., & Huysmans, T. (2021). *DINED Anthropometric database* https://dined.io.tudelft.nl/en/database/tool

Mont, O. K. (2002). Clarifying the concept of product–service system. *Journal of Cleaner Production*, *10*(3), 237-245. https://doi.org/https://doi.org/10.1016/S0959-6526(01)00039-7

Mueller, C. T., Irani, A., & Jenett, B. E. (2014). Additive manufacturing of structural prototypes for conceptual design. Proceedings of IASS Annual Symposia,

Munz, Y., Kumar, B. D., Moorthy, K., Bann, S., & Darzi, A. (2004). Laparoscopic virtual reality and box trainers: is one superior to the other? *Surgical Endoscopy*, *18*(3), 485-494. https://doi.org/10.1007/s00464-003-9043-7

Nacke, L., & Lindley, C. A. (2008). *Flow and immersion in first-person shooters: measuring the player's gameplay experience* Proceedings of the 2008 conference on future play: Research, play, share, New York, NY, USA. https://doi.org/10.1145/1496984.1496998

Natephra, W., Motamedi, A., Fukuda, T., & Yabuki, N. (2017). Integrating building information modeling and virtual reality development engines for building indoor lighting design. *Visualization in Engineering*, *5*(19). https://doi.org/10.1186/s40327-017-0058-x

Naumann, A., & Hurtienne, J. (2010). Benchmarks for intuitive interaction with mobile devices. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services* (pp. 401-402). ACM. https://doi.org/10.1145/1851600.1851685

Nederlandse Spoorwegen. (2021). *De reis van morgen*. ns.nl. Retrieved April 30, 2021 from https://www.ns.nl/over-ns/reis-van-morgen/interieur/treininterieurvisie.html

Nguyen, H., Pontonnier, C., Hilt, S., Duval, T., & Dumont, G. (2017). VR-based operating modes and metaphors for collaborative ergonomic design of industrial workstations. *Journal on Multimodal User Interfaces*, *11*(1), 97-111. https://doi.org/10.1007/s12193-016-0231-x

Nickel, P., & Lungfiel, A. (2018). Improving Occupational Safety and Health (OSH) in Human-System Interaction (HSI) Through Applications in Virtual Environments. *Digital Human Modeling: Applications in Health, Safety, Ergonomics, and Risk Management*, *10917*, 85-96. https://doi.org/10.1007/978-3-319-91397-1_8

Nisbett, R. (2004). *The geography of thought: How Asians and Westerners think differently... and why* (Reprint ed.). Free Press.

Nisky, I., Huang, F., Milstein, A., Pugh, C. M., Mussa-Ivaldi, F. A., & Karniel, A. (2012). Perception of stiffness in laparoscopy–the fulcrum effect. *Studies in Health Technology and Informatics*, *173*, 313. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4102265/pdf/nihms604049.pdf

Norman, D. (2013). *The design of everyday things* (Revised and expanded ed.). Basic books.

O'Brien, H. L., & Toms, E. G. (2008). What is user engagement? A conceptual framework for defining user engagement with technology. *Journal of the American society for Information Science and Technology*, *59*(6), 938-955.

Obbink, L. T. G. (2016). *Opening the closed: Design of a user-centered closed payment border*. https://repository.tudelft.nl/islandora/object/uuid%3A9f67bc29-4b71-4e34-83c6-981b733ebb00

Oculus. (2020). *Quest 2*. Retrieved November 09, 2021 from https://www.oculus.com/quest-2/

Osterlund, J., & Lawrence, B. (2012). Virtual reality: Avatars in human spaceflight training [Article]. *Acta Astronautica*, *71*, 139-150. https://doi.org/10.1016/j.actaastro.2011.08.011

Overbeeke, C. J., Djajadiningrat, J. P., Hummels, C. C. M., & Wensveen, S. A. G. (2002). Beauty in usability : forget about ease of use! In W. S. Green & P. W. Jordan (Eds.), *Pleasure with products : beyond usability* (pp. 9-18). Taylor &Francis.

Paavilainen, J., Korhonen, H., Alha, K., Stenros, J., Koskinen, E., & Mayra, F. (2017). The Pokémon GO experience: A location-based augmented reality mobile game goes mainstream. Proceedings of the 2017 CHI conference on human factors in computing systems, New York, NY, USA.

Paes, D., & Irizarry, J. (2018). A usability study of an immersive virtual reality platform for building design review: Considerations on human factors and user interface. Construction Research Congress 2018: Construction Information Technology, CRC 2018, New Orleans; United States.

Pallavicini, F., Toniazzi, N., Argenton, L., Aceti, L., & Mantovani, F. (2015). *Developing effective Virtual Reality training for military forces and emergency operators: From technology to human factors* 14th International Conference on Modeling and Applied Simulation, MAS 2015, Bergeggi, Italy. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84960845621&partnerID=40&md5=493628c0c9fbaa8fa755e629dfa315e7

Pan, Z., Cheok, A. D., Yang, H., Zhu, J., & Shi, J. (2006). Virtual reality and mixed reality for virtual learning environments. *Computers & Graphics*, *30*(1), 20-28.

Panicker, S. S., & Huysmans, T. (2020). Comfort of Aircraft Seats for Customers of Size using Digital Human Model in Virtual Reality. *Proceedings - 2020 IEEE International Conference on Artificial Intelligence and Virtual Reality, AIVR 2020*, 218-221. https://doi.org/10.1109/AIVR50618.2020.00045

Park, H., Moon, H.-C., & Lee, J. Y. (2009). Tangible augmented prototyping of digital handheld products. *Computers in Industry*, *60*(2), 114-125. https://doi.org/https://doi.org/10.1016/j.compind.2008.09.001

Park, J. Y., & Nagy, Z. (2018). Comprehensive analysis of the relationship between thermal comfort and building control research - A data-driven literature review. *Renewable and Sustainable Energy Reviews*, *82*, 2664-2679. https://doi.org/10.1016/J.RSER.2017.09.102

Parker, S. E. H., Laviana, A. A., Wadhera, R. K., Wiegmann, D. A., & Sundt, T. M. (2010). Development and Evaluation of an Observational Tool for Assessing Surgical Flow Disruptions and Their Impact on Surgical Performance. *World Journal of Surgery*, *34*(2), 353-361. https://doi.org/10.1007/s00268-009-0312-z

Parkes, D. C., & Wellman, M. P. (2015). Economic reasoning and artificial intelligence. *Science*, *349*(6245), 267-272. https://doi.org/doi:10.1126/science.aaa8403

Persoon, M. C., Broos, H. J., Witjes, J. A., Hendrikx, A. J., & Scherpbier, A. J. (2011). The effect of distractions in the operating room during endourological procedures. *Surg Endosc*, *25*(2), 437-443. https://doi.org/10.1007/s00464-010-1186-8

Persson, D., & Erlandsson, L. K. (2002). Time to Reevaluate the Machine Society: Post-industrial Ethics from an Occupational Perspective. *Journal of Occupational Science*, *9*(2), 93-99. https://doi.org/10.1080/14427591.2002.9686497

Peruzzini, M., Carassai, S., Pellicciari, M., & Andrisano, A. O. (2017). Human-centred design of ergonomic workstations on interactive digital mock-ups. In B. Eynard, V. Nigrelli, S. M. Oliveri, G. Peris-Fajarnes, & S. Rizzuti (Eds.), *Advances on Mechanics, Design Engineering and Manufacturing : Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing (JCM 2016), 14-16 September, 2016, Catania, Italy* (pp. 1187-1195). Springer International Publishing. https://doi.org/10.1007/978-3-319-45781-9_119

Peruzzini, M., Grandi, F., & Pellicciari, M. (2018). How to analyse the workers' experience in integrated product-process design. *Journal of Industrial Information Integration*, *12*, 31-46. https://doi.org/10.1016/j.jii.2018.06.002

Peruzzini, M., Grandi, F., Pellicciari, M., & Campanella, C. E. (2019). User experience analysis based on physiological data monitoring and mixed prototyping to support human-centre product design. AHFE International Conference on Ergonomics in Design, 2018, Orlando; United States.

Peruzzini, M., Pellicciari, M., & Gadaleta, M. (2019). A comparative study on computer-integrated set-ups to design human-centred manufacturing systems. *Robotics and Computer-Integrated Manufacturing*, *55*, 265-278. https://doi.org/10.1016/j.rcim.2018.03.009

Phillips, L., Ries, B., Kaeding, M., & Interrante, V. (2010, 20-24 March 2010). Avatar self-embodiment enhances distance perception accuracy in non-photorealistic immersive virtual environments. 2010 IEEE Virtual Reality Conference (VR),

Pietroni, E. (2019). Experience Design, Virtual Reality and Media Hybridization for the Digital Communication Inside Museums. *Applied System Innovation*, *2*(4), 35.

Pilke, E. M. (2004). Flow experiences in information technology use. *International Journal of Human-Computer Studies*, *61*(3), 347-357. https://doi.org/10.1016/j.ijhcs.2004.01.004

Pine, B. J., & Gilmore, J. H. (1999). *The experience economy: work is theatre and every business a stage*. Harvard Business Press.

Pine, B. J., & Gilmore, J. H. (2011). *The experience economy*. Harvard Business Press.

Piumsomboon, T., Dey, A., Ens, B., Lee, G., & Billinghurst, M. (2019). The effects of sharing awareness cues in collaborative mixed reality. *Frontiers in Robotics and AI*, *6*, 5. https://doi.org/10.3389/frobt.2019.00005

Piumsomboon, T., Lee, G. A., Irlitti, A., Ens, B., Thomas, B. H., & Billinghurst, M. (2019). *On the shoulder of the giant: A multi-scale mixed reality collaboration with 360 video sharing and tangible interaction* Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19, https://doi.org/10.1145/3290605.3300458

Pluyter, J. R. (2012). *Designing immersive surgical training against information technology-related overload in the operating room* (Publication Number 331) Tilburg University]. https://research.tilburguniversity.edu/en/publications/d48c5727-92fd-41b1-be5d-58e62eed6eb1

Pluyter, J. R., Buzink, S. N., Rutkowski, A. F., & Jakimowicz, J. J. (2010). Do absorption and realistic distraction influence performance of component task surgical procedure? *Surg Endosc*, 24(4), 902-907. https://doi.org/10.1007/s00464-009-0689-7

Pluyter, J. R., Rutkowski, A. F., & Jakimowicz, J. J. (2014). Immersive training: breaking the bubble and measuring the heat [journal article]. *Surg Endosc*, *28*(5), 1545-1554. https://doi.org/10.1007/s00464-013-3350-4

Polanyi, M. (2009). *The Tacit Dimension* (Revised ed.). University of Chicago Press.

Pontonnier, C., Dumont, G., Samani, A., Madeleine, P., & Badawi, M. (2014). Designing and evaluating a workstation in real and virtual environment: toward virtual reality based ergonomic design sessions [Article]. *Journal on Multimodal User Interfaces*, *8*(2), 199-208. https://doi.org/10.1007/s12193-013-0138-8

Psotka, J. (1995). Immersive training systems: Virtual reality and education and training. *Instructional science*, *23*(5-6), 405-431.

Pucillo, F., Becattini, N., xf, & Cascini, G. (2016). A UX Model for the Communication of Experience Affordances. *Design Issues*, *32*(2), 3-18. http://www.jstor.org/stable/43830695

Redelmeier, D. A., & Kahneman, D. (1996). Patients' memories of painful medical treatments: real-time and retrospective evaluations of two minimally invasive procedures. *Pain*, *66*(1), 3-8. https://doi.org/10.1016/0304-3959(96)02994-6

Reiners, D., Davahli, M. R., Karwowski, W., & Cruz-Neira, C. (2021). The Combination of Artificial Intelligence and Extended Reality: A Systematic Review. *Frontiers in Virtual Reality*, *2*, 721933. https://doi.org/10.3389/frvir.2021.721933

Rekimoto, J. (1996). *Transvision: A hand-held augmented reality system for collaborative design*

Rice, P. S. (2005). It “ain’t” always so: Sixth graders’ interpretations of Hispanic-American stories with universal themes. *Children's literature in Education*, *36*(4), 343-362.

Richards, L. G. (1980). On the psychology of passengers. *Human Factors in Transport Research*, *2*, 15-23.

Rieuf, V., Bouchard, C., Meyrueis, V., & Omhover, J.-F. (2017). Emotional activity in early immersive design: Sketches and moodboards in virtual reality. *Design Studies*, *48*, 43-75.

Riva, G., Mantovani, F., Capideville, C. S., Preziosa, A., Morganti, F., Villani, D., Gaggioli, A., Botella, C., & Alcañiz, M. (2007). Affective interactions using virtual reality: the link between presence and emotions. *Cyberpsychol Behav*, *10*(1), 45-56. https://doi.org/10.1089/cpb.2006.9993

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, Å., & Gorecky, D. (2016). Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. CIE 2016: 46th International Conferences on Computers and Industrial Engineering,

Rubio, S., Díaz, E., Martín, J., & Puente, J. M. (2004). Evaluation of subjective mental workload: A comparison of SWAT, NASA-TLX, and workload profile methods. *Applied psychology*, *53*(1), 61-86.

Russell, J. A. (2003). Core affect and the psychological construction of emotion [doi:10.1037/0033-295X.110.1.145]. *Psychological Review*, *110*, 145-172. https://doi.org/10.1037/0033-295X.110.1.145

Saalfeld, P., Mewes, A., Luz, M., Preim, B., & Hansen, C. (2015). Comparative evaluation of gesture and touch input for medical software. In S. D. Martin Pielot, Niels Henze (Ed.), *Mensch und Computer 2015–Proceedings* (pp. 143-152). Oldenbourg Wissenschaftsverlag.

Salzmann, H., Moehring, M., & Froehlich, B. (2009). *Virtual vs. Real-World Pointing in Two-User Scenarios* Proceedings of the 2009 IEEE Virtual Reality Conference, https://doi.org/10.1109/VR.2009.4811011

Sankaranarayanan, G., Li, B., Manser, K., Jones, S. B., Jones, D. B., Schwaitzberg, S., Cao, C. G., & De, S. (2016). Face and construct validation of a next generation virtual reality (Gen2-VR) surgical simulator [journal article]. *Surg Endosc*, *30*(3), 979-985. https://doi.org/10.1007/s00464-015-4278-7

Santos, L. R., & Montagna, G. (2019). Digital ergonomics: Understanding the bridges to the digital world. AHFE International Conference on Ergonomics in Design, 2018, Orlando; United States.

Sauer, J., & Sonderegger, A. (2009). The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion. *Applied Ergonomics*, *40*(4), 670-677. https://doi.org/10.1016/j.apergo.2008.06.006

Sauerwein, E., Bailom, F., Matzler, K., & Hinterhuber, H. H. (1996, February 19-23). The Kano model: How to delight your customers. International Working Seminar on Production Economics, Innsbruck, Igls, Austria.

Scataglini, S., & Paul, G. (2019). From greek sculpture to the digital human model - a history of "human equilibrium". *DHM and Posturography*, 3-5. https://doi.org/10.1016/B978-0-12-816713-7.00001-5

Scharff, R. B. N. (2021). *Soft robotic manipulators with proprioception* [Dissertation, Delft University of Technology]. Delft.

Schifferstein, H. N., & Desmet, P. M. (2007). The effects of sensory impairments on product experience and personal well-being. *Ergonomics*, *50*(12), 2026-2048.

Schijven, M. P., & Jakimowicz, J. J. (2005). Validation of virtual reality simulators: Key to the successful integration of a novel teaching technology into minimal access surgery. *Minim Invasive Ther Allied Technol*, *14*(4), 244-246. https://doi.org/10.1080/13645700500221881

Schijven, M. P., Jakimowicz, J. J., Broeders, I. A. M. J., & Tseng, L. N. L. (2005). The Eindhoven laparoscopic cholecystectomy training course - improving operating room performance using virtual reality training - Results from the first EAES accredited virtual reality trainings curriculum. *Surgical Endoscopy and Other Interventional Techniques*, *19*(9), 1220-1226. https://doi.org/10.1007/s00464-004-2240-1

Schmalstieg, D., Fuhrmann, A., Hesina, G., Szalavri, Z., Encarnao, L. M., Gervautz, M., & Purgathofer, W. (2002). The studierstube augmented reality project. *Presence: Teleoperators and Virtual Environments*, *11*(1), 33--54. https://doi.org/10.1162/105474602317343640

Schmitt, B. (1999). Experiential Marketing. *Journal of Marketing Management*, *15*(1-3), 53-67. https://doi.org/10.1362/026725799784870496

Schubert, T. (2017). *Virtual Reality for smart cities and urban planning*. Esri Australia. Retrieved January 14, 2022 from https://esriaustralia.com.au/blog/virtual-reality-smart-cities-and-urban-planning

Schuemie, M. J., van der Straaten, P., Krijn, M., & van der Mast, C. A. P. G. (2001). Research on presence in virtual reality: A survey. *CyberPsychology & Behavior*, *4*(2), 183-201. https://doi.org/10.1089/109493101300117884

Schumpeter, J. A. (1976). *Capitalism, Socialism and Democracy* (1st ed.). Routledge. https://doi.org/https://doi.org/10.4324/9780203202050

Scott, D. J., Bergen, P. C., Rege, R. V., Laycock, R., Tesfay, S. T., Valentine, R. J., Euhus, D. M., Jeyarajah, D. R., Thompson, W. M., & Jones, D. B. (2000). Laparoscopic training on bench models: better and more cost effective than operating room experience? *Journal of the American College of Surgeons*, *191*(3), 272-283.

Sekimizu, K. (2010). *STCW a Guide for Seafarers*. https://www.itfglobal.org/media/1391/stcw_revised_rk-bb_small.pdf

Seth, A., Vance, J. M., & Oliver, J. H. (2011). Virtual reality for assembly methods prototyping: a review. *Virtual Reality*, *15*(1), 5-20. https://doi.org/10.1007/s10055-009-0153-y

Seymour, N. E., Gallagher, A. G., Roman, S. A., O'brien, M. K., Bansal, V. K., Andersen, D. K., & Satava, R. M. (2002). Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Annals of surgery*, *236*(4), 458. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1422600/pdf/20021000s00008p458.pdf

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591--611.

Shaw, F. X. (2021, November 12). Microsoft Cloud at Ignite 2021: Metaverse, AI and hyperconnectivity in a hybrid world. https://blogs.microsoft.com/blog/2021/11/02/microsoft-cloud-at-ignite-2021-metaverse-ai-and-hyperconnectivity-in-a-hybrid-world/

Shin, D. (2018). Empathy and embodied experience in virtual environment: To what extent can virtual reality stimulate empathy and embodied experience? *computers in human behavior*, *78*, 64-73.

Shneiderman, B., Plaisant, C., Cohen, M. S., Jacobs, S., Elmqvist, N., & Diakopoulos, N. (2016). *Designing the User Interface: Strategies for Effective Human-Computer Interaction* (6th ed.). Pearson.

Silvennoinen, M., & Kuparinen, L. (2009, 22-25 June). Usability challenges in surgical simulator training. Proceedings of the ITI 2009 31st International Conference on Information Technology Interfaces, Dubrovnik, Croatia.

Slater, M. (2003). A note on presence terminology. *Presence connect*, *3*(3), 1-5.

Slater, M., Spanlang, B., Sanchez-Vives, M. V., & Blanke, O. (2010). First Person Experience of Body Transfer in Virtual Reality. *PLoS ONE*, *5*(5), e10564. https://doi.org/10.1371/journal.pone.0010564

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, *6*(6), 603-616. https://doi.org/https://doi.org/10.1162/pres.1997.6.6.603

Smets, G. J., & Stappers, P. J. (1995). Designing in virtual reality: perception-action coupling. *Simulated and virtual realities: Elements of perception*, 189.

Sousa Santos, B., Dias, P., Pimentel, A., Baggerman, J.-W., Ferreira, C., Silva, S., & Madeira, J. (2009). Head-mounted display versus desktop for 3D navigation in virtual reality: a user study. *Multimedia Tools and Applications*, *41*(1), 161-181. https://doi.org/10.1007/s11042-008-0223-2

Spaner, S. J., & Warnock, G. L. (1997). A brief history of endoscopy, laparoscopy, and laparoscopic surgery. *J Laparoendosc Adv Surg Tech A*, *7*(6), 369-373. https://doi.org/10.1089/lap.1997.7.369

Spronck, P., André, E., Cook, M., & Preuß, M. (2018). Artificial and Computational Intelligence in Games: AI-Driven Game Design (Dagstuhl Seminar 17471).

Stafford, A., & Piekarski, W. (2008). *User evaluation of god-like interaction techniques*

Stappers, P. J., Hekkert, P., & Keyson, D. (2007). Design for interaction: consolidating the user-centred focus in industrial design engineering. DS 43: Proceedings of E&PDE 2007, the 9th International Conference on Engineering and Product Design Education, University of Northumbria, Newcastle, UK, 13.-14.09. 2007,

Steed, A. (1993). *A survey of virtual reality literature*. Citeseer.

Stein, J. (2016). Why Virtual Reality Is About to Change the World. *Time.com*. http://time.com/3987022/why-virtual-reality-is-about-to-change-the-world/

Stephenson, N. (2000). *Snow Crash*. Random House Worlds.

Strachan, I. W. (2000). Technology Leaps All Around Propel Advances in Simulators-Simulation and Training Industry: Changes in the Corporate Landscape. *National Defense*, 86-93.

Sütfeld, L. R., Ehinger, B. V., König, P., & Pipa, G. (2019). How does the method change what we measure? Comparing virtual reality and text-based surveys for the assessment of moral decisions in traffic dilemmas. *PLoS ONE*, *14*(10), e0223108-e0223108. https://doi.org/10.1371/JOURNAL.PONE.0223108

Taekman, J. M., & Shelley, K. (2010). Virtual environments in healthcare: immersion, disruption, and flow. *International Anesthesiology Clinics*, *48*(3), 101-121.

Tan, K. C., & Shen, X. X. (2010). Integrating Kano's model in the planning matrix of quality function deployment. *https://doi.org/10.1080/095441200440395*, *11*(8), 1141-1151. https://doi.org/10.1080/095441200440395

Tao, Q., Kang, J., Sun, W., Li, Z., & Huo, X. (2016). Digital evaluation of sitting posture comfort in human-vehicle system under industry 4.0 framework. *Chinese Journal of Mechanical Engineering 2016 29:6*, *29*(6), 1096-1103. https://doi.org/10.3901/CJME.2016.0718.082

Taylor, R. M. (2011). Situation awareness rating technique (SART): the development of a tool for aircrew systems design. In *Situational Awareness in Aerospace Operations* (1st ed., pp. 18). Routledge.

Thalen, J. P., & van der Voort, M. C. (2012). Facilitating User Involvement in Product Design Through Virtual Reality. In T. Xin-Xing (Ed.), *Virtual Reality* (pp. 105-122). IntechOpen. https://doi.org/10.5772/48602

Thomas, J. C., & Stuart, R. (1992). Virtual Reality and Human Factors. *Proceedings of the Human Factors Society Annual Meeting*, *36*(3), 207-210. https://doi.org/10.1518/107118192786751871

Toma, M. I., Girbacia, F., & Antonya, C. (2012). A comparative evaluation of human interaction for design and assembly of 3D CAD models in desktop and immersive environments. *International Journal of Interactive Design and Manufacturing - Ijidem*, *6*(3), 179-193. https://doi.org/10.1007/s12008-012-0144-1

Tontini, G., & Picolo, J. D. (2014). Identifying the impact of incremental innovations on customer satisfaction using a fusion method between importance-performance analysis and Kano model. *International Journal of Quality and Reliability Management*, *31*(1), 32-52. https://doi.org/10.1108/IJQRM-05-2012-0062/FULL/PDF

Torkashvand, G., Stephane, L., & Vink, P. (2019). Aircraft interior design and satisfaction for different activities; a new approach toward understanding passenger experience. *International Journal of Aviation, Aeronautics, and Aerospace*, *6*(2), 5.

Torkashvanda, G., Li, M., & Vink, P. (2021). Concept evaluation of a new aircraft passenger privacy bubble using virtual prototyping: A Human-Centered Design framework. *Work*, *68*(s1), S231-S238. https://doi.org/10.3233/WOR-208020

Tran Duy, H. (2017). *Designing a Virtual Reality Psychological Game* Lahti University of Applied Sciences]. Lahti, Finland. Bachelor

Tseng, K. C., Giau, D. T. N., & Huang, P.-H. (2017). A systematic review of the potential application of virtual reality within a user pre-occupancy evaluation. International conference on universal access in human-computer interaction,

Tulving, E. (1972). Episodic and semantic memory. In *Organization of memory.* (pp. xiii, 423-xiii, 423). Academic Press.

Undre, S., Koutantji, M., Sevdalis, N., Gautama, S., Selvapatt, N., Williams, S., Sains, P., McCulloch, P., Darzi, A., & Vincent, C. (2007). Multidisciplinary crisis simulations: the way forward for training surgical teams [journal article]. *World J Surg*, *31*(9), 1843-1853. https://doi.org/10.1007/s00268-007-9128-x

Van Boeijen, A., Daalhuizen, J., & Zijlstra, J. (2020). *Delft Design Guide: Perspectives, Models, Approaches, Methods*. BIS Publishers.

Van de Ven, J., Van Baaren, G., Fransen, A., van Runnard Heimel, P., Mol, B., & Oei, S. (2017). Cost-effectiveness of simulation-based team training in obstetric emergencies (TOSTI study). *European Journal of Obstetrics & Gynecology and Reproductive Biology*, *216*, 130-137.

van der Bijl-Brouwer, M., & Dorst, K. (2017). Advancing the strategic impact of human-centred design. *Design Studies*, *53*, 1-23. https://doi.org/10.1016/J.DESTUD.2017.06.003

Van Dijk, A. H., Lamberts, M., Van Laarhoven, C. J. H. M., Drenth, J. P. H., Boermeester, M. A., & De Reuver, P. R. (2014). Laparoscopy in cholecysto-choledocholithiasis. *Best Practice & Research Clinical Gastroenterology*, *28*(1), 195-209. https://doi.org/10.1016/j.bpg.2013.11.015

Van Houwelingen, B. C. G., Rutkowski, A. F., Ganni, S., Stepaniak, P. S., & Jakimowicz, J. J. (2020). Effects of surgical flow disruptions on surgeons' resources: a pilot study. *Surgical Endoscopy*, *34*(10), 4525-4535. https://doi.org/10.1007/s00464-019-07239-2

van Kuijk, J., Kanis, H., Christiaans, H., & van Eijk, D. (2017). Barriers to and Enablers of Usability in Electronic Consumer Product Development: A Multiple Case Study. *Human-Computer Interaction*, *32*(1), 1-71. https://doi.org/10.1080/07370024.2015.1117373

VARJO. (2021). *Varjo XR3*. Retrieved November 09, 2021 from https://varjo.com/products/xr-3/

Vereczkel, A., Bubb, H., & Feussner, H. (2003). Laparoscopic surgery and ergonomics: It's time to think of ourselves as well. *Surgical Endoscopy and Other Interventional Techniques*, *17*(10), 1680-1682. https://link.springer.com/content/pdf/10.1007/s00464-003-9020-1.pdf

Verlinden, J., & Bekker, A. (2017, 12 June). *Architecture Through the Looking Glass: Augmenting Fabrication in the Built Environment* SCF '17: Proceedings of the 1st Annual ACM Symposium on Computational Fabrication, Cambridge, Massachusetts.

Vink, P., Bazley, C., Kamp, I., & Blok, M. (2012). Possibilities to improve the aircraft interior comfort experience. *Applied Ergonomics*, *43*(2), 354-359. https://doi.org/10.1016/J.APERGO.2011.06.011

Vink, P., & Hallbeck, S. (2012). Editorial: comfort and discomfort studies demonstrate the need for a new model. *Appl Ergon*, *43*(2), 271-276. https://doi.org/10.1016/j.apergo.2011.06.001

Wang, D., Guo, Y., Liu, S., Zhang, Y., Xu, W., & Xiao, J. (2019). Haptic display for virtual reality: progress and challenges. *Virtual Reality & Intelligent Hardware*, *1*(2), 136-162. https://doi.org/10.3724/SP.J.2096-5796.2019.0008

Wang, G. G. (2002). Definition and Review of Virtual Prototyping. *Journal of Computing and Information Science in Engineering*, *2*(3), 232-236. https://doi.org/10.1115/1.1526508

Wang, P., Zhang, S., Bai, X., Billinghurst, M., He, W., Sun, M., Chen, Y., Lv, H., & Ji, H. (2019). 2.5DHANDS: a gesture-based MR remote collaborative platform. *International Journal of Advanced Manufacturing Technology*, *102*(5-8), 1339--1353. https://doi.org/10.1007/s00170-018-03237-1

Wang, P., Zhang, S., Bai, X., Billinghurst, M., Zhang, L., Wang, S., Han, D., Lv, H., & Yan, Y. (2019). A gesture- and head-based multimodal interaction platform for MR remote collaboration. *International Journal of Advanced Manufacturing Technology*, *105*(7-8), 3031--3043. https://doi.org/10.1007/s00170-019-04434-2

Wang, X., Ong, S. K., & Nee, A. Y. C. (2016). A comprehensive survey of augmented reality assembly research. *Advances in Manufacturing*, *4*(1), 1-22. https://doi.org/10.1007/s40436-015-0131-4

Weistroffer, V., Paljic, A., Callebert, L., & Fuchs, P. (2013). A methodology to assess the acceptability of human-robot collaboration using virtual reality. the 19th ACM Symposium on Virtual Reality Software and Technology - VRST '13, Singapore.

Werner, N. E., Jolliff, A. F., Casper, G., Martell, T., & Ponto, K. (2018). Home is where the head is: a distributed cognition account of personal health information management in the home among those with chronic illness. *Ergonomics*, *61*(8), 1065-1078. https://doi.org/10.1080/00140139.2018.1435910

Whitman, L. E., Jorgensen, M., Hathiyari, K., & Malzahn, D. (2004). Virtual reality: its usefulness for ergonomic analysis. Proceedings of the 2004 Winter Simulation Conference, 2004., Washington, DC, USA.

Wiegmann, D. A., Elbardissi, A. W., Dearani, J. A., Daly, R. C., & Sundt, T. M. (2007). Disruptions in surgical flow and their relationship to surgical errors: An exploratory investigation. *Surgery*, *142*(5), 658-665. https://doi.org/10.1016/j.surg.2007.07.034

B

Wiklund, M. E., Kendler, J., & Strochlic, A. Y. (2015). *Usability Testing of Medical Devices* (2nd ed.). CRC press. https://doi.org/10.1201/b19082

Witmer, B. G., Jerome, C. J., & Singer, M. J. (2005). The factor structure of the presence questionnaire. *Presence-Teleoperators and Virtual Environments*, *14*(3), 298-312. https://doi.org/10.1162/105474605323384654

Witmer, B. G., & Singer, M. J. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, *7*(3), 225-240. https://doi.org/10.1162/105474698565686

Xue, H., & Desmet, P. M. (2019). Researcher introspection for experience-driven design research. *Design Studies*, *63*, 37-64.

Yao, X., & Vink, P. (2019, August 29-30). A Survey and a Co-creation Session to Evaluate Passenger Contentment on Long-haul Flight, with Suggestions for Possible Design Improvements to Future Aircraft Interiors. International Comfort Congress (ICC2019), Delft, Netherlands.

Yoon, B., Kim, H.-i., Lee, G. A., Billinghurst, M., & Woo, W. (2019, mar). *The Effect of Avatar Appearance on Social Presence in an Augmented Reality Remote Collaboration* 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), https://ieeexplore.ieee.org/document/8797719/

Zhang, A., Hünerbein, M., Dai, Y., Schlag, P. M., & Beller, S. (2008). Construct validity testing of a laparoscopic surgery simulator (Lap Mentor®). *Surgical Endoscopy*, *22*(6), 1440-1444. https://doi.org/10.1007/s00464-007-9625-x

Zhang, J., Johnson, T. R., Patel, V. L., Paige, D. L., & Kubose, T. (2003). Using usability heuristics to evaluate patient safety of medical devices. *Journal of Biomedical Informatics*, *36*(1-2), 23-30. https://doi.org/doi.org/10.1016/S1532-0464(03)00060-1

Zhang, L., Helander, M. G., & Drury, C. G. (2016). Identifying Factors of Comfort and Discomfort in Sitting. *Human Factors*, *38*(3), 377-389. https://doi.org/10.1518/001872096778701962

Zheng, B., Jiang, X., Tien, G., Meneghetti, A., Panton, O. N. M., & Atkins, M. S. (2012). Workload assessment of surgeons: correlation between NASA TLX and blinks. *Surgical Endoscopy*, *26*(10), 2746-2750. https://doi.org/10.1007/s00464-012-2268-6

Appendix

Table A.11 The leaders from the industry who had applied XR technologies in their design-relevant practices

Title	Industry
Design director	Volkswagen Future Center
Director	Volkswagen Research Centre China (VRC)
Senior designer	Daimler AG
Senior product designer	Océ-Technologies B.V.
Chief manager	KLM crew training and security center
Senior XR manager	KLM crew training and security center
Product strategy manager	Customer Experience AMS/CX, KLM
Business class manager	Airbus
Senior designer	NS
Product developer	Hyperloop Delft
Senior designer	VanBerlo
Design manager	VanBerlo
Design director	Spark Design Studio
XR design researcher	Invocate Design
Product research manager	Philips consumer lifestyle
Product manager	Simbionix,3D Systems
Founder of the VR development tool	*VRmaster*
Head of MR research	*Mozilla*
Founder	*TWNKLS | AR*
VR developer	*Enversed Studio*
Manager	*Flight and Drive Simulation Center, TU Delft*
PM automotive	*Human Factors of Automated Driving, TU Delft*
Research director	*OV-chipkaart Graduation Lab, TU Delft*
Manager	*VR zone, TU Delft*
Project leader	*Fraunhofer FKIE*
Head of Project Management	*Auviea GmbH*
Deputy Director	*Department of Augmented Vision, DFKI*
Global Head and Chief Scientist	*Bosch Research*
Manager	*Adobe Research Big Data Experience Lab*

Table A.21 The 65 XR cases of the scoping review

1.source	2.0 Year	2.1 ACC	2.2 Publication: Journal Conference	2.3 Data collection: Quant. Qual. Both	2.4 Data type: Subjective Objective Both	3.0 Product/services	3.0.1 Modulor: 0<27 1=27; 2=43; 3=70; 4=86; 5=113; 6=140; 7=183; 8=226;	3.1 DDM; 1=discover; 2=define; 3=develop; 4=delivery;	3.2HCDs: 1=observation; 2=generation; 3=prototype; 4=testing	4.1 Qualities- efficiency, effectiveness, satisfaction	4.2 Type of UX	6.1 Type of XR	6.2 Display: CAVE, projection, headset, other	6.3 Artificiality: 1=mostly physial; 2= hybrid; 3= mostly ditigal	5.1 Interaction: control, anticipation, natural control, modify objects	5.2 Sensory: Influencial sensory, multimodal presentation, consistency	5.3 Realism: scene realism, consistency of real world, meaningfulness	5.4 Involvement: isolation, invisible interface
Almeida, A., et al. (2016). Development of a virtual	2016	0.4	conference	both	both	Safety: warning	9	1	2	effectiveness; satisfaction	cognitive	VR	headset	3	free walk-through; OM (gamepad);	3D vision; 3D sound;	real-size shelves; texture render	isolation; no UI
Aromaa, S. and K. Väänänen (2016). "Suitability of virtual	2016	24	journal	both	subjective	large machine (rock	9	2	4	effectiveness; satisfaction	physical	VR	headset	3	free walk-through; mocap; verbal for DHM;	3D vision	real-size rock crushing machine;	isolation; no UI
same	2016	24	journal	both	subjective	large machine (rock	9	2	4	effectiveness; satisfaction	physical	AR	other	1	free walk-through; OM (tablet)	2D vision	real-size product; texture render	no isolation; UI
Arora, R., et al. (2018). SymbiosisSketch;	2018	29.7	conference	quant.	objective	AR sketching	0	3	2	efficiency	physical	AR	headset	2	free walk-through; OM (a mouse button, tablet);	3D vision	texture rendering; Real-size	no isolation; UI
Arroyave-Tobón, S. and G. Osorio-Gómez (2017). "Ergonomic	2017	1.3	journal	quant.	objective	furniture	5	2	2	effectiveness	physical	AR	headset	2	free walk-through; mocap (hand posture);	3D vision	Real-size blocks	no isolation; no UI
Bennes, L., et al. (2012). Virtual reality as a support tool for	2012	2.1	conference	qual.	subjective	workstation	5	3	2	effectiveness	physical	MR	CAVE	2	free walk-through; 3D control (Wii remote);	3D vision; haptic (colision feedback);	real-size products;	no isolation; no UI
Bergroth, J. D., et al. (2018). "Use of Immersive 3-D Virtual	2018	2.3	journal	both	both	control room	9	4	4	efficiency	cognitive	VR	headset	3	OM (keyboard and mouse); active navigation	3D vision; 3D sounds	Real-size control room; texture	isolation; no UI
Bernard, F., et al. (2019). Virtual reality simulation and	2019	2.5	conference	quant.	objective	large parts	6	2	1	efficiency	physical, cognitive	MR	projection	2	free walk-through; mocap (head, hands and feets);	3D vison; physical object feedback	real-size product; DHM;	no isolation; no UI
Bordegoni, M. and F. Ferrise (2013). "Designing	2013	7.4	journal	both	both	home appliance: washing	4	3	3	effectiveness	physical	VR	projection	2	free walk-through (head tracking); OM (haptic	3D vision; sounds; force feedback;	real-size product; Texture	no isolation; no UI
Bordegoni, M., et al. (2013). Development of virtual prototypes	2013	0.4	conference	quant.	both	home appliance: refrigerator	8	3	3	effectiveness	physical	VR	projection	3	free walk-through (head tracking); 3D control (hand	3D vision; haptic (vibration) feedback,	real-size product; texture	no isolation; no UI
Caruso, G., et al. (2011). Collaborative mixed-reality	2011	0.7	conference	qual.	subjective	control panel	3	3	4	effectiveness	physical	MR	other	2	OM (haptic interaction);	3D vision	real-size car panel;	no isolation; no UI
same	2011	0.7	conference	qual.	subjective	control panel	3	3	4	effectiveness	physical	MR	headset	2	OM (dynamic dashboard and physical seatbuck);	3D vision, tactile feedback	real-size car panel; real texture;	no isolation; no UI
Caruso, G. and G. M. Re (2010). Interactive Augmented Reality	2010	1.4	conference	quant.	subjective	home appliance: cooking	1	3	4	effectiveness	physical	AR	headset	1	OM (Wii remote);	3D vision, sound	real-size applicance;	no isolation; no UI
Cowgill Jr, J. L., et al. (2013). The VERITAS facility; A virtual	2013	0.3	conference	quant.	objective	cockpit; Safety: city threat	6;9	1	1	efficiency	cognitive, organizational	VR	CAVE	3	active navigation (pointing wand to move, path	3D vision; 3D sounds;	real-size product; texture	no isolation; no UI
De Amaral, L. R., et al. (2018). Evaluation of a virtual	2018	1.0	conference	quant.	both	Safety: signs	9	4	3	effectiveness	cognitive	VR	headset	3	active navigation (gamepad)	3D vision, 3D sound	real-size product; texture	isolation; no UI
Deb, S., et al. (2017). "Efficacy of virtual reality in pedestrian	2017	29.8	journal	quant.	objective	Safety: pedestrian	9	4	3	effectiveness	cognitive	VR	headset	3	free walk-through;	3D vision, 3D sound	Real-size objects; textured	isolation; no UI
Delangle, M., et al. (2017). "Using motion capture to	2017	1.3	journal	quant.	objective	reachable space	8	2	3	effectiveness	physical	VR	projection	3	free walk-through; mocap; OM (control of	3D vison	real size tags, DHM, virtual room	no isolation; no UI
Demirel, H. O. and V. G. Duffy (2017). "Incorporating Tactile	2017	2.8	journal	quant.	both	medical cart	5	3	3	effectiveness	physical	MR	other	1	OM (force feedback); mocap;	2D vision; force feedback	task simulation; DHM;	no isolation; no UI
Di Gironimo, G., et al. (2012). "Improving quality of train	2012	0	conference	quant.	subjective	Train cabinet	9	3	4	efficiency	physical	VR	projection	3	passive navigation	3D vision	real-size cabinet; texture	no isolation; no UI
Dinardo, C. and L. Rizzi (2013). Design Validation of	2013	0	conference	quant.	objective	home medical service;	9	4	4	effectiveness	physical	MR	projection	3	free walk-through; OM (haptic device);	3D vision; haptic feedback	real-size products; DHM;	no isolation; no UI
Duarte, E., et al. (2014). "Behavioral compliance for	2014	13.4	journal	quant.	objective	Safety: sign	9	1	1	effectiveness	cognitive	VR	headset	3	OM (2D pointer); mocap;	3D vision; sound;	textured rendered; real-size	isolation; no UI
Favi, C., et al. (2019). "Virtual reality-enhanced	2019	3.0	journal	quant.	objective	workstation	5	4	4	effectiveness; satisfaction	physical	VR	projection	3	free walk-through; OM (Xbox controller)	3D vision;	real-size ship bridge; texture	no isolation; no UI
Forbes, T., et al. (2018). A study into the influence of	2018	1.3	conference	both	both	furniture: armchair	5	3	3	effectiveness	physical	AR	other	1	free walk-through;	2D vision	real size armchair; texture	no isolation; no UI
same	2018	1.3	conference	both	both	furniture	5	3	3	effectiveness	physical	VR	headset	2	free walk-through	3D vision	real size armchair; texture	isolation; no UI
Friemert, D., et al. (2018). "Similarities and Differences in	2018	1.3	conference	quant.	objective	logistic machine	8	1	3	effectiveness	physical	VR	headset	3	free walk-through; 3D control (VR controllers);	3D vision, vibration feedback	real-size order picking station;	isolation; no UI
Goedicke, D., et al. (2018). "VR-OOM; Virtual reality on-	2018	13.7	conference	qual.	subjective	Vehicle	6	3	3	efficiency	cognitive	MR	headset	2	free drive-through; mocap (arms);	3D vision, physical feedback,	real-size cockpit; virtual arms;	isolation; no UI
Gregoriades, A., et al. (2015). "Human Requirements	2015	0.5	journal	quant.	objective	cockpit	5	1	4	efficiency	cognitive	MR	CAVE	2	OM (steer wheel and foot pedals); behaviour	3D vision; haptic (pedals and steering	texture render; task	no isolation; no UI
Hoonakker, P., et al. (2019). Healthcare in a virtual	2019	0	conference	quant.	objective	home medical service;	9	1	3	effectiveness	cognitive	VR	CAVE	3	free walk-through, OM (joystick)	3D vision;	real-size houses; photo-	no isolation; no UI
Hsieh, S. Y. and J. M. Lu (2019). Feasibility evaluation for	2019	0	conference	quant.	objective	robotic arm	4	1	3	effectiveness	physical, cognitive	VR	headset	3	Mocap (hand); OM (hand posture);	3D vision; sound	full scale objects; texture	isolation; no UI
Hu, B., et al. (2012). "Impact of multimodal feedback	2012	2.4	journal	quant.	both	manufacture tasks	6	2	1	effectiveness	physical	VR	headset	2	mocap (arm and hand tool tracking);	3D vision; 3D sound; haptic feedback	full scale targets and hand tools;	isolation; no UI
Kim, H.-J., et al. (2016). miniStudio; Designers' Tool for	2016	4.2	conference	both	both	building design: down-sized	9	2	2	efficiency	cognitive	AR	projection	2	OM (based on location, distance, motion and	2D vision, haptic feedback (physical	task simulation;	no isolation; UI
Koppenborg, M., Nickel, P., Naber, B., Lungfiel, A., &	2017	13.3	journal	quant.	both	human-robot collaborati	9	2	1; 4	efficiency	organizational	VR	projection	3	free walk-through; OM (physical control panel);	3D vison	Full scale workstation; texture	no isolation; no UI
Langlois, S., et al. (2016). "Virtual head-up displays for	2016	2.0	conference	quant.	objective	cockpit	5	3	3	effectiveness	cognitive	MR	projection	2	OM (static driving simulator);	3D vision; physical feedback	real cockpit; photo-realisitic	no isolation; no UI
Lawson, G., et al. (2015). "The use of virtual reality and	2015	5.3	journal	both	both	cockpit	5	2	4	effectiveness	physical	MR	CAVE	2	free walk-through;	3D vision; physical haptic feedback	Physical seat and wheel; real texture;	no isolation; no UI
Lee, Y., et al. (2010). "Immersive modeling system (IMMS) for	2010	2.3	journal	both	subjective	consumer electronics	0	3	2	effectiveness	physical, cognitive	MR	headset	2	OM (projection on physical object with QR code,	3D vision; 3D sound feedback;	physcial parts; rendered GUIs and materials;	isolation; no UI
Li, B., et al. (2018). "Design in context of use; An experiment	2018	2.0	journal	both	subjective	cockpit	5	2	2	effectiveness	organizational	VR	projection	3	OM (manipulate mock-up, user); OM (virtual	3D vision;	real scale model; rendered	no isolation; no UI

Liston, P. M., et al. (2012). "Evaluating the iterative	2012	0.6	journal	both	both	large parts	6;9	3	1; 2; 4	efficiency	physical	VR; AR	na	na	na	na	na	na
Luquetti dos Santos, I. J. A., et al. (2009). "The use of	2009	3.8	journal	quant.	subjective	workstatio n	5	3	4	effectiveness	cognitive	VR	projection	3	free walk-through;	3D vision	real-size control desk; texture	no isolation; no UI
Mahdjoub, M., et al. (2013). Multidisciplinary	2013	1.3	conference	qual.	subjective	cockpit	5	2	2	efficiency	physical, organizatio nal	VR	projection	3	free walk-through (turn around the mock-up and	3D vision; physical seats	real-size cart; Texture rendered;	no isolation; no UI
Mallam, S. C., et al. (2019). Design of experiment	2019	4.5	journal	both	both	Safety: wayfinding training	9	1	3	efficiency; satisfaction	cognitive	VR	headset	3	free walk-through; 3D control (VR controller);	3D vision; 3D sound; vibration	Real-size objects; photo realistic	isolation; no UI
Mengoni, M., et al. (2008). "Performing ergonomic analysis in	2008	1.0	conference	both	both	home appliance: washing	4	2	4	effectiveness	physical, cognitive	MR	headset	2	free walk-through (head tracking); OM (physical	3D vision; haptic feedback;	real scale product; texture	isolation; no UI
Michalos, G., et al. (2018). "Workplace analysis and design	2018	17.0	journal	quant.	objective	workstatio n	5	2	1	efficiency	physical	VR	CAVE	3	free walk-through; 3D control (object tracking);	3D vision, haptic feedback (vibration)	real-size workstation; texture	no isolation; no UI
Nguyen, H., et al. (2017). "VR-based operating modes and	2017	2.3	journal	quant.	objective	workstatio n	5	3	2	efficiency	organizatio nal	VR	CAVE	3	free walk-through; Mocap (upper body);	3D vision	real-size simplified assembly line	no isolation; no UI
Nickel, P. and A. Lungfiel (2018). "Improving	2018	1.7	conference	quant.	objective	Safety- mobile elevating	9	2	1; 4	effectiveness	cognitive	VR	projection	3	free walk-through; OM (joystick);	3D vision	real-size vehicles; texture	no isolation; no UI
same	2018	1.7	conference	both	both	Safety: electro- sensitive	9	2	1; 4	effectiveness	cognitive	VR	projection	2	active navigation (naviation via rotary table)	3D vison;	Full scale safety zone; texture	no isolation; no UI
Oberhauser, M. and D. Dreyer (2017). "A virtual reality flight	2017	10.5	journal	quant.	both	cockpit	5	2	3	efficiency	cognitive	VR	headset	2	active navigation (flight controls); 3D control (hand	3D vision;	real-size cockpit (HUD); texture	isolation; no UI
same	2017	10.5	journal	quant.	objective	cockpit	5	4	3	effectiveness	cognitive	VR	headset	2	3D control (hand and finger tracking);	3D vision; physical haptic (control	real-size cockpit (horizon	isolation; no UI
same	2017	10.5	journal	quant.	both	cockpit	5	1	1	effectiveness	cognitive	MR	headset	2	3D control (hand and finger tracking);	3D vision; physical haptic (control	real-size cockpit (overhead	isolation; no UI
Oehlschlaeger, H., et al. (2008). New virtual development	2008	na	conference	quant.	subjective	cockpit	5	3	2	effectiveness	physical	VR	headset	2	active navigation (seat buck); OM (seat buck);	3D vision; physical seat and steer wheel;	Real-size cockpit; texture	isolation; no UI
Paes, D., et al. (2017). "Immersive environment for	2017	37.0	journal	quant.	subjective	building design	9	3	3	effectiveness	cognitive	VR	projection	3	active navigation (keyboard-mouse)	3D vision	Virtual replication of an entrance	no isolation; no UI
Paes, D. and J. Irizarry (2018). A usability study of an	2018	6.0	conference	quant.	both	building design	9	4	4	effectiveness	cognitive	VR	headset	3	active navigation (keyboard-mouse)	3D vision	real-size building; texture	isolation; UI
Parsons, T. D., et al. (2009). Neurocognitive	2009	2.6	conference	quant.	both	cockpit (as context)	5	1	1	effectiveness	cognitive	VR	headset	3	active navigation (gamepad);	3D vision; sound; haptic;	real-size HUMVEE cockpit;	isolation; no UI
Peruzzini, M., et al. (2018). "How to analyse the workers'	2018	5.3	journal	quant.	objective	large parts	6	2	1	efficiency; satisfaction	physical, cognitive	MR	projection	2	free walk-through; motion tracking (full-body);	3D vision; sound; physical haptic	physical part; DHM; simulated	no isolation; no UI
Peruzzini, M., et al. (2019). "A comparative study on	2019	20.0	journal	both	both	large parts	6	3	3	effectiveness	physical, cognitive	MR	projection	2	free walk-through; motion tracking (full-body);	3D vision; 3D sound; physical tools	real-size virtual and 3D printed	no isolation; no UI
Pontonnier, C., et al. (2014). "Designing and evaluating a	2014	9.6	journal	both	both	workstatio n	5	3	3	effectiveness	physical	VR	projection	3	free walk-through; mocap (upper body);	3D vsion;	real size workstation and objects;	no isolation; no UI
same	2014	9.6	journal	both	both	workstatio n	5	3	3	effectiveness	physical	MR	projection	2	free walk-through; mocap (upper body);	3D vsion; force feedback	real size workstation and objects;	no isolation; no UI

Reinschluessel, A. V., et al. (2017). Virtual Reality for User-	2017	5.5	conference	quant.	both	OR (touchless interaction)	9	4	4	effectiveness	cognitive	VR	headset	3	free walk-through; 3D control (hand gesture);	3D vision;	Real-size screen; photo-realistic	isolation; no UI
Toma, M. I., et al. (2012). "A comparative	2012	3.4	journal	quant.	objective	VR modelling	0	3	2	efficiency	cognitive	VR	CAVE	3	free walk-through; 3D control (hand gesture);	3D vision; sound; force feedback;	real-size models; task	no isolation; no UI
Uchida, N., et al. (2017). "Development of an	2017	8.0	journal	quant.	objective	cockpit	5	1	1	efficiency	cognitive	AR	other	2	free drive- through; OM (physical	2D vision, physical haptic feedback;	video from real world (size and	no isolation; no UI
Vilar, E., et al. (2014). "Effects of competing environmental	2014	11.6	journal	quant.	objective	Safety: sign and wayfinding	9	1	1	efficiency	cognitive	VR	projection	3	active navigation (joystick);	3D vision, 3D sound	real-size sign and layout; texture	no isolation; no UI
Vosniakos, G. C., et al. (2017). On immersive Virtual	2017	4.8	conference	quant.	both	workstatio n	5	4	4	efficiency	physical	MR	headset	2	free walk-through; mocap (full body); OM (virtual hand;	3D vision; physcial tools feedback;	real-size parts and work station;	isolation; no UI
Weistroffer, V., et al. (2013). A methodology to	2013	3.8	conference	quant.	both	workstatio n: human- robot	8	2	2	satisfaction	organizatio nal	VR	projection	3	free walk-through; OM (hand tracking);	3D vision;	real-size robots; rendered	no isolation; no UI
Werner, N. E., et al. (2018). "Home is where the head is; a	2018	5.3	journal	qual.	subjective	home medical service;	9	1	1	effectiveness	cognitive	VR	CAVE	3	free walk-through; OM (joystick);	3D vision;	highly accurate 3D replica of	no isolation; no UI
Zare, M., et al. (2019). Application of virtual reality to	2019	0.5	conference	qual.	subjective	control room	9	3	3	effectiveness	physical	VR	CAVE	3	free walk-through;	3D vision, sound; physical seat;	Real-size control room; texture	no isolation; no UI
Zimmermann, M., et al. (2014). Acting together by mutual	2014	6.4	conference	both	both	cockpit	5	2	3	effectiveness	organizatio nal	MR	projection	2	active navigation; OM (steer whiee, brake,	3D vision, sound; physical parts	real-size driving simulator;	no isolation; no UI

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Table A.31 The enablers and barriers in 65 XR experiences for UX studies

Aspects	Enablers (n of cases)	Barriers (n of cases)
Physical Well-being		
System feature	+ Graphic quality, e.g., rich visual information (3) + Multimodal modules, e.g., auditory-haptic feedback, visual-force feedback (2) + Effective interaction, e.g., multi-sensory object manipulation (2) + Motion capture, e.g., full-body motion capture (2) + Integrated well with real-world (1) + High maturity of elements, e.g., scene creation, scenario development, and interaction with users (1) + Minor system errors (1)	- Haptic fidelity, e.g., limited fidelity, missing touch, missing occlusion (5) - Visual fidelity, e.g., limited field-of-view, delays of video streaming, distortion of visualization (3) - System robustness, e.g., delay, blurriness, free movement, defects (3) - Complex study preparation, e.g., prototyping interactivity (3) - Human factors of headsets, e.g., constrained movements by wires (1) - Missing digital humans (1)
Design elements	+ Realistic biomechanical and behavioral data, e.g., upper limbs postures, human movements, push-pull-related ergonomics (5) + Visibility, reachability, accessibility (3) + Shape, distance, configuration (aesthetics), usage, and assembly (3) + Multi-dimensional evaluation, e.g., aesthetics and ease-of-use, product impression and ergonomics (3) + Task load (e.g., mental demand, physical demand, temporal demand, and frustration), performance and presence interaction (2) + Design validation, e.g., procedure validation (2)	- Discomfort, simulation sicknesses, accuracy, effort, mental workload, presence (5) - Shape distortion (2) - Materials and controls simulation (1) - Entry and exit issues (1)
Design activities	+ Effort-time saving, such as real-time analysis, continuous improvements, rapid edit/switch prototypes, easy to program and flexible, easy customizing (6) + Emotional involvement, e.g., feelings, subjective fidelity, enjoyment in design, confidence in judgment (6) + Embodiment for judgments, performing in contexts, imagining usages, spatial references, and the natural motion of avatars (3) + Gain more data, e.g., tests recording, or capturing under impossible situations, symbolic overview (3) + Participatory design, e.g., reducing misunderstanding, multidisciplinary teams, efficient convergence (3) + Mixture of 2D and 3D sketching (2)	- Imprecise estimation, e.g., different joint angles, unnatural motion, dependence on body sizes, and impossible to evaluate the shape (6). - Prototyping barriers, e.g., hard in sketching large objects, time of 3D modeling, hard in interacting, hard in creating free-form objects, not fully adapted to the development context, raised costs (5) - Testing barriers, e.g., influences from physical surroundings, limited product scales (2) - Misleading moods, e.g., user's fear to move, misplaced confidence of designers (2) - Unfamiliarity, e.g., timely inadequate, perceived more difficulties (2)
Cognitive Well-being		

Table A.31 Continued

Aspects	Enablers (n of cases)	Barriers (n of cases)
System feature	+ Free walk-through (5) + Flexibility and robustness, e.g., flexible levels of usability and complexity, open-source coding (4) + New data registration and analysis, e.g., head, hands, eyes, and lips tracking (3) + Sensory quality, e.g., adequate resolution for detailed evaluation (5) + Distributed system, e.g., possibilities of telemetry (3) + Narrative consistency and coherence (4) + Intuitive and natural interfaces, e.g., voice and gesture interaction (1) + Low-cost hybrid reality simulators (1) + Realism of 3D models (1) + Isolation in designated environments (1)	- Visual fidelity, e.g., the field-of-view and resolution, latency (4) - Hand controllers, e.g., ergonomics (4) - Restricted movements (3) - Auditory fidelity, e.g., missing ambient sound (2) - Virtual bodies (1) - Realism in rendering, e.g., lighting (1) - Interactive scenario, e.g., cockpit (1) - Fixed virtual camera (1)
Design elements	+ Spatial perception, e.g., interaction considering physical relationships, understanding real scales (with digital humans), spatial-geometric arrangement, estimate distances, holistic spatial configuration (7) + Ecological validity (4) + Cognitive workload (3) + Performance, e.g., reaction time (modeling), assembly performance (3D visualization) (1) + Functionality and accuracy evaluations (1) + Impacts of potential confounds (1) + Tangible demonstrations (1) + Reproduce the “depth gap” (1) + Empirical data from users in-situ (1)	- Simulation sickness symptoms, e.g., difficulty concentrating, "full of head", dizziness with eyes open, eye strain, focusing difficulty, nausea, blurred vision, and general discomfort (9) - Physical stress, e.g., the effort in navigating (5) - Negative effects on performance (2) - Depth perception (2) - Evaluating alarms and controls (2 - Architectural design (2)

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Table A.31 Continued

Aspects	Enablers (n of cases)	Barriers (n of cases)
Design activities	+ Precise and efficient experimental control, e.g., manipulating complexity and intensity of the stimulus, dynamic simulation at low costs, post-hoc simulation, high reproducibility, natural responses from low fidelity graphics, many trials in a short time (10) + Safe and unlimited simulation, e.g., safety-critical environments, hazardous tasks, accidents, fire or smoke, and logistic issues (10) + Personalization, e.g., customization in contexts, support decision-making, on-demand simulation training, good learning outcomes, good mobility and accessibility (7) + Trustworthy awareness and responses, e.g., similar responses to hazards, similar performance (6) + Rapid integrating prototypes, e.g., integrating external components, integrating new concepts in contexts, and efficient design representation of large products (5) + Emotionally salient, e.g., high degrees of involvement and engagement, user's engagement (5) + Design effectiveness, e.g., user participation, cost savings, fewer sources' requirements, efficient design-relevant communication (4) + Supporting early-stage evaluation, e.g., comparing concepts (2) + Integrate with the HCD stages, e.g., facilitate design iterations (1) + Accurate participants classification (via attention) (1) + Delivering interaction intuitively (1)	- System usability, e.g., multimodal interfaces, its influences on outcomes, slow to perform, mentally demanding (7) - Reliability of behaviors and judgment, e.g., differences in key behaviors, detailed interaction, trajectories, and low perceived stresses (4) - Realism, e.g., mismatching experience, limited psychological fidelity (3) - Long familiarity time (2) - Ineffective decision-making, e.g., incompetent in understanding design (2) - Spatiality expressions, e.g., flattened spatial experience, the ability to express 3D spaces (1) - Virtual environments as confounding effects (1) - Requiring large spaces (motion capturing) (1) - Difficult in programming learning (1) - Acceptances of stakeholders (1)
Organizational Well-being		
System feature	+ Spontaneous modifications (1)	- Tracking latency (2) - Rigid actions (2) - True-to-life simulation of work tasks (1)
Design element	+ Anxiety and task loads (2) + Human-machine collaboration, e.g., human-robot co-production, various human-machine function allocations (2)	

Table A.31 Continued

Aspects	Enablers (n of cases)	Barriers (n of cases)
Design activities	+ Realistic conditions, e.g., interaction and collaboration (3) + Cost efficiency, e.g., time-saving, being cost-effective and efficient without impeding productivity (2) + Facilitating experience design, e.g., first-person viewpoint, project personal experience in the contexts (2) + Surveying effects of individual requirements (2) + Designer-user co-design, e.g., co-creation scenarios, help to communicate their needs, encourage collaboration via gaiety (1) + Answering well-being constraints, e.g., more comfortable design (1) + Simulating the complexity of cooperation (e.g., co-driving) (1) + More intuitive and natural role play (1) + Involving body in the judgment (1)	- Lacking tools to enable consistent remote interaction between design stakeholders, e.g., views of users (3) - Low learnability, e.g., unfamiliar with the environment and the tasks (3) - Different emotions of users (2) - Simplified use cases (2) - Questionable risk analyses (1)
Linked Well-being		
System feature	+ Multi-modal interfaces, e.g., introducing haptics, physical parts (2) + Sensor-tracking, e.g., motion-tracking, eye-tracking (1) + Natural, intuitive, and comfortable interaction (1) + Simulate functions completely (1) + Minimal sets of hardware (1) + Real-scale visualization (1) + Virtual Human (1)	- Visual fidelity, e.g., no photorealistic rendering (1) - Haptic fidelity, e.g., unrealistic feedback (1) - Single-person setup (1)
Design elements	+ Task durations and motion strategies (1) + Postural tools, e.g., RULA, Borg, and APACT (1) + Dimension validation (1) + Human-robot interaction (1) + Safety, posture, and force indicators (1) + Attentional demands (1)	- Simulation sickness, e.g., different exposure times to different postures and conditions (2) - Missing specific motion strategies (1)

Table A.31 Continued

Aspects	Enablers (n of cases)	Barriers (n of cases)
Design activities	+ Facilitate vast analyses, e.g., posture, visibility, reachability, occlusion, mental, and emotional, more detailed data than in the real world (2) + Good accuracy and reliability, e.g., similarity in subjective measurements (2) + Production efficiency, e.g., reusing existing artifacts, better comparisons between concepts, creating different alternatives, reducing design iterations (2) + Predict critical features, e.g., expecting future use by relevant experience, experiencing users' gest to highlight design convergences (2) + Reduced analysis time, e.g., enable semi-automatic data post-processing (1) + Significantly improved usability, e.g., detecting more design errors (1) + Support design processes efficiently and proactively (1) + Define new solutions easily and intuitively (1) + Investigates complex tasks (1) + Dangerous or expensive studies (1) + More efficient training (1)	- High costs of implementing, such as hardware (motion capture), licensed software (digital human), development time, and training, as well as the high effort and the shortage of personnel (3) - Missing co-location, e.g., no remote participation (1) - Insufficient familiarization (1)

Table A.41 The first impression from design professionals on the XR prototype

Roles	Positive	Neutral	Negative
Experts	+ cool + very helpful + looks nice + good simulation + flexible system + Resolution to be proposed + useful to reduce prototypes	*Visualization to reduce prototyping *Real-like visual impression *Should be used in combination with physical prototypes	-strange -very abstract
Novices	+innovative (2) +nice impression of the cabin +easy to handle +fast implementation +new +interesting +good start	*Immersive (2) *Sound, *Headset, *Privacy, *Abstract, *Only for initial concepts,	- a designer tool not suitable for engineers

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LIST OF PUBLICATIONS

Aschenbrenner, D., Li, M., Dukalski, R., Verlinden, J., & Lukosch, S. (2018, 18-22 March 2018). Collaborative Production Line Planning with Augmented Fabrication. 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Tuebingen/Reutlingen, Germany.

Aschenbrenner, D., Li, M., Dukalski, R., Verlinden, J., & Lukosch, S. (2018). Exploration of different Augmented Reality Visualizations for Enhancing Situation Awareness for Remote Factory Planning Assistance. Fourth IEEE VR International Workshop on 3D Collaborative Virtual Environments (3DCVE 2018),

Ganni, S., Botden, S. M. B. I., Chmarra, M., Li, M., Goossens, R. H. M., & Jakimowicz, J. J. (2020). Validation of Motion Tracking Software for Evaluation of Surgical Performance in Laparoscopic Cholecystectomy. *Journal of Medical Systems*, *44* (3). https://doi.org/10.1007/s10916-020-1525-9

Ganni, S., Li, M., Botden, S. M. B. I., Nayak, S. R., Ganni, B. R., Rutkowski, A.-F., Goossens, R. H. M., & Jakimowicz, J. (2020). Virtual Operating Room Simulation Setup (VORSS) for Procedural Training in Minimally Invasive Surgery – a Pilot Study. *Indian Journal of Surgery*, *82* (5), 810-816. https://doi.org/10.1007/s12262-020-02131-z

Li, M., Albayrak, A., Zhang, Y., & van Eijk, D. (2019). Multiple Factors Mental Load Evaluation on Smartphone User Interface. In S. Bagnara, R. Tartaglia, S. Albolino, T. Alexander, & Y. Fujita (Eds.), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* (pp. 302-315). Springer International Publishing. https://doi.org/10.1007/978-3-319-96059-3_33

Li, M., Albayrak, A., Zhang, Y., van Eijk, D., & Yang, Z. (2019). Comparison of Questionnaire Based and User Model Based Usability Evaluation Methods. In S. Bagnara, R. Tartaglia, S. Albolino, T. Alexander, & Y. Fujita, *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* IEA 2018, Florence, Italy.

Li, M., Aschenbrenner, D., van Tol, D., van Eijk, D., & Vink, P. (2022). A Human-Centered Design Procedure for Conceptualization Using Virtual Reality Prototyping Applied in an Inflight Lavatory. In N. L. Black, W. P. Neumann, & I. Noy, *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)* IEA2021, Cham.

Li, M., Ganni, S., Albayrak, A., Rutkowski, A. F., Van Eijk, D., & Jakimowicz, J. (2021). Proficiency from Immersion---A User-Centered Design in Cross-Cultural Surgical Training. *Frontiers in Virtual Reality*, *2*, 65.

Li, M., Ganni, S., Ponten, J., Albayrak, A., Rutkowski, A.-F., & Jakimowicz, J. (2020). Analysing usability and presence of a virtual reality operating room (VOR) simulator during laparoscopic surgery training. 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Atlanta, GA, USA.

Li, M., Houwing, D., Albayrak, A., Shidujaman, M., & van Eijk, D. (2023). Mapping XR Platforms: Analyzing Immersion from the Designer's Perspective. In M. Kurosu & A. Hashizume, *Human-Computer Interaction* HCII2023, Copenhagen.

Li, M., Slijkhuis, T., Huigen, R., Albayrak, A., & van Eijk, D. (2021, 4-8 Oct. 2021). Two-way Augmented Reality Co-location Under Telemedicine Context. 2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Bari, Italy.

Li, M., Wu, X., & Yang, Z. (2021). A Review of Data-Driven Human Centred Design the Training of Immersive Surgery for Virtuality-Reality Fusion. *Creativity and design (创意与设计)*, *73*(2), 25-31.

Li, M., Yao, X., Aschenbrenner, D., van Eijk, D., & Vink, P. (2022). *Ergonomics 4.0: Human-Centered Procedure for Ergonomic Design Using Virtual Reality Prototyping* INCOSE International Symposium, Virtual event.

Lingan, C. L., Li, M., & Vermeeren, A. P. (2021). The immersion cycle: Understanding immersive experiences through a cyclical model. *Proceedings of the Design Society*, *1*, 3011-3020.

Torkashvanda, G., Li, M., & Vink, P. (2021). Concept evaluation of a new aircraft passenger privacy bubble using virtual prototyping: A Human-Centered Design framework. *Work*, *68*(s1), S231-S238. https://doi.org/10.3233/WOR-208020

Wu, X., Luo, T., Xiong, S., Liu, Y., & Li, M. (2022, July 24-28, 2022). Introduction of Distractions in Immersive Virtual Reality Laparoscopic Surgery Training – a Pilot Study.*AHFE International* 13th AHFE International Conference on Physical Ergonomics and Human Factors., New York, USA