Elements of XR Prototyping: Characterizing the Role and Use of Prototypes in Augmented and Virtual Reality Design

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ABSTRACT

Current research in augmented, virtual, and mixed reality (XR) reveals a lack of tool support for designing and, in particular, prototyping XR applications. While recent tools research is often motivated by studying the requirements of non-technical designers and end-user developers, the perspective of industry practitioners is less well understood. In an interview study with 17 practitioners from different industry sectors working on professional XR projects, we establish the design practices in industry, from early project stages to the final product. To better understand XR design challenges, we characterize the different methods and tools used for prototyping and describe the role and use of key prototypes in the different projects. We extract common elements of XR prototyping, elaborating on the tools and materials used for prototyping and establishing different views on the notion of fidelity. Finally, we highlight key issues for future XR tools research.

CCS CONCEPTS

• **Human-centered computing → Interface design prototyping**; **Mixed / augmented reality**.

KEYWORDS

prototyping; mixed reality; augmented reality; virtual reality, XR; authoring; interaction design; interface design.

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1 INTRODUCTION

While the Human-Computer-Interaction (HCI) community has been researching XR for decades, XR adaption to mass markets has only just started. Since hardware and software capabilities and potential application domains are evolving rapidly, keeping up with the current pace of innovation is proving difficult.

With that challenge comes a new interest in enhancing XR accessibility by creating new authoring and creativity support tools for designers with low to no technical skills. The tool gap [36] when prototypes transition from lower to higher fidelity stages and the resulting design difficulties have refueled debates about authoring tools from earlier XR tools research [27]. With industry practitioners' increased adoption of XR, current research efforts are focusing on supporting non-technical designers, hobbyists, and end-user developers [2]. However, there is relatively little research into the experience and knowledge held by experts in the XR industry, where a tool gap can also be observed [20].

XR still has to come a long way to accomplish standardized tool chains, development processes, user interface design conventions, or good design practices [21, 41]. The concepts and interpretations of the medium's principles, as well as their beneficial application, are just beginning to emerge in both academia and practice. However, a thorough understanding of practices and creativity is necessary to inform supportive design tools for creators [19]. We follow an expert designer-centered approach to boost the currently underrepresented focus on XR industry practitioners. As there is not yet a common definition of XR, we use it as the overarching term referring to AR, VR, and MR [29, 40]. Where required for clarification, we explicitly use AR, VR, or MR, following Milgram and Kishino's [31] definitions.

In line with previous work into ubiquitous computing and interaction design [10, 45, 46, 51] aiming at supporting the development of compelling user interfaces and creativity [19], we investigate industry practitioners' prototypes as a *"core means of exploring and expressing designs for interactive computer artifacts"* [16]. Since prototypes are used as aids in thinking [37] and communication of ideas and concepts [10], we expect to learn more about design practices, challenges, and types of XR content in and approaches to creating better experiences for end-users. Rather than analyzing tools used for prototype creation, our research into the tool gap studies what prototypes entail and convey and why different prototypes are created. The research addresses the following three questions:

Q1 What roles do prototypes play in industrial XR development practices?
Q2 How do designers create and use XR prototypes?
Q3 Where do prototypes reach their limits and what can we learn about designing supportive design tools?

By discussing and analyzing our empirical work, our paper contributes the following:

- We provide empirical insights into prototyping practices in the XR industry, giving an overview of 23 projects and two general approaches from 17 interviewees working on professional XR projects.
- We provide a taxonomy of XR prototypes consisting of classes, manifestation types, and elements of XR prototyping. This taxonomy can help in the analysis and better understanding of key prototype characteristics and how they differ from more traditional 2D prototypes, e.g., for mobile and web platforms.
- We identify future directions of XR prototyping and tools research including the need to differentiate more precisely between tools for thinking and tools for creating[46]; the need to focus on the different aspects of XR prototyping included in our taxonomy; and the need to to create shareable applications by improving prototype accessibility, e.g., by looking into solutions for explaining the surroundings and situation for which an XR experience was designed.

2 RELATED WORK

Our work builds on previous research into design support for XR as well as on studies of the role and function of prototypes in general. Consequently, we first provide an overview of current tools research in XR design in line with identified XR specific design and tool challenges. Then, as a theoretical basis for our research, we proceed with an overview of the role and understanding of prototypes in design processes.

2.1 XR Design Approaches and Authoring Tools

Recent HCI research has studied new design strategies and tools for XR. A common focus of that work has been on empowering novice designers. Early work includes DART [27], a toolkit targeted at media designers to help transition 2D storyboards to 3D animatic actors, allowing designers to explore interactive stories for new AR experiences without the need for programming. A ten-year review of the use of DART by novice designers [13] identified major challenges due to designer backgrounds and workflows, a lack of processes and best practices, problems related to debugging, and finally that many DART prototyping features were under-utilized. Since DART, research has proposed many new authoring tools for both AR and VR, demonstrating a variety of prototyping techniques including physical prototyping [34, 35, 42], immersive authoring [23, 50], video-based editing [24, 25], live sharing [48, 53], and asynchronous/asymmetric collaboration [33, 49].

Despite the advances in tools research, designers are still facing many challenges. Nebeling & Speicher [36] identified five classes of increasingly sophisticated but also complex tools. Tools such as A-Frame, Unity, and Unreal are in the highest class and often considered out of reach for novices. Tools in the lower classes are more accessible to a broader spectrum of designers as they require less training and provide layers of abstraction and automation. However, this lower barrier to entry usually also limits the fidelity that can be achieved, known as the threshold and ceiling in tools research [32]. Ashtari *et al.* [2] elicited eight common barriers to entry with three groups of novice XR creators (trained designers, domain experts, and end-user developers), from finding the right examples and tools for XR design, to guidelines and metrics that constitute a good XR experience.

While existing studies and tools primarily targeted novice XR designers, the challenges are not unique to them. Speicher *et al.*'s [41] XR expert interviews highlight the confusions regarding XR terminology, concepts, and technologies even among experts from academia and industry. An interview study with 26 professional XR creators by Krauß *et al.* [20] identified four key roles: concept developers, interaction designers, content authors, and technical developers. An XR creator often encompasses several of those roles and faces the combined challenges of each, from contextual inquiry to deployment. The authors find similar challenges between novice and professional XR creators due to misconceptions about XR as a medium; a lack of tool support, particularly for spatial design in the prototyping stages; and the absence of a common language and shared concepts within development teams.

In our paper, we pick up on these attempts to highlight more professionalized practices around XR development, complementing and adding to existing research, and looking specifically at the role prototypes play in industry development practices. Rather than focusing on the act of prototyping by developing new tools, we investigate prototypes and their meaning in a professional context. Previous work from interaction design and ubiquitous computing has taken a similar approach [10, 46, 51]. With our work, we provide a conceptual perspective on XR prototyping rooted in both practices from industry and theoretical work in HCI research. Consequently, we reflect on the meaning, potential, and limitations of prototypes in XR design. We start this reflection by exploring recent HCI work into what prototypes are and how they are used. This overview is provided in the next section.

2.2 Prototypes in Interactive System Design Research

Prototypes play an important role in designing software applications in general [12, 16] as well as in research of relevance to interaction design practitioners [10, 26]. However, conceptual reflections on prototypes' XR design properties are rare.

Software development prototypes can vary in form and meaning. Consequently, several attempts have been made to define and classify them. A prominent yet controversial approach is to distinguish between low-fidelity, high-fidelity [38, 39], and mixed-fidelity prototypes [30]. Low-fidelity prototypes are described as being limited in function, explorative, and easy to create, in contrast to high-fidelity prototypes, which take more effort to create and deliver more refined results close to the final product [38, 39]. Mixed-fidelity describes how prototypes can have aspects of varying fidelity and therefore do not match the definition of low- or high-fidelity [30]. In the context of prototyping, fidelity is also associated with methods [28, 47] used for creating prototypes, such as paper prototyping [38] as a low-fidelity method. Furthermore, fidelity is aligned with the skills and resources required to operate prototyping tools [36].

Over the past decades, several attempts have been made in interactive system design to create taxonomies of prototypes. Floyd's "three E model" [12] focuses on *prototyping as a process*. According to Floyd, there are three categories of prototypes: *exploratory*, which focus on early stages of design; *experimental*, which aim to get feedback from users, or *evolutionary*, which are flexible regarding project contexts and requirements [12]. Bäumer *et al.* add to that model by further distinguishing the results of prototyping as an activity: exploratory prototyping produces *presentation* and *functional* prototypes, experimental prototyping results in *breadboards* depicting technical aspects, and evolutionary prototyping creates *pilot systems* close to the product [4].

Other approaches support a broader perspective. For instance, Houde and Hill [16] argue that everything could be a prototype depending on how a designer uses it, even a brick [16], and call for shifting attention towards the *purpose of a prototype* rather than the prototype itself [16]. They therefore propose a tripartite model of *role*, *implementation*, and *look and feel*. Opposing the free interpretation of prototypes and their manifestation, Beaudouin-Lafon and Mackay define a prototype as being *a tangible design artefact* and *"a concrete representation of part or all of an interactive system"* [5], which also *"supports creativity, encourages communication, and permits early evaluation"* [5]. They further propose four dimensions to analyze prototypes: *representation*, *precision*, *interactivity*, and *evolution* [5]. Rather than relying on the concept of artifacts, Buchenau and Suri describe a manifestation of prototypes that requires active engagement to be understood, and they concentrate on experience during usage as well as on what a user can learn from it [6] (e.g. Wizard-of-Oz [14]).

Instead of focusing on how prototypes are being used in a design process, Lim *et al's* metaphor of filters [26] aims to create a fundamental understanding of prototypes. They describe three prototyping principles: the *fundamental principle of prototyping* as an activity that creates manifestations that act as filters to observe design qualities, the *economic principle of prototyping* as a principle of efficiency and effectiveness, and the *anatomy of prototypes*, which act as filters for traversing a design space and concretize and externalize ideas [26]. They further emphasize that there is a need both for establishing a fundamental understanding of prototypes and for further investigations into how prototypes are being used [26].

While work has focused on what different types of prototypes are being used in design work and how they could be described based on their properties and forms, to our knowledge, no studies have investigated how prototypes are practically used in the context of XR-development in industrial practice. Our study does not aim to build a better or more comprehensive taxonomy for (XR) design theory. Instead it uses existing concepts as an analytic lens to observe practices and what can be learned about prototypes' rationales and use, especially in relation to the tools used to create them.

3 STUDY DESIGN AND ANALYSIS

We based our study on qualitative, semi-structured interviews with 17 professionals actively working on XR projects and UX design. Our questions (see Appendix A) were related to understanding prototyping in the context of projects chosen by participants and to obtaining insights into their practices, particularly how they use prototypes in their design work.

3.1 Recruitment and Participants

As industry professionals were hesitant about participating in a study about their working practices, we relied on snowball sampling, which took place between February and May 2021. First, we contacted professional XR designers we personally knew, asking them to participate and distribute our request in their networks. Additionally, we recruited via local XR hubs and on social networks via dedicated XR design Facebook groups, Slack channels, Discord servers, LinkedIn, and Twitter. We specifically asked for professional UX designers actively working on XR projects. Our aim was to sample a diverse group of participants regarding experience, domains, devices, and nationalities who were willing and able to discuss their design approaches and prototypes based on a project.

We recruited 17 participants (5 female, 10 male, 2 other; age groups: 18–24 (2), 25–34 (6), 35–44 (6), and 45–54 (2)) from Europe and North America (Austria (1), Canada (1), Germany (9), Ireland (1) Switzerland (1), USA (4)). Their average experience in the field was 6.4 years with a maximum of 24 years and major differences between participants in background and experience with XR, including varying coding skills (see Table 1).

3.2 Data Collection

Prior to the interviews, our participants were told that we would discuss prototyping in the context of one of their projects and were asked to choose one project. We requested that the selected project complied with non-disclosure agreements (NDAs), was recently completed or still ongoing, would ideally demonstrate the participants' use of prototypes, and covered the process until the final product.

We then conducted online interviews using video conferencing software with cameras switched on and participants sharing their screens to present their prototypes. Two demonstrated their prototypes via live video feeds on their target devices while describing their work. We further asked participants to share their presented prototypes with us post-study. Four participants were not able to directly share or show their prototypes due to NDAs. We therefore discussed their design approaches as detailed as possible. We discussed 25 individual projects, as summarized in Table 1. Our participants provided detailed insights into processes, tools, and prototypes for 13 projects or an overview over general approaches including the most representative prototypes for an additional ten. Two participants discussed two general design approaches with described prototypes without the context of a specific project.

Our initial questions focused on their contributions to the project, team size, application domains, target users and XR devices or platforms. We further asked about their design experience prior to the chosen XR project before we moved on to the main interview questions (see Appendix A). We structured the main portion of

Table 1: Summary of our participants regarding occupation, experience (XP) in XR in years, and background (m = Master's degree, b = Bachelor's degree, d = (German) Diploma).

ID	Occupation	XP (years)	Background	Project	Platform
P01	AR Designer	5	Human-Computer Interaction (m)	Immersive tour with 360 images in VR	Samsung Odyssey
P02	Research Fellow/ Developer	8.5	Media Informatics (m)	Mini-games for customers to play while grocery shopping	Smartphone
P03	Interaction Designer	8	Studied graphics design and anthropology	Educational, dystopian story-based tour through a museum's art exhibition	Smartphone
P04	UX Designer	5	Digital Media (m)	Productivity application featuring a calendar, tabular data, and a todo list/task reminder	nReal light
P05	AR Product Designer	5.5	Game Design (b)	Explained a general approach based on a 2D smartphone app	Smartphones, Tablets, HMD
P06	Lead Designer/Director	24	Architecture (d)	Software for meetings in VR with enhanced moderator features	Oculus Quest (1, 2)
P07	PhD Researcher	3	Software Engineer (m)	Monitoring and support tool for solving the Rubik's Cube	HoloLens 2
P08	CEO/Producer for Interactive Media	10	Entrepreneurship & AI Development (m)	360 immersive documentary about cacao farmers in Brazil	WebXR
P09	Principal XR Designer	4	Computer Science (b)	Immersive, spatial concert visualization tool	Oculus Quest/device agnostic
P10	Technical Consultant	2.5	Computer Science (m)	Telemaintenance application	HoloLens (1, 2)
P11	Technical Director	3	Computer Science (m)	Guided story about the history of a building	iPad
P12	Experience Designer/Director	6	Media Management (d)	Various projects (n=7)	Smartphone, Tablet, HMD
P13	Senior Technical Consultant/ Concepter/3D Artist	8	Interactive Media Systems (m)	Explained a general approach without showing prototypes and without project context	HMDs
P14	UX Designer	1	Film production, 2D animations and Visualizations (m)	Explained the approach without showing prototypes and without project context	AR HMD (e.g. HoloLens)
P15	Product Owner AR/VR Technologies	7	Media Informatics and HCI (b)	Collaborative walk-through a power plant	VR HMD
P16	Interaction Designer/ Developer	2	No formal degree	Interaction techniques development for XR	XR HMD
P17	PhD Research Assistant	6	Biomedical Engineering (m)	Supporting medical workers in cancer treatment procedures	HoloLens 2

the interview based on an established question catalog [1, 17] for context interviews, which we adapted to our research questions. We designed the questions to cover the whole design process from planning, preparation, execution, and evaluation to transfer. Finally, we asked the participants to provide their demographic information such as age, gender, educational background, years of experience in XR, job title, and current occupation. We collected 1317.87 minutes (~22 hours) of interview data (min: 32.38 min; max: 119.93 min; mean: 77.52 min). The interviews were conducted in German or English; the transcripts were translated to English by a German native speaker with a C1 skill level in English.

3.3 Data Analysis

To analyze the data, we organized each interview individually on a virtual whiteboard using Miro (e.g., Figure 1). First, we extracted project metadata and demographic information from automated transcripts. Based on the video data, we arranged images of provided prototypes and their verbal description in process-like mind maps to visualize how the prototypes were used and evolved over time for each interview (see as an example, Figure 1). Descriptions, statements, opinions, used tools, and our participants' quotes were aligned with the prototypes. This approach was repeated for each interview and resulted in 25 mind maps, each representing either a described project with prototypes (13), a general approach with

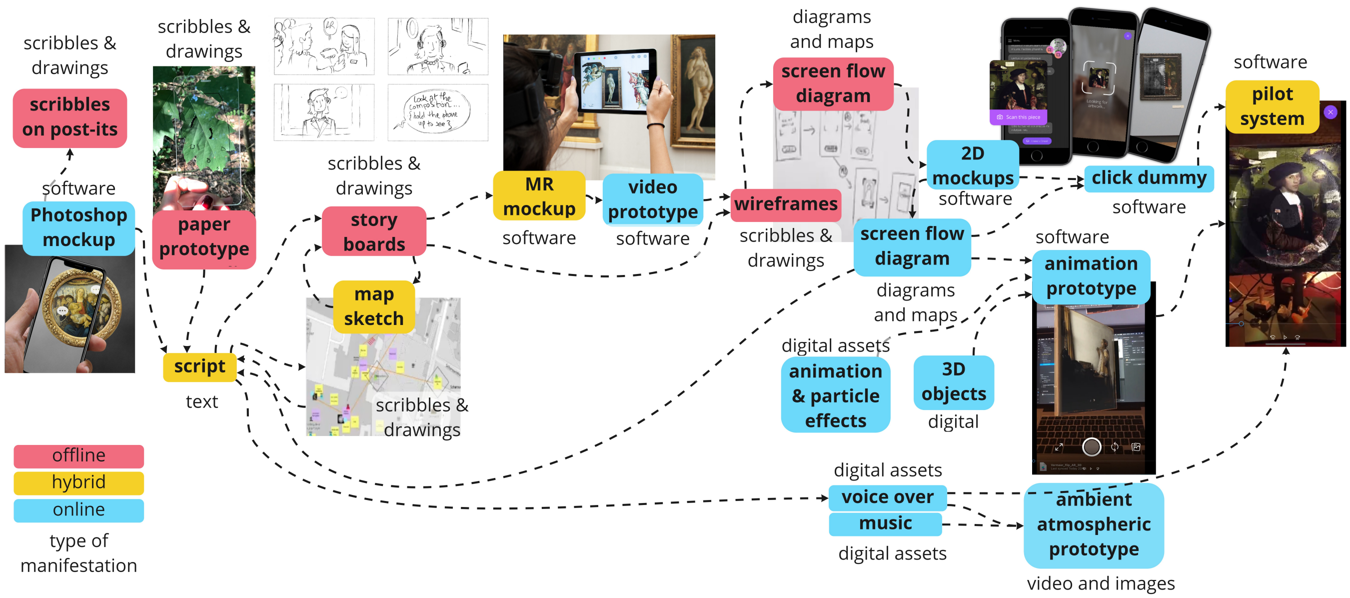

Figure 1: A simplified process visualization of a story-telling application for an art exhibition in a museum explained by P03. The project followed a user-centered and iterative approach, which we simplified to see how concepts and ideas were manifested and transformed as prototypes. The depicted order is roughly temporal, flowing from left to right, showing a common transformation of prototype manifestations for handheld XR applications: sketches to storyboards, wireframes, click-dummies, and mockups. Applications on head-mounted devices often use manifestations flowing from sketches (drawn in perspective or spatial) to storyboards, spatial mock-ups, 3D renderings of the target space, XR, especially VR prototypes, to pilot systems. However, development processes are individual and based on specific project requirements.

the most illustrative prototype (8), a specific project with described prototypes (2) or, where no specific project and no artifacts could be presented, a general approach (2). Some participants explained more than one project, such as P12, who detailed seven projects. Given the exploratory nature of our study, we adopted an open coding approach to identify common themes across projects, as suggested by Strauss and Corbin [9], without aiming to develop axial and selective codes. All transcripts were coded by one researcher. Both the resulting codes and the interim results were then discussed with two additional senior researchers to reduce bias and identify misconceptions. We performed multiple passes, each focusing on a different aspect, including tools, prototypes, methods, hindrances, and workarounds arising during the participants' daily work. We further extracted reasons for tool selection and the application of prototypes as well as their manifestations and fidelity.

To analyze the prototypes' common themes, we arranged them independently of their original project in a combined virtual whiteboard as a thematic mind map. We iteratively clustered prototypes regarding their depicted concepts and drew lines to neighboring clusters if a prototype described more than one aspect. By doing so, we identified themes such as menu structure, screen structure, dynamic content behavior, and recreating aspects of the target environment. After we had arranged all prototypes in the mind map, we proceeded to combine subtopics of related aspects to overarching topics to finally formulate ten elements addressed by XR prototypes, detailed in Section 4.

4 PROTOTYPES AND PROTOTYPING IN XR

The general roles and application of prototypes in XR software development align with those of prototyping studies from other domains. Table 2 summarizes our specific observations in this regard. The respective findings are discussed in Section 6.1.

In this section, we establish our taxonomy by describing what our dataset reveals about manifestations, types and elements of XR prototypes. Furthermore, we report our findings regarding the creation and usage of prototypes in practitioners' XR design approaches.

4.1 Taxonomy of XR Prototypes

We describe three main classes of manifestations by building on Beaudouin-Lafon and Mackay's notion of *online* for software-based and *offline* for analogue prototypes [5]. We also consider hybrid prototypes as those that consist of both offline and online elements. Several of our participants reported switching from offline to online prototyping approaches such as digital or digitized sketches and shared digital whiteboards due to Covid-19 restrictions, when offline prototypes such as sketches were often digitized to be shared.

To build our taxonomy, we analyzed prototypes in terms of their manifestation to get a better overview of practices, materials, and tools originating from classic 2D graphical user interface (GUI) as well as from XR design. To learn about how ideas and features develop in XR, we also analyzed how different types of manifestations

Table 2: Prototypes and their origins, target audience, project internal use, and application during development as reported by participants. Our observations are discussed in detail in Section 6.1.

	Description
Prototypes' origin	*Project internal*: created by the project team for a specific and project-related design goal
	Project external: existing applications or artifacts originating from previous projects, game or app stores, and social media
Target audience	*Project internal*: project team members, customers, end-users
	Project external: potential customers, stakeholders
Project internal use	Create and evolve *features* of the application under development
	Discover *potential and limitations* of hardware and software
	Explain XR as a *medium*
Application during development	*Evaluation*: rarely done with end-users due to limited resources (time, money, availability of end-users), prototypes were more often evaluated with colleagues or customers
	Documentation: documentation of design decisions and processes
	Communication: alignment between project team members

are applied or transformed. We call this analysis **structural analysis** and describe the respective results in Section 4.1.1. In a second step, we characterized the different aspects depicted in the prototypes and described by our participants in a **semantic analysis**, detailed in Section 4.1.2. This analysis enabled us to understand the challenges in XR application design and how prototypes support overcoming them.

4.1.1 *Structural Analysis.* For our **structural analysis** of the prototypes, we organized the prototypes according to their manifestations. We identified eight different manifestations: 1) sketches and drawings, 2) diagrams and maps, 3) text, 4) video and images, 5) digital assets (audio and multi-dimensional objects), 6) physical models, 7) ephemerals (prototypes without a persistent form), and 8) software. The categories and reported prototypes are further detailed in Table 3.

In summary, XR prototypes demonstrate the need to describe ideas in space, time, and motion, often in the context of an imagined virtual environment, an existing physical environment, or a digital clone of the target real-world space. The use of physical models and especially ephemerals is prominent, and many of the challenges faced by participants were related to software tools.

Some features were more easily explained in specific prototypes, which were therefore preferred by participants, such as diagram-based prototypes to layout an application's information architecture and interaction flow, or sketches from a spectator's view to explain distances and dimensions (see Figure 2). Other elements could only be described efficiently with a limited set of manifestations, for example, digital 3D objects require manifestation as online prototypes at some point to be fully graspable. Similarly spatial features require manifestation as either digital or physical models if dimensions and space are to be experienced.

We note that prototypes can manifest in various forms that are not always easy to differentiate. As we further describe in Section 4.2, prototypes can transition between manifestations while keeping aspects of their original form. One example of such a transformation is the creation of a click-dummy based on a scribbled wireframe (sketches and drawings), which is then transformed into a click-dummy (software). The increased interactivity caused by the aforementioned transformation also increases the fidelity of this prototype. However, transforming manifestations can also negatively affect a prototype's fidelity, as discussed in Section 4.2.

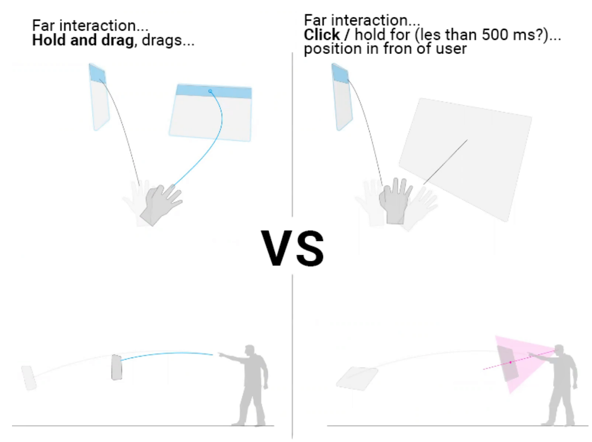

Figure 2: Representation of a sketch created in Figma, provided by P06. The sketch depicts two alternatives of interacting with distant window panels: hold and drag (left) vs. click (right). This sketch depicts various elements, e.g., spatiality by showing different perspectives (top: ego perspective; 3rd person view: bottom), proportions, and cast shadows; interactivity by highlighting interactive areas (blue); control by showing gestures and movement paths. The font size has been altered for readability.

4.1.2 *Semantic Analysis.* As a second step, we performed a **semantic analysis** of the reported prototypes across projects with a focus on concepts and how they were depicted. We identified ten key elements of XR prototyping: (1) *spatiality*, (2) *physicality*, (3) *world-building*, (4) *flow – story*, (5) *flow – hierarchy*, (6) *control*, (7) *locomotion*, (8) *interactivity*, (9) *content*, and (10) *cinematography*. Table 4 provides an overview of these dimensional elements of XR prototypes. Typically, prototypes combined a subset of those elements on differing levels of detail, depending on factors such as the designer's goal, time, skill, or requirements. For example, Figure 4 illustrates physicality, spatiality, and interactivity (P12). While the spatial features of the floor plan in an early stage were close to the final product, both the content and assets evolved and were depicted in increasing detail.

Table 3: Summary of the observed and reported manifestations of prototypes.

Manifestation	Type	Description	Example
Sketches & drawings	Offline, online, hybrid	Visual representations of ideas created in various ways and with various materials. Often have spatial components or are drawn in ego or third person perspective. This class also contains storyboards and wireframes.	Recreation of the translucent look-and-feel of XR holograms by drawing on acrylic glass (P03); arrangements of elements and lines to sketch interaction (P06) depicted in Figure 2.
Diagrams & maps	Offline, hybrid	Used when an interaction, animation, or various types of behavior had to be displayed over time or space; explain technical details such as animation curves, data structure, and camera movement.	Camera transition graph (P06) in Figure 3; map of the target space demonstrating the walking path of a user (P03).
Text	Offline, online, hybrid	Often as annotations of animations or transitions in visual prototypes such as storyboards; as a prototype itself less common but found in, e.g., the form of scripts for storytelling or story crafting.	Annotated story board (P01), early voice over descriptions (P01, P03).
Video & images	Online	Images such as screenshots, photographs, or renderings; videos in the form of screen captures or experienced applications filmed from a third perspective; also function as placeholder assets in a software prototype, document application features or (target) space properties or generated to create access to otherwise closed manifestations.	Short movie for communicating the narrative of the target application (P03), video recordings from within the application to share the experience (P09).
Digital assets	Online	Audio and multi-dimensional objects; content in prototypes or prototypes themselves, such as music samples, audio synthesis, voice messages to simulate vocal explanations or dialogues, and virtual 3D objects; often refined or substituted through several iterations and can be prebuilt or downloaded from platforms.	Sung and sampled music piece to acquire the support of musicians (P09); 3D hexagons arranged to prototype the structure of and interaction with an app launcher depicted in Figure 7 (P16).
Physical models	Offline	Representation of parts or features of the application target space, such as distances, dimensions or topography; physical replicas of an exhibit or props for physical tools made of cardboard, styrofoam, wood, or other physical modeling material; physical objects or space featuring similar properties as a to-be developed virtual model, such as dimension or weight.	Styrofoam ship as a substitute for the final exhibit (P12) in Figure 5; recreating an expensive X-ray device as wooden prop to prototype the mapping of physical and virtual properties (P17).
Ephemerals	Offline, hybrid	Prototypes that lack a persistent form when not explicitly transformed, for example, by recording them on video; such prototypes include experience prototypes [6] using Wizard-of-Oz or demonstration by example [10], and more passive and unrefined or verbalized prototypes; those prototypes are interactive and dynamic.	Referring to the same existing application and acting out envisioned changes to agree on an interaction method (P01), using physical props as reference points to understand spatial properties and gestures (P09).
Software	Online, hybrid	(Spatial) click-dummies, experience scenery models in the form of gray-boxed environments or (walkable) spatial 3D renderings, VR/MR prototypes ranging from mock-ups to functional prototypes implemented as pilot systems.	Grey-boxing spatial features of applications (P12) in Figure 4, walkable scenery models (P06, P13) in Maya or Blender, VR prototypes in Microsoft Maquette (P15).

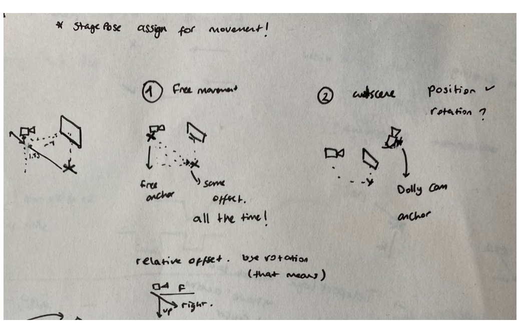

Figure 3: Diagrams and sketches depicting camera movement and transitions provided by P06 to answer cinematographic questions.

1) Spatiality depicts positions, proportions, scales, and distances of and between virtual and physical elements as well as the relationship between a body height and the surrounding experience. Examples included sketches drawn in perspective, 3D models and gray-boxed or fully fleshed-out experience scenery models. Figure 4 shows an example from P12. P03 used a sketched path over the map representation of the target space to explain the physical layout of the application. Spatial properties were sometimes represented as physical props. For example, P09 used a telescope in a bodystorming session as a physical prop to prototype interaction gestures because the telescope's size was similar to the target virtual model of a planet.

2) Physicality depicts physical aspects of an application, such as tangible or graspable objects or rooms. Figure 5 shows the evolution from sketch, to a placeholder prop, to the final physical model. Representative prototypes were, for example, sketches or storyboards and models built from various materials such as foamed plastics, wood, or cardboard (P03, P11, P17). Our participants also used sketches or tape marks on floors, objects, or walls (P11, P12) or incorporated final physical models from the beginning if they were available (P02, P07).

Table 4: Summary of the dimensional elements of XR prototypes.

Element	Description	Manifestation
Spatiality	The relation of real and virtual object regarding the distance, scale, and rotation.	Sketches drawn in perspective, 3D models, grey-boxed spatial layouts, experience scenery models, physical props
Physicality	Physical properties of an XR application, such as tangible artifacts or rooms.	Sketches, storyboards, models built from various materials such as foamed plastics, wood, or cardboard, tape marks on walls and floors
World-building	Background for the story telling.	Video (ambient prototype), script
Flow – Story	The story an XR application wants to mediate.	Sketches, storyboards, text snippets, (audio) narration, mood boards, scripts
Flow – Hierarchy	The logical structure of the XR application including menus.	Wireframes, interaction or screen flow diagrams, mockups, storyboards, click-dummies
Control	Interaction techniques with or without controllers	(Animated) sketches, acted-out or envisioned with props or the target controller, storyboards, script, text
Locomotion	User movement and navigation in a space, includes techniques for moving in VR, such as teleporting	Sample applications, VR mockups, storyboards, animated sequences, sketches in perspective, sketches on a map
Interactivity	Reactive and animated aspects	Sketches, storyboards, sample applications, animations, bodystorming, diagrams, software prototypes
Cinematography	Cinematic elements such as camera angles, camera movement, scenery, and color	Sketches drawn in perspective, diagrams, experience scenery models
Content	Digital assets and inner elements	Aural elements, 2D and 3D objects, textures

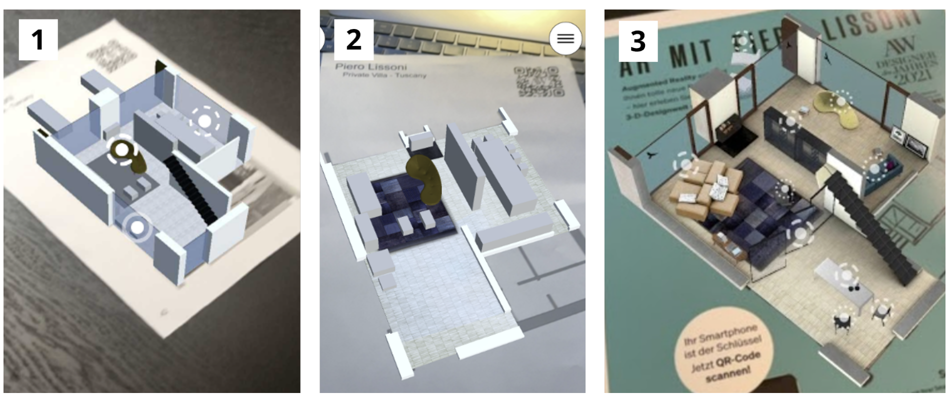

Figure 4: Evolution of an application from an initial grey-boxed layout (1) to the final product (3) (P12)

Figure 5: Evolution of an application featuring a physical model in a handheld application on iPads: From (1) sketch over (2) substitution prop to the (3) final physical model (P12).

3) World-building is a concept from fiction and describes "the process of building a fictional world" [15]. While world-building is closely related to story-telling, it addresses different aspects. World-building creates a world in which a story is told. P03 reported the only prototype in our dataset that addressed the aspect of world-building: his ambient prototype or application teaser was a video showing how a protagonist moves through the application's target space while a narrator explains how the future has changed how data and knowledge are stored. The narrator further sets up the context in which the application takes place and guides the user through both the application itself and its story.

4) Flow – Story denotes details about the final product's story. We identified two different aspects to flow. Examples included annotated sketches, storyboards, text snippets, (audio) narrations, mood boards, or narration scripts.

5) Flow – Hierarchy focuses on menu structures and logical application flows. This is the second aspect to flow for which our participants reported wireframes, interaction or screen flow diagrams, mockups, storyboards, or click-dummies designed to elaborate on the information architecture of the final product.

6) Control establishes how users control an application in terms of interaction techniques with or without controllers. In our dataset, this element included multi-modal interaction, such as speech or gestures, as well as the use of virtual or physical buttons or controllers. New interaction techniques were evident, which were digitally sketched-out and animated (P16) or imagined before being acted-out with props (P09) or the target controllers. Sketches and storyboards are also used to showcase control. In that case, gestures are often depicted by using hands or hand icons for gestures, colors, faded-out icons, and lines for describing movement and interactive buttons or areas (see Figure 2). There were also sketches and raycast visualizations of controllers. Speech was manifested as text or scripts.

7) Locomotion focuses on how users move and navigate through the application space and might therefore also incorporate other related aspects such as spatiality, physicality, flow – story, and control. In general, differentiation is possible between virtual and physical locomotion. Virtual locomotion happens virtually without users necessarily changing their physical location, e.g., via teleporting (P15) or moving between various virtual rooms or locations (P01). Physical locomotion requires users to physically change location, for instance, when walking through a real or virtual building. P03 used floorplans with sketched-out paths to plan the users' routes through a physical space. Both types of locomotion use similar prototypes. Our interviewees reported prototyping locomotion methods such as teleporting by being inspired by and testing with already existing applications before recreating the same or similar functionality in software tools such as Unity or, if possible, as virtual mockups, a simulation, or animation. Other prototypes used for depicting locomotion were, for example, storyboards, animated sequences, sketches drawn in perspective, and VR prototypes.

8) Interactivity is closely related to locomotion and control but focuses on reactive and animated aspects of a prototype. We differentiate between passive interactivity, such as animations and interface behavior created to increase the user experience of a system (for instance damping of movement paths of tag-along interface elements), and active interactivity such as reactive and nudging screen elements, dialogues, and virtual or physical objects a user can interact with. Our participants reported using sketches, storyboards, existing applications demonstrating the required behavior, and animations created in 3D modeling, compositing or animation software. Our participants also reported applying bodystorming (P09) or reenactment (P01) to iterate through interactivity alternatives. More technical aspects of interactivity were also modeled as diagrams (P06). Finally, customizing and adapting the respective implementation to the final product requirements typically required the interactivity to be implemented in tools such as Unity and Unreal Engine.

9) Cinematography describes and investigates cinematic elements such as camera angles, camera movement, scenery, and color. The reported prototypes addressing those features were sketches drawn in perspective, diagrams detailing camera movement, or experience scenery models.

10) Content groups digital assets and inner elements that form the content of an XR application as opposed to navigation or behavior. Content is perhaps the most tangible element of XR prototypes and often used as an umbrella term to refer to a prototype's assets. Examples range from aural elements such as voice-over and sound to 2D or 3D objects and textures.

Our participants reported facing the most challenges when prototyping XR specific elements, such as spatiality, physicality, control, locomotion, interactivity, or aspects of content. We provide more detail on those challenges in Section 5.

4.2 Creation and Usage of Prototypes

We continued our study by investigating how prototypes were created and used for communicating, documenting, and evaluating project work. Our participants reported following an iterative design approach. While some mentioned concrete process models such as SCRUM, others described their process as agile or user-centered. However, we let our participants describe their workflow based on prototypes created for specific projects so as not to bias them by referring to formalized process models. We identified the following six practices regarding creation and use of XR prototypes.

1) Prototypes and their manifestation were a compromise of time, skill, design intent, target group, requirements, and tools. Participants often reported preferring a minimum viable approach – whatever works is used for creating prototypes. This process also included using unconventional tools or tools in an unconventional way. P03 for example reported having created a prototype using GIPHY – a free online collection of gif files and animated stickers:

> *"I've done prototypes with GIPHY [...] just like quickly patching things together, because that was what was available and quick. Yeah, it is anything you can do quickly for certain for a particular purpose."* (P03)

However, the target group was also an important factor. Based on P03's reports, there was rarely a clear distinction between project-internal and project-external prototypes. Few prototypes were being explicitly produced for project-internal use; they were more often built for project-external use, such as marketing material. Further, our participants reported that aligning with customers sometimes requires producing visually more sophisticated looking

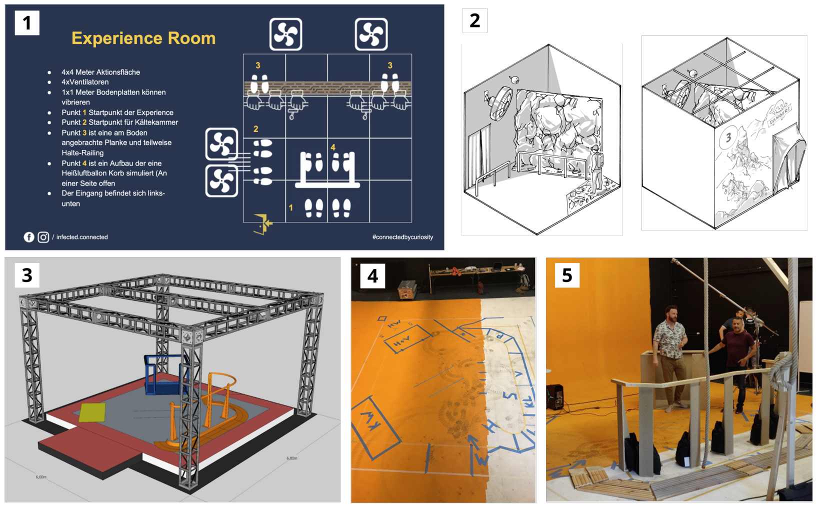

Figure 6: Evolution of the physical aspects of a virtual reality experience room featuring an outdoor adventure including a rock path, hot air balloon, and a sleigh ride starting with the textual description and a floor plan (1), initial sketches of the room layout (2), initial 3D models of the surroundings (3), taped marks to create properties of the physical environment (4), and first interactions on the rock path as a physical model (5). This example describes how features require different types of manifestation to describe aspects from different perspectives (P12).

and therefore more timely prototypes. For example, P01's project was based on 360° photographs of her customer's head office. Based on that, she built a tour in VR:

> *"It is hard to define what's like a wireframing stage in VR applications because. in web or mobile, you can easily keep the graphics on the same level of abstraction. But in this application, you could not keep the environment on a wireframing level since it was high-resolution and high-fidelity from the beginning. If you would combine ugly looking text with such a high-fidelity photograph, the customer would be a bit confused about the looks. This is a trust building thing." (P01)*

In contrast, we learned that experienced teams who knew each other well used less sophisticated prototypes, which required less time for creation and to communicate alterations and behavior to colleagues, such as sketches, screenshots, or acted-out interactivity based on referencing material. For example, P01 reported that, to agree on interactivity and control methods with a colleague she knew well from previous projects, they both relied on a shared mental library of sample applications. A shared mental library necessitates at least two people sharing the same knowledge. In the described case, this library was built based on artifacts such as applications, movies, experiences, and games. When P01 and other team members designed details of interaction techniques, they used ephemeral prototypes and referenced, for example, Tilt Brush's menu structure to discuss how to adapt it to their application. P01 described their approach as being fast and easy (P01).

P01 also emphasized that this approach is not always possible, especially when teaming up with colleagues with whom she had no previous work experience. Such prototypes are reportedly not documented but rapidly iterated until the team members agree on a potential solution that is then developed. Consequently, prototyping does not always produce persistent results.

2) Prototyping did not always produce persistent manifestations. Building on the above observation and also as described in Table 3, some participants detailed how they used methods based on reenactmend and story-telling to explain interactivity and create an ephemeral experience or idea rather than a persistent manifestation. Participants reported using such prototypes, for example, if a common ground of understanding is needed and the team lacks experience. For example, P09 describes how an inexperienced team developed an application's interactivity that featured interacting with a planet based on props and bodystorming:

> *"You could walk around this 6 ft diameter planet and terraform it. And you could pick up people from the North Pole and set them down on the South Pole. And my team had a really hard time in communicating what this would look like. [...] And then I went and got my telescope. And it's just nothing like a planet, it's just a telescope on a stand, and I placed it in my living room and we all stood around it and we started like doing these motions of reaching around a planet. I wouldn't describe it as a light bulb moment, but all our light bulbs went on at the same time and now we understood what we were building. The artist could picture the art in their mind and the designer could picture the mechanics." (P09)*

Other participants reported using such techniques if the team knew each other well and a common understanding was already established. In that case, they rely, for instance, on referencing existing applications and narrating or acting out how to incorporate or change features. Finally, experienced participants reported doing several iterations of prototyping in their mind before they produce visible manifestations of their work:

> *"I think about which steps I would have to do to reach certain actions or goals in the application. I then do several internal loops [in my brain] to see if [the UX concept] is easy enough, also for somebody unlike me, who has been doing this already for several years, but is rather doing it for the first time. [...] A lot of things happen in my brain before I do anything with a PC or sketch with a pencil."* (P15)

Finally, we noticed that the distinction between prototypes and assets in XR is often blurry.

3) Prototypes were or became assets. According to the participants' reports, assets could be either a byproduct of the prototyping process or the prototype itself. For instance, P15 reported using Maya, a 3D rendering software, to gray-box aspects such as spatiality and flow–hierarchy of an application's feature. Also, P16 developed interaction concepts and menu structures (flow–hierarchy, interactivity, content) based on assets imported into a virtual space (see also Figure 7). Other participants reported having experimented with the legibility of font sizes in virtual reality based on previously built 3D models (content, spatiality).

P15 reported that gray-boxed elements already resemble the ones to be used in the final application and are visually polished after spatial and flow-hierarchy aspects are sorted out. However, we acknowledge and emphasize that prototyping and asset creation are not the same but – as the above example shows – might overlap regarding tool usage and outcome.

Figure 7: A prototype created in Tilt Brush depicting an interactive app launcher. The prototype drafts elements of spatiality, control, flow – hierarchy, interactivity, and assets. (P16)

We identified several practices in terms of the use and evolution of prototypes.

4) Prototypes or their concepts were transformed in their manifestation. As described by P15 and mentioned by other participants, for various reasons, the manifestations of some prototypes are transformed during a project's progress. Reasons included creating shareable artifacts, documenting design decisions, or evaluating the current state of the project (see Table 2). Some transformations were done because the designers needed to create an accessible, shareable, or persistent form. Such situations can be the digitization of offline manifestations to transform them into a shareable object. However, some transformations can negatively affect a prototype's XR-specific elements, such as spatiality, physicality, or interactivity. For example, video-recording an MR-prototype reduces the fidelity of interactivity and spatiality. This reduction is bothersome if the target group lacks experience in XR and fails to fill-in the gaps caused by reduction of XR features through the altered manifestation. For instance, P09 reported on a spatial music visualization tool that had to be shared with musicians in order to convey the application's idea. He developed and iterated the application in Unreal Engine and transformed it into a shareable video:

> *I have worked with a musician [...] so I needed to explain this idea over and over again. [...] Even by watching a video, it is hard to follow what is happening because spatialization is so specific to how your head moves in a VR setting. [...] So I'm like doing this iteration in VR with the VR tools, increasing the fidelity in every stage and then downsampling it into a video, which is a way less impressive experience. But as I'm raising the bar in VR, I also raise the bar in the downsampled video experience. [...] That has been a really frustrating process and it costs me social capital, every time that I bring this half-baked idea and then ask for a bunch of work.* (P09)

In contrast, other transformations enhance both the interactivity and the fidelity of a prototype. Some of our participants reported digitizing offline wireframes to transform them into more interactive click-dummies if the project provided this functionality, which leads to the next practice.

5) Prototypes were evolved as living artifacts or thrown away after they served their design intent. Some prototypes are created once, kept alive, and evolve over time. Our participants reported them as "living documents" (P03) that were continuously updated and sometimes required the use or creation of version control mechanisms and editing policies. Contrastingly, some prototypes are built quickly with an intended short life span – those so-called *throw-away prototypes* [18] are discarded after they have fulfilled the designer's intention.

In practice, both approaches of evolutionary and throw-away prototypes were combined. Figure 1, as an example of an XR application process flow, depicts the co-existence of both types – often, throw-away prototypes were applied to identify features and design solutions, which were then incorporated in the evolutionary prototype. When discussing throw-away and evolutionary prototypes, we also asked about the concept of fidelity.

6) Fidelity was often used with different interpretations. When we asked our participants about fidelity, we realized that there were various interpretations and applications of this concept. Some participants explained fidelity as being defined on the visual maturity level and grouped in the three stages low-fidelity, medium-fidelity, and high-fidelity through which concepts are advanced linearly. Other participants described the concept of fidelity as a spectrum.

There was a general consensus that low-fidelity correlates with a low amount of invested time and effort used to create prototypes, whereas high-fidelity depicts the closeness to the final product and also requires greater resource investment. We further saw that the fidelity of a prototype is only loosely coupled to the overall project's progress: our participants reported that prototypes of low-fidelity were produced even though the overall project was already close to production. Complementary, P01 reported having worked on a project where assets were high-fidelity from the beginning since the project was centered around already existing 360° photographs.

When we analyzed the evolution of features based on the elements of XR prototypes, we realized that prototype manifestations reported by our participants depict maturity levels of XR elements on different scales – even in the same manifestation. For example, as shown in Figure 1, P03's project featured an early low-fidelity MR mockup. However, when specifically observing interactivity, the maturity level was higher than those of several prototypes produced later in the project, such as screen flow diagrams or assets. Finally, we observed that fidelity was not related to a prototype being offline, online, or hybrid. XR applications reported by our participants can – depending on the amount of virtual or physical components – consist of both virtual and physical content. Therefore, elements of the final product as well as their prototypes might be bound to using specific materials, such as physical models or digital assets, whereas their fidelity can be on either end of the fidelity spectrum.

5 GOOD PRACTICES AND DRAWBACKS OF PROTOTYPES AND TOOLS

Prototypes and the tools used for their creation are closely related. In our dataset, we found four reasons for tools application during prototyping: creation, alteration, documentation, and evaluation. In this paper, we only provide minimum detail about designers' tool choices and use. Especially when it comes to problems, tools are often mentioned as failing to support a designer's intent or being too bothersome or overwhelming to use.

5.1 Workarounds and Good Practices

To get a more complete picture about hindrances in design practice, we discussed three workarounds and useful practices: 1) tools were repurposed, adapted, or enriched with personalized assets to create accessible artifacts, 2) keeping the context of use while recording ephemerals for documentation softened the effect of down sampling an experience, and 3) ready-made assets and a common design languages reduced workload and design complexity.

1) Tools were repurposed, adapted, or enriched with personalized assets to create accessible artifacts. Several participants reported repurposing tools for prototyping due to their availability and accessibility for customers and team members since sharing XR prototypes was challenging. P01, for example, created a clickable storyboard in Google slides to share and discuss approaches with customers since the target device was not yet available and the customers were inexperienced with the medium. P02 used a similar approach by repurposing Microsoft PowerPoint. While he described this prototype as being very helpful when communicating with the customer on a feasible level, it was difficult to convey spatiality.

Inaccessible prototypes for designers caused by highly technical high-fidelity tools [36] were worked around by using the experience of team members with a higher technical skill level. For example, P06 reported that the developers created a widget for Unity to allow designers to tweak and adjust features such as damping in animations while running the application without the need to code. P03 further reported that his team developed a XR spatial mock-up software to enable designers to rapidly prototype applications in the target space on the target device without needing to have an additional laptop to compile application variants.

2) Keeping the context of use while recording ephemerals for documentation softened the effect of down sampling an experience. Ephemerals reportedly played a crucial role when participants had to describe a design's interactive behavior. To overcome the side effect of reducing their interactivity when recording them, P03 explained his approach: Rather than just recording a video feed, a person was recorded interacting with the target device in the target space combined with the content displayed on the target device. By taking the perspective of an observer, the recordings preserve the context of use as well as the physical surroundings. Therefore, users, devices, and the application itself did not lose their relation to the environment.

3) Ready-made assets and a common design language reduced workload and design complexity. P06 reported that, when the team used its own design language in the form of color conventions in sketches, internal and external communication regarding interactivity and spatiality was enhanced. Furthermore, the team relied on sketching as the main communication and created mapping and animation curve diagrams whenever useful to discuss timing and animation behavior. This worked well as soon as all team members and affected customers knew how to read those diagrams. Furthermore, the team saved discussion and prototyping time by relying on sketches and diagrams following those design language conventions. For prototyping in virtual environments, P09 mentioned that he often advised creating spatial experience models with pre-built 3D artifacts and respective tools, such as Google Blocks, because spatial sketching or drawing in 3D was hard, especially for non-artists.

5.2 Pitfalls of XR Prototyping

Participants reported several issues during their prototyping activities, which we grouped into the following categories: conveying the feeling of XR, colors and display technology, text, time and effort from prototyping till evaluation, entry hurdles of high-fidelity tools, limitations of low-fidelity tools, lack of design conventions and interaction metaphors. We also observed that tools' limitations negatively impacted prototyping. Besides issues already documented in the literature [2, 20], such as a high entry-hurdle for high-fidelity tools, low-fidelity tools with too many limitations, and a lack of design conventions and interaction metaphors, we identified three additional pitfalls: 1) Conveying the feeling of XR with justifiable effort was difficult, 2) display technology tampered with colors, and 3) designing legible text was difficult.

1) Conveying the feeling of XR with justifiable effort was difficult. Many participants reported issues in explaining and designing the feeling of XR. For example, P06 reported sometimes creating design solutions *"that look cool in Figma but do not work or [feel] weird in Unity"* (P06). Also, P01 mentioned that classic design manifestations such as storyboards lacked the power to communicate the experience of spatial applications to a customer. However, storyboards were often used by our participants. Participants further explained that the main problem was iterating and trying out their design solutions regarding the feeling of teleporting or walking around (locomotion, spatiality), interacting with virtual as well as physical objects (interactivity, control, physicality, spatiality), occluding virtual and physical objects (spatiality, physicality), and wearing or holding the target device (spatiality, physicality). Aside from lacking a viable way to evaluate design solutions through trial and error, P15 further explained

> *"It's also about bringing the customer to the world they have never experienced before. They have only heard about smartglasses: 'Such a cool thing, I can work hands-free and get information projected in my environment!' But the experience, how it feels is completely missing."* (P15)

2) Display technology tampered colors. Participants who had to use colors following a corporate design styleguide reported that there are three main issues with colors for AR applications. Due to the additive screens used in XR displays, colors appear different from those defined for 2D media. Furthermore, textures and shaders affect their appearance, as also depicted in Figure 8. P04 furthermore reported the issue of using black and white in a design concept:

> *" Black is not really black because it will be transparent. Black black is more like the darkest gray possible. White is mostly like light gray, I would say, light gray is the new white."* (P04)

P04 reported that performing color tests was bothersome because different variations had to be defined, compiled in an application, and run on the target device in multiple iterations due to a lack of tools supporting experimentation with color variations in physical space.

3) Designing legible text was difficult. Text and legibility was often mentioned as being a problematic design task due to missing spatiality or a lack of text creation features in design tools. Participants reported that both, color combinations and text sizes, were difficult to create. P04 came up with a complex workaround of rendering texts as a 3D objects in varying sizes, importing them in the virtual meeting room tool Spatial.io as assets, and evaluating different combinations to deduce usable combinations. P04 further mentions that this approach was time consuming but still better than asking the developers each time to try out different configurations.

6 SUMMARY AND DISCUSSION

Our explorative study describes current approaches to prototyping based on a group of 17 UX/UI designers from XR industry, who discussed with us 23 projects and two general approaches. Compared to prior work that often focused on novice XR creators, our

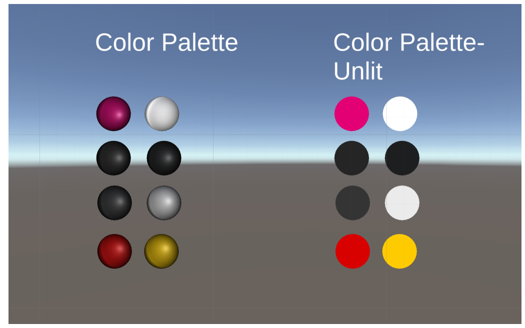

Figure 8: Color palette tests in the Unity Emulator (P04). Due to the three-dimensionality and light effects, color palettes defined by corporations do not reflect the intended color. Furthermore, when displayed on the target device, additive screens tamper with colors in AR applications.

dataset was rich in the variety and complexity of XR prototypes. As a summary of our work, we answer our research questions from Section 1 and discuss existing and potential future work.

6.1 What roles do prototypes play in industrial XR development practices? – Q1

We highlighted in Table 2 that prototypes originated from either *project-internal* or *project-external* sources and, independent of their origin, addressed two different target groups: *project-internal* (colleagues, customers, users) or *project-external* stakeholders (potential customers). In our analysis, we found that prototypes serve three main roles.

(1) **Answering questions about XR as a medium.** Here, prototypes fulfilled the role of onboarding inexperienced project members or customers and explained XR characteristics.
(2) **Answering questions about potential limitations of hardware and software.** In this role, prototypes were applied in technical feasibility tests.
(3) **Answering questions about an application's specific features.** In this role, prototypes were used for communication, documentation, or evaluation of design solutions and decisions.

As our study showed, prototypes have an important function for project internal learning, knowledge exchange, and communication, similar to how prototypes are used in classic 2D projects [8, 16, 20, 22]. However, in XR, prototypes have an additional function as *boundary objects* for collaboration with the customer, as was frequently emphasized by our participants. Here, the novelty of the medium and the central role of spatiality as a new design dimension add to the complexity and require additional explanations and knowledge exchange with customers. Existing work has already reported on the related issues regarding the difficulties of recruiting experienced users for evaluating XR systems [2] or the need to create adaptive and interactive artifacts [20]. However, with so many prototypes being created to support onboarding to XR as a medium, new opportunities have arisen for further research on XR tools and theory [41].

In line with prior work [16], we identified three main classes of XR prototypes: *offline*, *online*, and *hybrid*, as a combination of the former two. We also highlighted eight different manifestations, described in Table 3 and ten elements of XR prototypes, detailed in Table 4 to form our taxonomy. In line with Lim*et al.'s* notion of prototypes as filters [26], our taxonomy can help to structure challenges in XR design and to develop new solutions in future work. By analyzing prototypes both in terms of structure and semantics, we contribute to knowledge about their "complex nature" [26] and enable a more effective use regarding creation and communication [16]. Our data shows that XR applications can incorporate the 10 different elements in varying detail and complexity. Prototypes functioned as manifested filters to observe properties of those elements, whereas features describe a combination of elements.

Further, we find that, while maintaining the same features, prototypes can transition from one manifestation to another as a project evolves. Those transitions function as a shift in perspective through adding or removing detail about elements composing a feature. Resultingly, transitions affect a prototype's complexity. For example, a sketch drawn in perspective depicts the element of spatiality, describing how the dimensions of virtual objects relate to a user's point of view. When being transformed into an experience scenery model, this change in manifestation adds further complexity by introducing the elements of locomotion and interactivity as well as adding a third dimension to the element of spatiality.

One of the key practical challenges we found is that participants often had different understandings of what denotes a prototype – for example, project external artifacts were often considered as not being one since they were not created by the project team members or did not comply with our participants' understandings of manifesting an idea. However, participants created and applied those artifacts similar to how they worked with those they identified as prototypes. Thus, despite controversial discourses in literature [7], we also classified sketches and ephemerals as prototypes. We therefore agree with Houde and Hill's interpretation of anything potentially being a prototype, depending on how the designer uses it [16].

Finally, we found that the manifestation type of prototypes is strongly affected by the rationale of their usage, in line with the observations summarized above, as they are artifacts the purposes of which are denoted by the respective context of use. While XR prototypes do not differ much from manifestations of 2D prototypes in that regard (as both can manifest as offline, online, or hybrid prototypes and use similar manifestation types), they are nonetheless different in terms of their rationality as a means to communicate ideas about a rather novel and experimental medium with the customer, and bring the additional overhead of needing to create for spatiality.

6.2 How do designers create and use XR prototypes? – Q2

Our study provides insights into prototyping practices in industry projects: Prototypes and their manifestations were a compromise of time, skill, design intent, target group, requirements, and tools. Further, we find that XR prototypes did not always have a persistent manifestation and that some were or became assets. Participants often transformed prototypes or their concepts regarding their manifestation. Also, prototypes either evolved or were thrown away – both types were used simultaneously over a project's course. Furthermore, we report how our participants had mixed conceptions about fidelity.

Our observations comply with Lim *et al.'s* economic principle of design [26]: *"the best prototype is one that, in the simplest and the most efficient way, makes the possibilities and limitations of a design idea visible and measurable"* [26]. Our participants also often reported using ephemeral prototypes that do not have a persistent form but rely on internal libraries of experiences, mental imagery [3], and discussions with colleagues. We argue that, regarding Lim *et al.'s* economic principle, this use is frequently for two reasons. First, XR requires prototypes of a decent interactivity level to explain an application's behavior [20]. However, expressing interactivity requires time, effort, and a certain skill level in operating high-fidelity tools [2, 20, 36]. However, both that literature and our results show that those assets are not always accessible to all designers. Second, ephemerals as described by our participants focused on communicating experiences [6], often by referencing shared past experiences such as known applications or movies and reenacting or recalling specific attributes of interest. Our participants described this approach as fast and easy. Nevertheless, ephemerals are – to the best of our knowledge – rarely described in recent work [6, 10] or considered in XR tools research. We therefore see potential for future work focusing on this type of manifestation so that a further understanding of design challenges can be developed and XR design tools can be designed to overcome the tool gap.

Our reports about the mixed application of throw-away prototypes and evolutionary prototypes is in line with previous work from the field and similar to observations described in 2D design [18].

Finally, our participants had different interpretations of fidelity, ranging from a two-stage model of low and high fidelity describing the efficiency of visual design to a concept similar to a multi-dimensional spectrum based on XR elements. From our observations, we argue that the concept of fidelity in XR design is coupled to the economic principle of design [26] and the tool gap [36], in addition to aspects such as target audience and resources needed for prototyping. Therefore, fidelity needs to be reflected in relation to a medium's properties. However, further research is required to fully understand how fidelity is represented in XR prototypes or applications with similar properties, such as virtual environments and games, ubiquitous computing systems, or interfaces for voice and sound.

6.3 Where do prototypes reach their limits and what can we learn about designing supportive design tools? – Q3

To conclude our investigation, we focused on good practices and pitfalls of XR prototyping and tools. Our participants reported having repurposed, adapted, or enriched tools with personalized content to create accessible prototypes. We further showed how keeping the context of use for documenting ephemerals dampened the effect of down-sampling. Finally, our participants reported having used ready-made assets and a common design language to reduce workload and design complexity.

In contrast, we also reported drawbacks: Participants struggled to convey the feeling of XR with justifiable effort and faced problems regarding display technology tampering with colors and in designing legible text.

Repurposing, adapting, or enriching tools is a phenomenon of tool appropriation and tailorability and well presented in Computer-Supported Collaborative Work (CSCW) discourses around supporting learning and appropriation in IT-environments [11, 44]. Due to the complexity and knowledge-intensive nature of the work to be supported, as well as the novel and often experimental characteristics of the medium, it is not clear if existing approaches and ideas from this domain will work or how they would need to be adapted for XR-related work practices. Our findings give some insights into these aspects. They imply that there is a strong need to support tailorability and flexibility in applications as requirements and that mediums can be highly diverse across different projects in the XR domain.

Our findings are in line with Stolterman *et al.'s* idea of building tools for designers to support both thinking and outcome [46]: While tools for thinking support designers in understanding the design problem and trying out various solution ideas, tools for outcome enable designers to produce artifacts of a certain quality. We find that our participants reported on a lack of tools for thinking rather than for production since, in the reported cases, designers were supported by developers for production.

For prototyping interactivity, existing work proposes several approaches, such as Wizard-of-Oz [43] or reactive path-based programming [52]. As we learned in our study, prototyping interactivity can already be done if the designer has access to a collection of examples. This aspect of a shared library of interactive artifacts to further explore design solutions could be particularly useful when applied in, for instance, community-based tools.

6.4 Limitations

Recruit interview participants from industry willing to give us details about their work practices and additionally showcase prototypes was challenging. Hence, we had to rely on convenience sampling and not all of our 17 participants could provide in-depth insights into their work due to fears of breaking confidentiality agreements. Additionally, NDAs prevented us from including details of several prototypes used in our analysis. Furthermore, our study is based on interviews and therefore relies on reports mirroring what designers say they did rather than on observing them in action. Therefore, future research would benefit from further observatory or participatory design studies. Finally, we noticed that our dataset lacks specific types of XR, such as diminished reality [40]; multi-sensual aspects such as motion, haptics, taste/flavor, and smell; or in-depth aspects of application areas such as collaborative environments, space-robustness, or outdoor experiences [21, 41]. While our prototype sample might represent the current situation in industry, future work should aim to complete the proposed taxonomy by adding the perspective of prototypes that are available from the literature or previous research.

7 CONCLUSION

We have presented the findings from our prototype-centered exploratory study with 17 industry practitioners from the field of XR UX / UI design. In addition to a classification of XR prototypes in terms of their roles and function in the larger design process, we identified eight manifestation types. Furthermore, we proposed an initial taxonomy for describing XR prototypes in terms of their key characteristics with the goal of better understanding designers' challenges with new XR mediums. We finally describe good practices and pitfalls of current prototyping approaches in XR. With our work, we contribute to the ongoing tools and design research discourses in the XR community by providing detailed insights into prototyping practices in industry.

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REFERENCES

[1] Deutsche Akkreditierungsstelle. 2010. Leitfaden Usability. http://www.dakks.de – retrieved in December 2019. retracted in January 2020.

[2] Narges Ashtari, Andrea Bunt, Joanna McGrenere, Michael Nebeling, and Parmit K. Chilana. 2020. Creating Augmented and Virtual Reality Applications: Current Practices, Challenges, and Opportunities. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376722

[3] Uday A. Athavankar. 1997. Mental Imagery as a Design Tool. *Cybernetics and Systems* 28, 1 (1997), 25–42. https://doi.org/10.1080/019697297126236

[4] D. Baumer, W. Bischofberger, H. Lichter, and H. Zullighoven. 1996. User interface prototyping-concepts, tools, and experience. In *Proceedings of IEEE 18th International Conference on Software Engineering*. Institute of Electrical and Electronics Engineers, Berlin, Germany, 532–541. https://doi.org/10.1109/ICSE.1996.493447

[5] Michel Beaudouin-Lafon and Wendy Mackay. 2009. Prototyping Tools and Techniques. In *Human-Computer Interaction: Development Process* (1 ed.). CRC Press, Boca Raton, 137–160. https://doi.org/10.1201/9781420088892

[6] Marion Buchenau and Jane Fulton Suri. 2000. Experience Prototyping. In *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques* (New York City, New York, USA) *(DIS '00)*. Association for Computing Machinery, New York, NY, USA, 424–433. https://doi.org/10.1145/347642.347802

[7] Bill Buxton. 2007. *Sketching User Experiences*. Morgan Kaufmann, Burlington. 139–141 pages. https://doi.org/10.1016/B978-012374037-3/50059-6

[8] Herbert H Clark and Susan E Brennan. 1991. Grounding in communication. In *Perspectives on socially shared cognition.*, Lauren B. Resnick, John M. Levine, and Stephanie D. Teasley (Eds.). American Psychological Association, Washington, DC, US, 127–149. https://doi.org/10.1037/10096-006

[9] Juliet M. Corbin and Anselm Strauss. 1990. Grounded theory research: Procedures, canons, and evaluative criteria. *Qual Sociol* 13 (1990), 3–21. https://doi.org/10.1007/BF00988593

[10] Steven Dow, T. Scott Saponas, Yang Li, and James A. Landay. 2006. External Representations in Ubiquitous Computing Design and the Implications for Design Tools. In *DIS '06: Proceedings of the 6th conference on Designing Interactive systems*. Association for Computing Machinery, Pennsylvania, 241–250. https://doi.org/10.1145/1142405.1142443

[11] Sebastian Draxler, Adrian Jung, Alexander Boden, and Gunnar Stevens. 2011. Workplace Warriors: Identifying Team Practices of Appropriation in Software Ecosystems. In *Proceedings of the 4th International Workshop on Cooperative and Human Aspects of Software Engineering* (Waikiki, Honolulu, HI, USA) *(CHASE '11)*. Association for Computing Machinery, New York, NY, USA, 57–60. https://doi.org/10.1145/1984642.1984656

[12] Christiane Floyd. 1984. A Systematic Look at Prototyping. In *Approaches to Prototyping*, Reinhard Budde, Karin Kuhlenkamp, Lars Mathiassen, and Heinz Züllighoven (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 1–18.

[13] Maribeth Gandy and Blair MacIntyre. 2014. Designer's Augmented Reality Toolkit, Ten Years Later: Implications for New Media Authoring Tools. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 627–636. https://doi.org/10.1145/2642918.2647369

[14] Paul Green and Lisa Wei-Haas. 1985. The Rapid Development of User Interfaces: Experience with the Wizard of OZ Method. *Proceedings of the Human Factors Society Annual Meeting* 29, 5 (1985), 470–474. https://doi.org/10.1177/154193128502900515

[15] Trent Hergenrader. 2018. *Collaborative worldbuilding for writers and gamers*. Bloomsbury Publishing, London, Great Britain. 257 pages.

[16] Stephanie Houde and Charles Hill. 1997. Chapter 16 - What do Prototypes Prototype? In *Handbook of Human-Computer Interaction (Second Edition)* (second edition ed.), Marting G. Helander, Thomas K. Landauer, and Prasad V. Prabhu (Eds.). North-Holland, Amsterdam, 367–381. https://doi.org/10.1016/B978-044481862-1.50082-0

[17] ISO/TC 159/SC 4 Ergonomics of human-system interaction. 2019. *ISO 9241-210:2019 Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems* (2 ed.). Standard. International Organization for Standardization, Geneva, Switzerland.

[18] Jennifer Preece, Helen Sharp, and Yvonne Rogers. 2015. *Interaction Design: Beyond Human-Computer Interaction* (4 ed.). Wiley. https://www.wiley.com/en-us/Interaction+Design%3A+Beyond+Human+Computer+Interaction%2C+4th+Edition-p-9781119088790

[19] Hilary Johnson and Lucy Carruthers. 2006. Supporting creative and reflective processes. *International Journal of Human Computer Studies* 64 (10 2006), 998–1030. Issue 10. https://doi.org/10.1016/j.ijhcs.2006.06.001

[20] Veronika Krauß, Alexander Boden, Leif Oppermann, and René Reiners. 2021. Current Practices, Challenges, and Design Implications for Collaborative AR/VR Application Development. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Article 454, 15 pages. https://doi.org/10.1145/3411764.3445335

[21] Veronika Krauß, Florian Jasche, Sheree May Saßmannshausen, Thomas Ludwig, and Alexander Boden. 2021. Research and Practice Recommendations for Mixed Reality Design – Different Perspectives from the Community. In *27th ACM Symposium on Virtual Reality Software and Technology (VRST '21)* (Osaka, Japan). Association for Computing Machinery, New York, NY, USA, 13. https://doi.org/10.1145/3489849.3489876

[22] Carlye A. Lauff, Daniel Knight, Daria Kotys-Schwartz, and Mark E. Rentschler. 2020. The role of prototypes in communication between stakeholders. *Design Studies* 66 (2020), 1–34. https://doi.org/10.1016/j.destud.2019.11.007

[23] G.A. Lee, C. Nelles, M. Billinghurst, and G.J. Kim. 2004. Immersive authoring of tangible augmented reality applications. In *Third IEEE and ACM International Symposium on Mixed and Augmented Reality*. IEEE Computer Society, Arlington, VA, USA, 172–181. https://doi.org/10.1109/ISMAR.2004.34

[24] Germán Leiva and Michel Beaudouin-Lafon. 2018. Montage: A Video Prototyping System to Reduce Re-Shooting and Increase Re-Usability. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 675–682. https://doi.org/10.1145/3242587.3242613

[25] Germán Leiva, Cuong Nguyen, Rubaiat Habib Kazi, and Paul Asente. 2020. Pronto: Rapid Augmented Reality Video Prototyping Using Sketches and Enaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376160

[26] Youn-Kyung Lim and Erik Stolterman. 2008. The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas. *Transactions on Computer-Human Interaction* 15, 2 (2008), 1–27. https://doi.org/10.1145/1375761.1375762

[27] Blair MacIntyre, Maribeth Gandy, Steven Dow, and Jay David Bolter. 2004. DART: A Toolkit for Rapid Design Exploration of Augmented Reality Experiences. In *UIST '04: Proceedings of the 17th annual ACM symposium on User interface software and technology*. Association for Computing Machinery, Santa Fe, NM, USA, 197–206. https://doi.org/10.1145/1029632.1029669

[28] Martin Maguire. 2020. An Exploration of Low-Fidelity Prototyping Methods for Augmented and Virtual Reality. In *Design, User Experience, and Usability. Design for Contemporary Interactive Environments*, Aaron Marcus and Elizabeth Rosenzweig (Eds.). Springer International Publishing, Cham, 470–481.

[29] Steve Mann. 2002. Mediated reality with implementations for everyday life. *Presence Connect* 1 (2002), 2002.

[30] Michael McCurdy, Christopher Connors, Guy Pyrzak, Bob Kanefsky, and Alonso Vera. 2006. Breaking the Fidelity Barrier: An Examination of Our Current Characterization of Prototypes and an Example of a Mixed-Fidelity Success. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Montréal, Québec, Canada) *(CHI '06)*. Association for Computing Machinery, New York, NY, USA, 1233–1242. https://doi.org/10.1145/1124772.1124959

[31] Paul Milgram and Fumio Kishino. 1994. Taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems* E77-D, 12 (1994), 1321–1329.

[32] Brad Myers, Scott E Hudson, and Randy Pausch. 2000. Past, present, and future of user interface software tools. *ACM Transactions on Computer-Human Interaction (TOCHI)* 7, 1 (2000), 3–28.

[33] Michael Nebeling, Katy Lewis, Yu-Cheng Chang, Lihan Zhu, Michelle Chung, Piaoyang Wang, and Janet Nebeling. 2020. XRDirector: A Role-Based Collaborative Immersive Authoring System. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376637

[34] Michael Nebeling and Katy Madier. 2019. 360proto: Making Interactive Virtual Reality & Augmented Reality Prototypes from Paper. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300826

[35] Michael Nebeling, Janet Nebeling, Ao Yu, and Rob Rumble. 2018. ProtoAR: Rapid Physical-Digital Prototyping of Mobile Augmented Reality Applications. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173927

[36] Michael Nebeling and Maximilian Speicher. 2019. The Trouble with Augmented Reality/Virtual Reality Authoring Tools. In *Adjunct Proceedings - 2018 IEEE International Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2018*. Institute of Electrical and Electronics Engineers, Munich, Germany, 333–337. https://doi.org/10.1109/ISMAR-Adjunct.2018.00098

[37] Donald A. Norman. 1993. *Things That Make Us Smart -Defending Human Attributes in the Age of the Machine* (1 ed.). Vol. 1. Addision-Wesley Publishing Company, USA.

[38] Marc Rettig. 1994. Prototyping for Tiny Fingers. *Commun. ACM* 37, 4 (April 1994), 21–27. https://doi.org/10.1145/175276.175288

[39] Jim Rudd, Ken Stern, and Scott Isensee. 1996. Low vs. High-Fidelity Prototyping Debate. *Interactions* 3, 1 (Jan. 1996), 76–85. https://doi.org/10.1145/223500.223514

[40] Sanni Siltanen. 2012. *Theory and applications of marker-based augmented reality: Licentiate thesis*. Ph.D. Dissertation. Aalto University, Finland. Project code: 78191.

[41] Maximilian Speicher, Brian D. Hall, and Michael Nebeling. 2019. What is Mixed Reality?. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3290605.3300767

[42] Maximilian Speicher, Katy Lewis, and Michael Nebeling. 2021. Designers, the Stage Is Yours! Medium-Fidelity Prototyping of Augmented & Virtual Reality Interfaces with 360theater. *Proceedings of the ACM on Human-Computer Interaction* 5, EICS (2021), 1–25.

[43] Maximilian Speicher and Michael Nebeling. 2018. *GestureWiz: A Human-Powered Gesture Design Environment for User Interface Prototypes*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3173681

[44] Gunnar Stevens and Sebastian Draxler. 2010. Appropriation of the eclipse ecosystem: Local integration of global network production. In *Proceedings of COOP 2010: Proceedings of the 9th International Conference on Designing Cooperative Systems*. Springer, Aix-en-Provence, France, 287–308.

[45] Erik Stolterman. 2008. The Nature of Design Practice and Implications for Interaction Design Research. *International Journal of Design* 2, 1 (2008), 55–65. http://www.ijdesign.org/index.php/IJDesign/article/view/240/148

[46] Erik Stolterman, Jamie McAtee, David Royer, and Selvan Thandapani. 2009. Designerly Tools. In *Undisciplined! Design Research Society Conference 2008*. Sheffield Hallam University, Sheffield, UK, 16–19. http://shura.shu.ac.uk/491/

[47] Alexandra Thompson and Leigh Ellen Potter. 2018. Taking the 'A' Out of 'AR': Play Based Low Fidelity Contextual Prototyping of Mobile Augmented Reality. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts* (Melbourne, VIC, Australia) *(CHI PLAY '18 Extended Abstracts)*. Association for Computing Machinery, New York, NY, USA, 647–653. https://doi.org/10.1145/3270316.3271518

[48] Balasaravanan Thoravi Kumaravel, Fraser Anderson, George Fitzmaurice, Bjoern Hartmann, and Tovi Grossman. 2019. Loki: Facilitating Remote Instruction of Physical Tasks Using Bi-Directional Mixed-Reality Telepresence. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 161–174. https://doi.org/10.1145/3332165.3347872

[49] Balasaravanan Thoravi Kumaravel, Cuong Nguyen, Stephen DiVerdi, and Bjoern Hartmann. 2020. TransceiVR: Bridging Asymmetrical Communication Between VR Users and External Collaborators. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 182–195. https://doi.org/10.1145/3379337.3415827

[50] Haijun Xia, Sebastian Herscher, Ken Perlin, and Daniel Wigdor. 2018. Spacetime: Enabling Fluid Individual and Collaborative Editing in Virtual Reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 853–866. https://doi.org/10.1145/3242587.3242597

[51] Yasuhiro Yamamoto and Kumiyo Nakakoji. 2005. Interaction design of tools for fostering creativity in the early stages of information design. *International Journal of Human Computer Studies* 63 (2005), 513–535. Issue 4-5 SPEC. ISS..

https://doi.org/10.1016/j.ijhcs.2005.04.023

[52] Lei Zhang and Steve Oney. 2020. FlowMatic: An Immersive Authoring Tool for Creating Interactive Scenes in Virtual Reality. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 342–353. https://doi.org/10.1145/3379337.3415824

[53] Yu Zhu, Kang Zhu, Qiang Fu, Xilin Chen, Huixing Gong, and Jingyi Yu. 2016. SAVE: Shared Augmented Virtual Environment for Real-Time Mixed Reality Applications. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1* (Zhuhai, China) *(VRCAI '16)*. Association for Computing Machinery, New York, NY, USA, 13–21. https://doi.org/10.1145/3013971.3013979

A APPENDIX: INTERVIEW GUIDELINE

The questions listed below were used as a semi-structured interview guideline. Participants were asked to explain their approach and demonstrate artefacts if available in line with one of their current projects. The data collection is further described in Section 3.2.

A.1 Opening questions

(1) Who are you?
(2) What are you doing?
(3) Do you have experience in developing 2D interfaces (desktop, app, web, ...)?

A.2 Organizational structure

(1) Please describe your company's work philosophy (agile, waterfall, . . .)
(2) What is your team's size? Which roles do you have?
(3) Which interfaces to other domains do you have?
(4) What type of applications do you develop?
(5) For which devices do you develop (HMD, mobile, . . .)?

A.3 Prototyping process & tools

A.3.1 Overall prototyping. How do you develop XR applications? Please describe it using a recent project you have been or are actively working on.

(1) Please describe the process you were/are using.
(2) Which role does prototyping play for your daily work?
(3) What do you expect / learn from prototyping?
(4) Can you give examples based on your previous work?

A.3.2 Planning.

(1) What are your tasks?
(2) In case of bigger teams for similar tasks / roles in one project (n>1):
   (a) How are the tasks distributed?
   (b) How do you organize collaborative tasks?
(3) How do you start with your task?
(4) What is your motivation for prototyping / not prototyping?
(5) What do you prepare?
(6) What do you have prepared from others?
(7) Which are the available artifacts/input you have when starting a new project? Who created them?
(8) Which problems do you face?
(9) In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

A.3.3 Preparing.

(1) What do you need (for prototyping)?
(2) Which are the available external resources / contents (e.g. design guidelines, best practices, 3D library, proprietary software solutions and repositories) you are using?
(3) Which are the available internal resources / contents (e.g. design guidelines, best practices, 3D library, proprietary software solutions and repositories) you are using?
(4) Which problems do you face and how did you cope with them?
(5) In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

A.3.4 Executing.

(1) Which methods do you use?
(2) What are the available tools (software) you use?
(3) Do you use additional tools? When / for what?
(4) At which points did you reach your limits with the available tools and methods and how did you cope with that?
(5) In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

A.3.5 Evaluation.

(1) What is the role of testing?
   (a) How do you evaluate your ideas/work?
   (b) What is your motivation for testing?
   (c) Which tools do you use?
   (d) Which methods do you use for testing?
   (e) Are end-users involved?
   (f) When are end-users involved?
(2) How long did the overall process take (in case the project is done)?
(3) What took the most time during prototyping/development (regarding tasks)?
(4) What was the biggest hindrance during the prototyping/development process?
(5) In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

A.3.6 Transfer.

(1) What are the artifacts (deliverables) you created?
(2) Who will continue working with those artifacts?
(3) In case of collaborative tasks:
   (a) How are you communicating findings/changes, ...?
   (b) How do you combine your artifacts?
(4) In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

A.4 Closing questions / reiterate

- Do you always follow the same approach as described in your sample project? What are the differences?
- Do you always face the same problems?
- Do you always create the same deliverables?
- Do you always use the same interfaces to other divisions?
- What takes the most time during prototyping/development (regarding tasks)?
- What is the biggest hindrance you were facing in other projects?

- How long does the overall process take in general?
- In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

A.5 Demographic questions

(1) What is your job title?
(2) How much experience do you have on your job?
(3) What is your background? [degree, courses, self-taught, ...]
(4) Do you have experience in developing 2D interfaces (desktop, app, web, ...)?
(5) In which domain are you working? [Game Design, Architecture, Health, Science, ...]
(6) How old are you?
(7) What is your gender?