Constructing Realities – Professionals' Approaches to Prototyping XR Experiences

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Abstract

In recent years, eXtended Reality (XR) technology like Augmented Reality and Virtual Reality became both technically feasible as well as affordable which lead to a drastic demand of professionally designed and developed applications. However, this demand combined with a rapid pace of innovation revealed a lack of design tool support for professional interaction designers as well as a knowledge gap regarding their approaches and needs. To address this gap, this thesis engages with the work of professional XR interaction designers in a qualitative *research into XR interaction design* approach. Therefore, this thesis applies two complementary lenses stemming from scientific design and social practice theory discourses to observe, describe, analyze, and understand professional XR interaction designers' challenges and approaches with a focus on application prototyping.

With this as a basis, nine design implications regarding design tool support and potential future directions of interaction design research in an emerging field are derived. The respective empirical studies described in this work present 1) a sample design process based on a design case study, 2) an in-depth interview study with professional designers investigating their current challenges and general design approaches, 3) an in-depth interview study with professional designers combined with an artifact analysis focusing on prototyping practices and XR application prototypes, and 4) a literature review and comparative analysis of design guidelines originating from both academia and industry.

Finally, this thesis contributes to ongoing discourses as follows:

- Social practice theory perspective: this thesis provides a reflection of current interaction design practices and their challenges in an emerging field. A specific focus based on material, competence, and meaning on prototypes as well as their roles in current XR interaction design practices is provided and discussed. Finally, nine design implications for future XR interaction design tools with a focus on emerging practices are provided.

- Scientific design perspective: this thesis provides a perspective on interaction design practitioners as partners in interaction design research and relates observed practices with existing design theory and frameworks. Specifically, the notion of *ephemeral prototypes* is coined and described and an initial taxonomy for XR design space filters in a prototyping discourse is introduced.
- Interaction designers and tool creators: this thesis offers a collection of pitfalls, good practices, workarounds, and design implications for their own work.

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Related Publications

Some parts of this dissertation have already been published as conference papers:

Section 5: © 2020 IEEE. Reprinted, with permission, from Veronika Krauß and Yücel Uzun. 2020. Supporting Medical Auxiliary Work: The Central Sterile Services Department as a Challenging Environment for Augmented Reality Applications. In *2020 IEEE International Symposium on Mixed and Augmented Reality* (*ISMAR*). pp. 665-671, `https://doi.org/10.1109/ISMAR50242.2020.00096`

Section 6: 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* (*CHI '21*). Association for Computing Machinery, New York, NY, USA, Article 454, 1–15. `https://doi.org/10.1145/3411764.3445335`

Section 7: Veronika Krauß, Michael Nebeling, Florian Jasche, and Alexander Boden. 2022. Elements of XR Prototyping: Characterizing the Role and Use of Prototypes in Augmented and Virtual Reality Design. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (*CHI '22*). Association for Computing Machinery, New York, NY, USA, Article 310, 1–18. `https://doi.org/10.1145/3491102.3517714`

Section 8: 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 *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology* (*VRST '21*). Association for Computing Machinery, New York, NY, USA, Article 24, 1–13. `https://doi.org/10.1145/3489849.3489876`

Moreover, these publications contribute to the presented topic. However, they are not included as chapters of this thesis.

- Veronika Krauß, Yücel Uzun, Leif Oppermann, and René Reiners. 2019. Smartglasses in the Sterile Supply Process. In *Proceedings of Mensch und Computer 2019 (MuC'19)*. Association for Computing Machinery, New York, NY, USA, 859–861. `https://doi.org/10.1145/3340764.3345367`
- Jona Hebaj, Veronika Krauß, Yücel Uzun, Wolfgang Prinz, Matthias Jarke. 2021. Towards Design Guidelines for AR Training Applications in Controlled Environments. In *GI VR / AR Workshop*. Gesellschaft für Informatik e.V.. Sankt Augustin. 9.-10. September 2021. `https://doi.org/10.18420/vrar2021_1`

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Part I

Introduction and Overview

1 Introduction

1.1 Motivation

Augmented (AR) and Virtual Reality (VR) are related but distinct emerging technologies: While VR aims to substitute a user's environment and sensorial input with one that is fully computer-generated, AR is anchored in the physical world and enriches, alters, or diminishes it through adding, substituting, removing, or otherwise blending virtual and real content. However, the borders between the two technologies are fluent – as such, Milgram and Kishino describe both technologies as the alternating ends of a reality-virtuality continuum [235]. Both are often addressed using the umbrella term *eXtended Reality* (XR) (see Section 1.3).

Recently, XR technologies gained traction due to technological advances in both hardware portability and capability, leading to a drastic increase of the technology's relevance and popularity for end-users and industry. However, the fast pace of innovation led to an unclear market situation and revealed a lack of practical tool support for creating respective applications [248] as well-known tools and approaches from 2D software development fell short in the encounter of a third dimension [11]. Consequently, knowledge regarding the challenges faced by professional XR designers when creating XR applications, and how they overcome the current tool limitations in their daily work is scarce. This gap is addressed in this thesis, which informs HCI tool research with a focus on prototyping XR applications. The emphasis here is on practical approaches rooted in industry, bridging the gaps between HCI research and HCI practice in the field of XR.

Going back to the roots of XR technology, AR and VR are surprisingly old concepts: In 1957, Morton Heilig filed patent for what we today know as one of the first head-mounted, stereoscopic displays: the "Stereoscopic-television apparatus for individual use" [148], also known as *Telesphere Mask*.

In 1965, Ivan Sutherland, who is often seen as the founder of modern XR, published his vision of the *Ultimate Display* [338] – a display able to control the existence of matter to an extent where it becomes physical reality. In 1968, he constructed *The Sword of Damocles*, the first interactive head-mounted display that was capable of displaying 3D wireframe objects in a see-through display [339] and can therefore be seen as the first implementation of an AR headset [37].

What followed were almost six decades of research focusing on enhancing tracking algorithms, display technology, and multi-sensory hardware capabilities [37]. Finally, with the development of the commercial VR headset *Oculus Rift* in 2011 as well as powerful smartphones, a price point affordable by consumers was reached, with a resolution, field-of-view, and rendering capability that allowed for ever-increasing sense of presence and subsequent immersion in virtual environments. The technology had evolved to a point where widespread adoption could be expected in the near future, which resulted in increasing relevance for both private and industrial applications. As hardware and software developers embraced this technology, the number of applications and corresponding app stores grew as fast as the variety of products for end users and businesses. *Pokémon Go* [251] (2016), as one of the first successful location-based mobile games with AR elements, and VR games like *Beat Saber* [23] (2018) and *Half-life Alyx* [353] (2020) further spread awareness and acceptance of XR technology. Most recently, the company Meta announced to pursue *The Metaverse*, their vision of a shared physical-virtual space for work and leisure and seamless XR interfaces through which people connect [232].

However, when XR got to the brink of adoption on a larger scale, researchers and professionals faced a scarcity of design support – despite the past six decades of research. Since development for XR required a high degree of technical knowledge and programming skills, the entry hurdles for creators were high [195]. In addition to the *tool gap* [248] describing the lack of high-fidelity authoring or prototyping tools for non-technical creators, interaction and interface designers faced a convoluted mix of platform conventions [326], hardware capabilities, and diverse controller designs. Further, as XR just began to become mass-market ready, both creators and users were inexperienced in using the technology. Creators felt overwhelmed when encountering a medium that requires to incorporate a third dimension [11] because many of them originated in designing for traditional 2D media (e.g., [195]) and did not receive specific training. In addition, the field of XR was (and still is) in the early stages of developing design practices, tools, and a shared understanding of concepts and terminology [325, 123]. Against this background, the question arises why and how exactly interaction designers reportedly face a lack of support [11] – especially given the efforts and insights previous research work provided with respect to user-centered XR design and evaluation (e.g., [90, 27]).

Recently, XR-focused interaction design research aims to democratize the medium by providing, for example, new tools and methods for novice creators with low technical skills (e.g. [11, 123]). The resulting tools and prototyping techniques provide limited functionality and propose novel or adapted prototyping techniques for easy application creation. In addition, challenges for novice designers, hobbyists, and designers without dedicated technical training in XR are well observed and described in related work [11, 123]. Experienced and professional designers with an industrial background, however, are underrepresented in active interaction design research for XR. This results in a lack of understanding how respective design processes are implemented in a professional context, how tools are applied, how users or other stakeholders are involved, and what challenges they face in practice. Eventually, this might lead to a growing *theory-practice gap* (e.g. [83, 287, 333, 25]) in XR interaction design and tools research as such proposed guidelines, methods, and tools originating from research fail to understand and address the needs and approaches of XR interaction design practitioners. To prevent such a theory-practice gap, "adequately address[ing] the lived complexity of design practices" [132] is crucial if academic interaction design research wants to impact and support practitioners. As Speicher et al. showed in their work, industry and academia differ at least regarding their interpretation of XR terminology [325]. In order to verify if this discrepancy is also visible in proposed interaction design methods and tools originating from academic XR research, and, if it exists, how such a gap could be bridged, “empirically grounded descriptions and critical analyses of design practice activities“ [132] is crucial.

Therefore, this thesis complements the active tool and design practice debates in XR interaction design research. It attends to the lack of insights into design practices and challenges of XR professionals by taking a *research into design* [112, 219] or *science of design* [68, 70] approach and “examines, uncovers, analyzes, and interprets what interaction designers are already doing” [333] in the field of XR.

The presented work is guided by the following research questions:

RQ1 What are interaction design practices and challenges in professional XR application development?

RQ2 What are design implications for XR prototyping tools based on professionals’ XR interaction design practices?

1.2 Areas of Contribution

The presented work draws from a rich background of scientific design theory and practice (Section 2.1 and Section 2.2) as well as social practice theory (Section 2.4) to observe, describe, and analyze professional interaction designers’ approaches and challenges when working in an emerging field. Complementary to the two theoretical lenses *scientific design theory* and *social practice theory*, the third area of interest is situated in ongoing *XR interaction design research* (Section 2.3), specifically design tool discourses (see Figure 1).

The presented work follows a *research into (interaction) design* approach [132] in the sense that design activities and the respective processes and artifacts are the subject of interest [112, 219]. The main focus lies on *prototyping as a design practice*. Therefore, this thesis contributes to ongoing discourses in XR interaction design practice and tool research. As such, it sheds light on design practices and challenges of professional XR designers, provides implications for design regarding XR interaction design tool research as well as relates the findings to existing prototyping and design theories in the field of interaction design research.

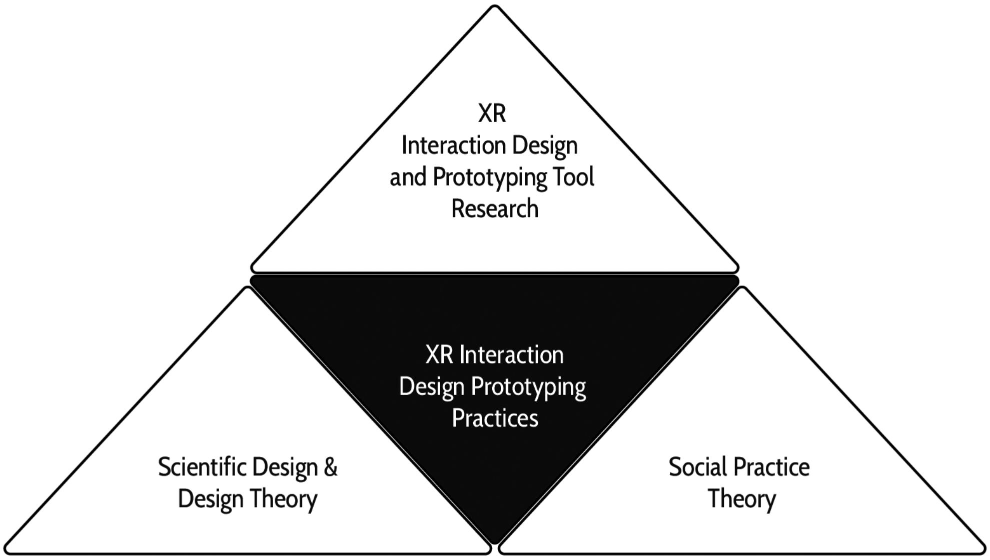

Figure 1
Fields providing the theoretical foundation of this thesis.

1.3 Terminology

XR as an emerging technology suffers from a lack of a common use of terminology [325] across academia and industry. As this thesis combines both perspectives, the discrepancy in terminology use becomes apparent. Therefore, this section distinguishes between and explains the terms augmented reality (AR), virtual reality (VR), mixed reality (MR) and XR by providing respective definitions.

The term *augmented reality* was first described as a technology “used to ‘augment’ the visual field of the user with information necessary in the performance of the current task” [56]. Following Azuma’s definition, AR combines real and virtual content, offers real-time interactivity, and is registered in 3D [15]. “Ideally the human mind would not be able to distinguish between the computer-generated stimuli and the real world” [166].

Complementing to AR, *virtual reality* is defined as “a computer-generated digital environment that can be experienced and interacted with as if that environment was real” [166]. As such, VR substitutes the physical environment and a user’s sensorial input of their surroundings with a virtual one that provides real-time interactivity [52]. However, the border between those two types of technology are fluid: Milgram and Kishino describe the range from the physical environment to a fully virtual one as a spectrum. The real environment or *physical reality* [37] on the left end denotes the unmodified world as it surrounds us. Contrasting to that, on the alternating end of the spectrum, resides the *virtual environment* (VE) which completely replaces the physical environment with virtual content. VE and VR are often used interchangeably [195]. Ranging between those two extrema, Milgram and Kishino placed AR and *augmented virtuality* (AV) with the latter referencing systems that are mostly computer-generated but with physical elements or people bleeding through [37].

Finally, as an inclusive umbrella term used to describe the transitional character between the spectrum's two extrema, Milgram's and Kishino's Reality-Virtuality continuum offers the term *mixed reality* (MR). However, as the reality-virtuality continuum was introduced in 1994, it focuses on visual aspects and is per definition limited to a single display [325, 235]. As technology evolved, so did design practices, device capabilities, and the interpretation of mixed reality, resulting in manifold interpretations of MR [325]. To cope with this fragmentation, Speicher et al. provide a more inclusive conceptual framework based on an interview study with ten experts from industry and academia [325]. This framework consists of the seven dimensions *Environments, Users, Level of Immersion, Level of Virtuality, Interaction, Input,* and *Output* and the six notions of MR elicited from the participants' respective interpretations *Continuum, Synonym for AR, Collaboration, Combination, Alignment,* and *Strong AR*.

A more recent term emerging around 2017 from industry is *XR*. However, this term is used ambiguously in both academia and industry [274] and usually abbreviates *cross reality*, *extended reality*, or a not further specified instance of a reality-altering system (e.g., [273, 250, 318, 239, 352, 37]). In the latter case, *X* in XR is interpreted as a placeholder. In general and simplified, the notion functions as an umbrella term for AR and VR, and is often inclusive regarding other forms of already existing or to be invented reality-altering technology (see Figure 2).

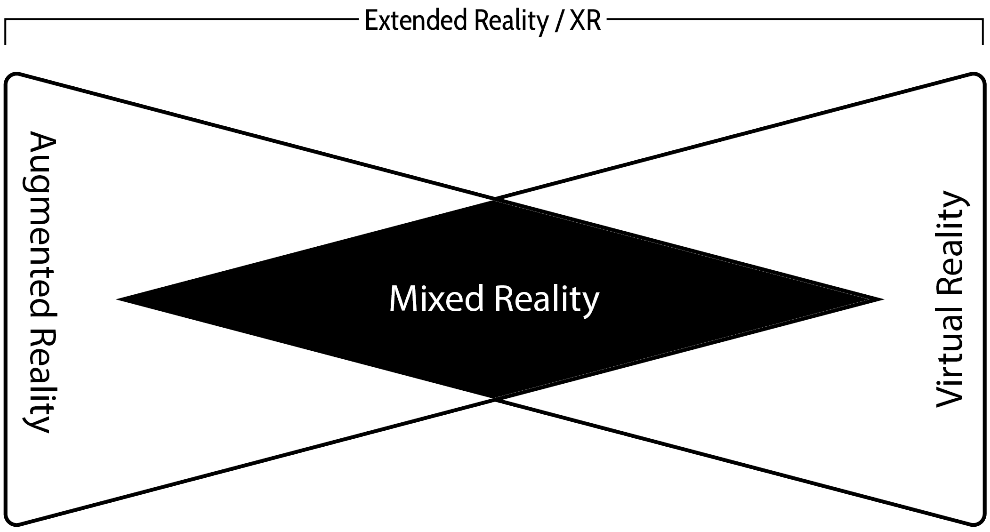

Figure 2
XR as an umbrella term includes all types of technology with reality-altering capabilities.

As it cannot be expected that a standard use of terminology will soon be established [325], this thesis uses XR as a more inclusive notion to address all sorts of reality-altering technology, or specifically mentions AR, VR or MR as previously described if more precision is needed.

1.4 Structure of the Thesis

This thesis consists of three parts:

Part I introduces the theoretical outline by detailing the motivation, terminology, and contributions. Section 2 introduces relevant previous work and highlights the research gap. Finally, Section 3 provides a summary of the research approach and interrelates the remaining sections.

Part II presents design practices in XR design based on four papers published in peer-reviewed conference proceedings of IEEE ISMAR, ACM VRST, and ACM CHI. Section 5 describes a design practice study of an AR application to provide an example of a user-centered design approach in XR. Section 6 sets out a general overview of professional XR design practices and challenges faced by respective creators. Section 7 details the use and creation of prototypes in professional design practices. Finally, Section 8 focuses on knowledge transition from research to practice through the investigation of guidelines.

Part III discusses the findings against related work. Further, limitations and future work are addressed.

2 Related Work

The related work presented in this section introduces the main concepts and current state of the art in the context of interaction design practices for commercial XR software application development. In addition, more detail is provided regarding software and UI prototyping and XR technology as both shape the thematic outline of this thesis. Finally, the social practice theory according to Shove [314] is introduced for the discussion of the empirical data presented in Part II. Consequently, this section is structured as follows:

As a theoretical foundation, Section 2.1 introduces design, specifically interaction design through a *scientific-design perspective*, also frequently referred to as *research into design* [112], *research-in-design* [219] or *science of design*. This section provides fundamental concepts of interaction design as a discipline, such as design activities, processes, and tools, and explores a designer's tool usage as well as the role of design guidelines in interaction design. Section 2.1 closes with the introduction of the theory practice gap as a phenomenon describing the discrepancy of interaction design in science and in professional practice.

Section 2.2 provides the scope of this thesis by introducing current theories of prototyping and prototypes in the context of commercial software application creation, as well as the role, application, and impact of respective tools and design guidelines. As prototyping is seen as one of the fundamental activities in creating new interactive artifacts in current software design practices, it is the central focus point of this thesis.

Section 2.3 shifts the attention from general interaction design to the field of XR and presents the current advances in XR interaction design and prototyping research and practice. Here, the focus lies on professional design tools and practices in XR industry and, due to a lack of existing research, general software engineering.

Finally, Section 2.4 introduces the fundamental aspects of the social practice theory as the analytical lens applied to understand XR interaction design practices. Consequently, this section introduces relevant tools and concepts for analyzing interaction design as a practice rather than a scientific discipline.

2.1 Interaction Design as a Design Discipline

In this section, fundamental concepts and terminology of interaction design research and practice are explained based on the current state of the art. However, since design as a discipline consists of diverse schools of thought, more context is required to interpret the core concepts of interaction design as intended in this thesis. Consequently, the *scientific design perspective* is summarized as an introduction to this related work section:

The modern history of *design* revolves around various perspectives and models that aim to define what design is, what designers do, and what defines the discipline of design in modern society [68, 70]. However, the discourses can be narrowed down to two main perspectives: design as a rational, scientific practice and design as a practice led by intuition, creativity, and tacit knowledge.

The *technical-rationality perspective* originates from the Methods Movement pioneered by, for example, Alexander and Jones in the 1960s [68, 70] and stems from the drive to provide structured and transparent processes and methods in an industrialized context [197, 178]. Those methods should support designers to tackle increasingly complex and ill-defined design problems based on rational decisions [68, 103] and prescriptive, structured activities [103]. A designer's doing is also led by "generic design principles such as guidelines" [103] that externalize design knowledge and expertise and transfer it from experienced to inexperienced designers [103]. Therefore, a designer takes a role similar to a scientist, who is following prescribed activities and guidelines to form artifacts of high quality as a result of applying transparent processes and performing rational decisions [103, 70].

In contrast, the *pragmatic and intuitive perspective* strongly builds on Schön's notion of a reflective practitioner who converses with tools and materials based on the current design situation [309]: according to

Schön, practitioners possess intuitive and tacit knowledge about their practices. Consequently, their practice is led by *knowing-in-action* – knowing what and how to do it without being able to describe their knowledge – and *reflection-in-action* – evaluating the current situation and their actions and immediately adapting them. The third concept, *reflection-on-action*, describes a practitioner's reflection on a past event or action and the process of identifying what needs to be done next. In a similar mindset, Cross describes how design has been taught "through a process of apprenticeship" [67] and coined the concept of *designerly ways of knowing* by drawing on a problem-solving experiment conducted by Lawson [198]. In this experiment, Lawson required science and architectural design students to arrange colored blocks to satisfy given and disclosed rules. He observed that the scientists followed a strategy that studied the nature of the problem, whereas the design students focused on identifying the best solution through experimenting with potential constellations [197, 198]. Consequently, Cross concludes that tacit design knowledge is also embodied in processes [67] and, as he further argues, in products of those processes.

As design as a discipline in science and practice matured the two contrasting perspectives converged into what Cross describes as "scientific design" [67, 69]:

> *"So we might agree that scientific design refers to modern, industrialized design – as distinct from pre-industrial, craft-oriented design – based on scientific knowledge but utilizing a mix of both intuitive and nonintuitive design methods. 'Scientific design' is probably not a controversial concept, but merely a reflection of the reality of modern design practice [69]."*

This thesis shares Cross' interpretation of scientific design and accordingly presents fundamental concepts of interaction design based on this understanding.

2.1.1 Fundamentals of Interaction Design

Originating from “early developments in experimental psychology” [13] and an evolving discipline of design, Bill Moggridge and Bill Verplank introduced the term *interaction design* in the 1980’s [62, 293]. As a design discipline based on “computer-science, film, and web design” [183] that designs products for people [13] and shapes digital artifacts [104], Cooper et al. define it as “the practice of designing interactive digital products, environments, systems, and services. Like most design disciplines, interaction design is concerned with form. However, first and foremost, interaction design focuses on something that traditional design disciplines do not often explore: the design of behavior” [62]. This requires interaction designers to have knowledge about available technology, its capabilities, and its limitations as well as an understanding of the desires, needs, abilities, and the context of people using products [267, 62]. Further, “understanding business, technical, and domain opportunities, requirements, and constraints” [62] is needed.
As its own interdisciplinary field, interaction design is strongly linked to and overlaps with, for example, Human-Computer Interaction, Human Factors, Informatics and Software Engineering, Ubiquitous Computing, and Social Science [267, 293].

Design observed through the scientific design lens often focuses on *design processes* as a collection of individual *activities* carried out by the designer, for example, prototyping and evaluation, *methods* applied during specific activities, and *artifacts* formed with *tools* and *techniques* as a result of or input for activities. As such, interaction design research frequently aims to influence or support design practices and the creation of artifacts by providing respective methods and tools (e.g., [334, 217, 85, 286]). Therefore, the following sections provide an overview of the meaning and use of predominantly methods and tools in interaction design research and their impact on practice.

2.1.2 Design Processes and Activities

Nowadays, it is generally acknowledged that design – and therefore also interaction design – consists of an iterative process in which several activities are carried out without a strict hierarchical structure in order to redefine and frame a problem or find potential solutions (e.g., [197, 290, 312, 62]). As such, it is both setting and solving [309, 103] often *complex* [360] or *wicked* [284] problems. Consequently, various process models and maps for interaction design exist to explain what designers do and how they approach designing. According to Cross, processes as well as people and resulting artifacts are the three key elements in which design knowledge resides [70]. In an attempt to describe a general design process, Lawson provides a three-dimensional representation of designing as "a negotiation between problem and solution through the three activities of analysis, synthesis and evaluation" [197]. Through the three-dimensional depiction, Lawson emphasizes the absence of linearity when moving between the problem and the solution space, and underlines that the three activities are intertwined but not ordered.

Two prominent and often referenced process models in interaction design are the user-centered design process model [161] and the double diamond [87]. The user-centered design process model is detailed in the ISO norm 9241:210 and consists of the five activities 1) planning the user-centered process, 2) understanding and specifying the context of use, 3) documenting user requirements, 4) producing respective design solutions, and 5) evaluating them based on the user requirements. According to this process model, designers can iterate through the activities 2 to 5 as needed and do not have to follow this model in a strict order [161]. Similarly, the double diamond process model [87] describes the transition from a design challenge to a result through two phases of the diverging-converging activities discover, define, develop, and deliver.

Despite process models often being adapted rather than directly applied in their original form in practice (e.g.[293]), they are regularly criticized for their prescriptive nature, strict hierarchy and linearity or formula-like description of design and the resulting mismatch with designers' actual ways of working (e.g. [111]). As a consequence, both of the aforementioned process models have been updated lately to emphasize a designer's role in guiding and *iterating* [103] through design activities based on their expertise and intuitivity, as well as reducing the impression of hierarchical and procedural activities [145, 161]. Nevertheless, such a map should be seen as a boundary object to discuss concepts of interdisciplinary approaches to design rather than a literal prescriptive model [197].

2.1.3 Methods and Tools in Interaction Design

Concluding from previous sections, interaction design processes – similar to other design discipline's processes – are frequently understood as a set of non-hierarchical activities that designers iterate through. Each of those activities and their respective design situations might require and likewise result in their own set of design methods and tools (e.g., [334, 335]). Therefore, methods and tools can be seen as an outcome of both scientific and practical design activities (e.g., [132]). As the distinction between methods and tools in interaction design literature is often blurry or ambiguous and research investigating the relationship between designers and their tools is scarce [335], further investigation is required to understand the application and adaptation of methods, tools, and techniques from theory to practice.

Methods are frequently addressed as means to guide and impact design activity [35]. As such, methods aim to share designers' knowledge they have accumulated through their activities over time and describe ways of organizing or structuring such activities and applying tools [35, 92, 227]. Therefore, they are often perceived as prescriptive blueprints [135]. However, similar to design process models (see Section 2.1.2), such method descriptions fail to convey tacit design knowledge [135] and cannot be applied by following them step by step [35, 135, 334]; instead, they require a certain level of skill, adaptation, and appropriation [135] to be applicable in practice. Consequently, methods can also be seen as performances and tools to support design practice [135].

Other perspectives on methods and tools are equally inclusive. Cooper et al. state that tools “consist of principles, patterns, and processes” [62]. Similarly, Stolterman et al. define *designerly tools* “as methods, tools, techniques, and approaches that supports [sic!] design activity in a way that is appreciated by practicing desingers” [334]. Further, their perspective includes “simple material tools such as the pen and paper and the whiteboard, but also [...] methods and techniques such as brainstorming and dialoguing, as well as more abstract tools such as conceptual frameworks and theories” or “taking a walk, playing games, listening to music” [335] in their definition. Gray’s inclusive view uses designerly tools and methods as an equivalent [134]. However, other than Stolterman et al., he sees tools, techniques, and approaches as entities that function as an operating platform that supports the design activity. Finally, Ehn describes that a good and well-made tool becomes an extension of their users’ bodies to a degree where the tool itself turns transparent – the tool enables its users to focus on their tasks as well as the material they are working with rather than on the tool itself [92]. Additionally, such a tool supports a designer in practicing and refining their skills [92].

To understand how designers choose their tools, Stolterman et al. investigated the designer-tool-relationship. They propose a *Tool-in-Use Model* [334] as an analytical lens based on a qualitative interview study with interaction design practitioners. This model describes how *purpose*, *activities*, and *tools* interrelate: designers choose their tools based on what they perceive as the purpose of their design action and consequently what kind of activity they see fit for addressing this purpose. However, there is no fixed order in which a designer performs this decision process as there is neither a linear, nor a causal relationship between the three concepts purpose, activities, and tools [334]. Stolterman et al. [334] highlight two distinct ways of tool use: for *thinking* about a designer’s ideas, actions, and challenges, and for producing *outcome* such as tangible artifacts [334].

Those two different ways of using a tool likely affect in which situation a designer chooses to work with them, for example, a whiteboard used for sketching might very well support a designer in idea exploration but fails to produce an artifact of certain visual quality [334]. In contrast, Adobe Photoshop can very well support the creation of visual appealing artifacts and might therefore be preferred when designers want to deliver polished visual designs [334]. However, as Stolterman et al. conclude, designers might also produce outcome using whiteboards, for example, when digitizing their sketches to incorporate them in a presentation. This demonstrates that reality is often more complicated than envisioned in this Tool-in-Use Model because a tool, depending on the purpose of its usage, can often support thinking as well as produce outcome [334].

2.1.4 Design Guidelines as Tools

Section 2.1.3 introduced a design-theoretical perspective on design tools and highlighted the inclusive interpretation in respective literature: a tool can be anything that supports the design activity and ranges from methods, principles, and guidelines as tools to structure and transfer design knowledge and expertise to software or hardware tools a designer uses to manifest their design concepts. Further, Section 1 and Section 2.3.2 highlight one of the core challenges for XR interaction designers: a lack of tools, particularly design guidelines. Therefore, the following section completes the theoretical perspective on interaction design provided in Section 2.1.2 and respective methods and tools in Section 2.1.3 by focusing on design guidelines as tools for supporting design activities.

Generally spoken, design guidelines are “prescriptive design knowledge” [311] gained from building and evaluating IT artifacts [268, 117]. This knowledge is meant “to promote *good* design” [170] and is usually based on empirical evidence and/or experience [170], can support design standardization [60] and the reduction of effort for both users [60] and developers [256]. Design guidelines or principles should "outlast the technological demands of the moment" [255] and therefore need to be based on human psychology and perception [170].

Unfortunately, related work is ambiguous when it comes to defining what design guidelines are and how they differ from design principles and heuristics. Further, definitions that properly differentiate between the three are scarce. Frequently, design principles and guidelines are used as synonyms whereas design heuristics are oftentimes applied to evaluate rather than create an artifact [267]. Preece et al. see guidelines and heuristics as closely related since the former can be transformed into the latter [267]. One of the more distinct classifications of principles, guidelines, and heuristics was published by Fu et al. [114]: They define a *principle* as a fundamental rule or law that is derived from extensive experience and empirical evidence. It provides guidance for the design process, increasing the likelihood of achieving a successful solution. A *guideline*, on the other hand, is a context-dependent directive based on experience and empirical evidence that provides direction for the design process to increase the chances of reaching a successful solution. Finally, a *heuristic* is a context-dependent directive that is based on intuition, tacit knowledge, or experiential understanding. It provides direction for the design process that increases the chances of reaching a satisfactory solution, even if it may not be optimal [114]. According to Johnson, the application of design guidelines is not straightforward but requires interpretation, intuition, and experience because such design rules often describe goals rather than specific actions for a designer to take [170].

This thesis is particularly interested in the perceived lack of design guidelines for XR systems and further discusses this issue in Section 8.

2.1.5 The Mismatch of Interaction Design Research and Practice

As a concluding aspect of the theoretical foundation laid out in this thesis, the following section turns towards one of the central motivators of this work: the mismatch of interaction design research and interaction design practice.

As design method modeling and application became popular, an increasing number of design researchers voiced their concerns regarding the underlying “understanding of design activity” [135] present in methods originating from interaction design research. Even though there are several works aiming to support interaction design practice [286], “there is an undesirable gap between HCI research aimed at influencing interaction design practice and the practitioners in question” [132]. This gap is often referred to as *theory-practice gap*.

In this regard, Rogers criticizes a lack of synchronization between how design is practiced and how respective theory is conceptualized [287]. She further argues that this mismatch results in inaccessible and hard to use theories proclaiming oversimplified core concepts that are easy to be misinterpreted as well as guidelines and analytical frameworks that fail to support designers’ activities [287]. Adding to Roger’s discussion, Goodman et al. see a lack of understanding design complexity on the researchers’ side as a potential additional cause [132]. According to Goodman et al., some researchers project their problem solving through scientific reasoning and prescriptive frameworks on how designers should approach design complexity. However, in contrast to scientific practices, design problems cannot be tackled through scientific reasoning alone as they require situated reflexivity and experiential approaches – this misunderstanding of design practice results in inapplicable methods, tools, and techniques as outcomes of interaction design research [132]. Furthermore, research outcomes tend to overgeneralize design situations and fail to recognize time pressure and limited budget, group dynamics, and the different prioritization of design exploration versus synthesis [286]. Similarly, Gray et al. report that designers’ experiences seldomly resonate with proposed methods from research as the latter lacks a profound grounding in practice [136].

There are several approaches arguing over how to overcome this gap and literature hints towards a lack of understanding what design practices are and how they can be supported. Rogers suggests a shift in perceiving the relationship between designers and researchers. Ideally, supportive design tools should focus on the design process and a designer’s need and preference of being supported. Therefore, researchers need to perceive designers as partners they engage with in an ongoing dialogue instead of an educator-learner relationship [287]. Other work suggests that interaction design research needs to be more thoroughly grounded in interaction design practice – therefore, more field studies and practice-based approaches are required [132, 286, 136]. This is also the course taken by this thesis. By providing insights into current interaction design practices in XR industry, this work aims to inform HCI and XR interaction design researchers about challenges, practices, and design implications for XR tool research aiming to influence or support XR practices or built on those insights to construct HCI design theories.

With the fundamental concepts for this thesis introduced, the following Section 2.2 shifts attention towards the scope of this work by introducing theories and practices revolving around prototyping and prototypes.

2.2 Prototyping and Prototypes

Prototyping and prototypes are – as important elements of any kind of design work – actively discussed across research communities such as HCI. Whereas *prototyping* is often referred to as a phase or activity in the development process of a product [109], a *prototype*, in general, addresses an early product version or a "specific kind of object used in the design process" [215]. In the context of interaction design, the terms *design artifact* and *prototype* are often used interchangeably. As prototyping and prototypes are two inseparable concepts, this thesis refers to *prototyping* as the activity of *generating* or *applying* prototypes, and *prototypes* as persistent or ephemeral externalizations of a design rationale or proposal that are used or produced during the prototyping process but differ from the final system regarding scope and accuracy.

Since both the activity prototyping and its results – prototypes – are deeply rooted in design practices of all kinds [215], manifold classifications and descriptions regarding their characteristics also exist. As prototypes are frequently used to communicate to various groups of stakeholders, this thesis focuses on prototypes in the context of HCI and interaction design practices in software creation. Respectively, the following sections provide a theoretical overview of prototyping as an activity in Section 2.2.1, prototypes as the corresponding artifacts in the context of software creation in Section 2.2.2, and conceptual perspectives of prototypes in Section 2.2.3. Consequently, this section lays out concepts and terminology of prototyping utilized in this thesis.

2.2.1 Prototyping as an Activity

Prototyping, in line with requirements engineering and analysis, design alternatives, and evaluation, is one of the four basic activities in interaction design [267]. Prototyping can be performed as an individual or collaborative activity in (interdisciplinary) teams [53, 84, 283, 127, 108]. Ideally, following a user-centered design, participatory design, co-design, or contextual design methodology, users are involved early in the process to enable both system creators and users "to learn the realities of the user‘s situation while the users strive to articulate their desired aims and learn appropriate technological means to obtain them" [319]. Literature in interactive system design offers manifold taxonomies and models to describe prototyping and prototypes. In the context of software engineering, Floyd's *three E model* characterizes prototyping as a process that "serves to introduce [...] an element of communication and feedback" [109] between stakeholders, specifically between users and software developers [51]. Floyd lists the three prototyping activities *exploration* for investigating if a design idea meets system expectations and requirements, *experimentation* for determining the fit of a design solution before implementing it in the target system, and *evolution* for successively adapting a system to changing requirements over time [109].

Floyd further describes prototyping as a four step process [109]:

Functional selection to determine which subset of the target system's feature collection should be incorporated and displayed in the prototype.

Construction of the prototype, which should always consume much less resources than the development of the final product.

Evaluation as the prototyping step that leads to decisions and informs the overall product development.

Further use in the sense that a prototype might be thrown away after it served its purpose, or might be integrated in total or partially into the final product.

Those four steps resemble the general design processes detailed in Section 2.1.2 – one can therefore conclude that prototyping itself is a design activity as this process is also supported by vast collections of dedicated tools and strategies (e.g., [24]).

Such a broadly adopted strategy is, for example, *horizontal* and *vertical prototyping* as described by Budde et al. [51] which is used to reduce a target system's complexity for the purpose of constructing a prototype. For example, horizontal prototyping focuses on prototyping the system's breadth of features in a layered manner but concentrates on only one of those layers. In contrast, vertical prototyping selects a set of features and models them in depth spanning all layers [51].

Similarly, especially agile software development methodologies foster an approach called *iterative prototyping* that "support[s] concurrent design and engineering" [337] in iterative cycles of refinement. This approach sees prototyping as a process of evolution that constructs an ongoing series of prototypes "that are gradually and incrementally being refined to more closely resemble the mythical target system" [131]. In this approach, prototypes focus on a selection of the target system's aspects while ignoring or compromising others [131].

Finally, in their work, Bäumer et al. propose four additional strategies of the prototyping process based on their analysis of nine industrial user interface prototyping projects [21]: communication between the users and the developers, communication in an interdisciplinary team, evolutionary system development, and the evaluation of the quality of potential development tools.

Concluding from the previous paragraphs, prototyping is not only a social design process involving multiple stakeholders, but also a practice that applies strategies to reduce, explore, and define a design problem's complexity. In the context of XR, however, the lack of supportive tools for system creation introduced in Section 1.1 and further detailed in Section 2.3 potentially imposes additional challenges on professional interaction designers that might further impact design strategies and approaches. Those strategies and approaches as well as design ideas, respective experience, and knowledge are embodied in design artifacts (i.e., prototypes) [215] that themselves fulfill dedicated purposes. As this thesis focuses on design practices in XR, it is therefore important to not only provide the fundamentals of prototyping, but also to tend towards the resulting artifacts of such a process. To further elaborate on the latter aspect, the following sections describe prototypes from two different lenses: artifacts (see Section 2.2.2) and concepts (see Section 2.2.3).

2.2.2 Prototypes as Artifacts

Prototypes are "a concrete representation of part or all of an interactive system" [24] and "are the means by which designers organically and evolutionarily learn, discover, generate, and refine designs" [215] in interactive system design. According to Houde and Hill, prototypes can be any object depending on how it is used in the prototyping process [156]. Consequently, they do not have to be self-explanatory as their meaning depends on a designer's intentional application and its respective context [156]. There are several prominent models and taxonomies used to categorize and describe prototypes based on their properties as well as their purpose and respective use. The following paragraphs introduce the main concepts applied in this thesis.

2.2.2.1 Properties of Prototypes An often applied but frequently criticized perspective on prototypes focuses on their properties, e.g., which *tools* (see Section 2.3.3) have been used or to what extent the resulting artifact resembles the final product regarding (multi-modal) interactivity, representation, and completeness. This is often described using the terms *low-fidelity*, *high-fidelity* [282, 291], or *mixed-fidelity* [229]. Low-fidelity prototypes are associated with low-cost creational methods, their explorative character, and their limited functionality. In contrast, high-fidelity prototypes are highly refined and close to the final product but require more effort and resources to be built [282, 291]. Finally, mixed-fidelity understands a prototype as a multi-property artifact that can have varying fidelity. Consequently, they do not fit in the binary classification of low-fidelity and high-fidelity [229]. However, using fidelity to express the resources to be spent on constructing a prototype and the closeness of the resulting artifact to the final product is also popular when describing prototyping methods [224, 343] and prototyping tools [248]. In addition, fidelity is also associated with the *materials* used to construct a prototype, such as paper [282] which is frequently applied as a low-fidelity or low-cost material [156].

Beaudouin-Lafon and Mackay further differentiate between *offline* prototypes that do not require a computer, for example paper-based prototypes, mock-ups on cardboard as well as videos, and *online* or software prototypes that are executed on a computer. The latter includes animations, software programs, interactive videos and presentations, and prototypes constructed with user interface design tools [24] (e.g., Figma, Adobe XD, Sketch). Finally, offline prototypes, according to Beaudouin-Lafon and Mackay, require less effort to be built and are often thrown away after they served their purpose, in contrast to online prototypes that might require skilled programmers and more effort to incorporate interactivity and visualization. Therefore, online prototypes “are usually more effective in the later stages of design, when the basic design strategy has been decided” [24].

Publications in this thesis utilize both, *fidelity* as a prominent concept in interaction design research and practice, and Beadouin-Lafon and Mackay’s notion of offline and online prototypes to describe properties of design artifacts. However, the focus on a prototype’s properties has been criticized. Houde and Hill, for example, argue that a general language to describe prototypes is missing and focusing on “such characterizations can be misleading because the capabilities and possible uses of tools are often misunderstood and the significance of the level of finish is often unclear, particularly to non-designers" [156]. Their alternative proposal shifts attention to a prototype's purpose, as detailed in the following section.

2.2.2.2 Purpose of Prototypes Based on their critique on the misleading focus of a prototype's properties, such as the tool used for construction or the fidelity, Houde and Hill argue to focus on the purpose of prototypes (i.e., what a prototype expresses) rather than their "incidental attributes" [156]. Their tripartite model consisting of a prototype's *role*, its *implementation*, and its *look and feel* [156] aims to support designers in asking a set of three design questions and find a matching prototyping strategy and respective tools. As such, *implementation* requires the construction of a software or working system, *role* focuses on the context of the artifact's application, and *look and feel* needs the simulation or modeling of the specific user experience [156]. The latter aspect not only details the visual representation of a system, but also includes experiential aspects of a systems as, e.g., further specified by Houde and Hill and also elaborated by Buchenau and Suri and their work on *experience prototyping* [49]: Buchenau and Suri coined the term *experience prototype* to "emphasize the experiential aspect of whatever representations are needed to successfully (re)live or convey an experience with a product, space or system" [49]. As such, experience prototypes afford some sort of interactivity and context ranging from storyboards to those who require active participation [49], for example, Wizard of Oz.

In their work, Beaudouin-Lafon and Mackay propose a model based on the four dimensions *precision*, *representation*, *interactivity* and *evolution* [24]. While precision, representation, and interactivity address the aforementioned properties of prototypes (see Section 2.2.2.1), evolution focuses on a prototype's life-cycle throughout the product development or design process. In this line, rapidly created and low-cost prototypes are usually thrown away (*throwaway prototype*) after they fulfilled their purpose. In contrast, *iterative prototypes* are evolved throughout multiple cycles of adaptation and alteration. A third class called *evolutionary prototypes* are a special case of iterative prototypes that evolve over time into the final system [24]. Additionally, Leiva proposes *takeaway prototypes* to emphasize the learning aspect of prototyping and the respective purpose of the resulting artifacts [207].

Due to the tool limitations reported for XR interaction design (see sections 1.1, and 2.3), it can be expected that prototyping itself as well as properties and purposes of prototypes are affected as designers develop their approaches to bridge the tool gap. Therefore, a third perspective needs to be taken to enable taking a holistic overview of prototyping and prototypes in XR interaction design: a conceptual perspective that allows to analyze more fundamental aspects of prototyping and prototypes. Therefore, subsection 2.2.3 introduces two fundamental concepts that complement the understanding of prototyping and prototypes in this thesis: *prototypes as filters* of a design space and *prototypes as boundary objects*.

2.2.3 Conceptual Perspectives on Prototypes

Despite numerous attempts to create classifications for and descriptions of prototypes, HCI research was lacking "knowledge [...] about the fundamental nature of prototypes" [215]. To close this knowledge gap, Lim et al. propose a framework viewing prototypes as tools that designers use to filter and traverse a design space. In this context, as cited by Lim et al., a design space contains all potential design solutions and rationales for a design problem [128, 238]. A design space can be both, filtered [215] and informed or expanded [144] and therefore possesses some kind of dynamic [144]. As a basis of their framework, they define prototypes as "purposefully formed manifestations of design ideas" [215] that "are for traversing a design space, leading to the creation of meaningful knowledge about the final design as envisioned in the process of design" [215]. Further, they propose three fundamental principles of prototyping:

The fundamental prototyping principle defines prototyping as an activity that aims to create a manifestation for filtering the qualities a designer is interested in without introducing bias or distortion of the overall design problem or target system.

The economic principle of prototyping states that the best prototype is one that visualizes possibilities and limitations in the simplest and most efficient way. Further, a prototype makes such possibilities and limitations measurable.

The anatomy of prototypes defines prototypes as filters used for traversing a design space. They are externalized and concrete manifestations of design ideas.

Finally, when viewing prototypes from an organizational and social perspective, they can be seen as serving the purpose of *boundary objects* as described by Star and Griesemer: A boundary object is “an object that lives in multiple social worlds and which has different identities in each” [331]. As such, prototypes influence and support the process of finding a common ground and exchanging ideas in interdisciplinary design teams [283] as well as outside the organization, e.g., when communicating with users.

As laid out in this section, the theoretical background of prototyping is based on a rich body of work. In addition to the two perspectives on prototypes as artefacts, namely their properties and their purpose (see Section 2.2.2), this thesis shares the conceptual perspectives on prototypes, specifically prototypes as filters [215] and prototypes as boundary objects [331]. In the following section, the narrative shifts from a general perspective on interaction design and prototyping theory towards XR design practices and latest advances of respective research. It further highlights the gap this thesis is addressing.

2.3 Interaction Design and Prototyping in XR

Interaction design research in XR can roughly be organized in four areas: 1) a hardware and algorithm based stream that aims to understand the opportunities, limits, and laws of computational challenges and hardware capabilities, 2) an interaction techniques and devices stream investigating ways of interacting with XR systems, 3) a context and applications stream creating and testing XR applications in various contexts, and 4) an authoring and design tools and methods stream that researches how hobbyist and professional designers can be supported in creating usable, safe, and secure applications and experiences. As this thesis focuses on the latter, the following sections provide an overview of current advances in XR prototyping tool research and design practices applied to create XR applications.

2.3.1 Interaction Design Challenges in Professional Software Development

XR software teams in the industry face complex and diverse design challenges on a daily basis. As a result, respective teams consist of experts who specialize in different roles and skills required to create software, for example software design and programming, 3D asset design, and UI/UX design [354]. This specialization in skills is expected to increase as the technology and its respective field continues to mature [123]. However, this “cross-competence collaboration between UI designers and software developers” [40] combined with the lack of tool support for non-technical creators [11, 244] requires an overhead of communication efforts to overcome the teams’ *asymmetry of knowledge* [107, 285]. Arguably, the situation for XR developing teams might even be more difficult compared to more established domains of software development, as the lack of tool support [248] and design resources [11] might amplify already known challenges encountered in interdisciplinary teams. However, existing work lacks respective insights, and this gap is addressed in this thesis.

While there is a lack of insights regarding XR design practices, existing works already observe interaction designers’ challenges in interdisciplinary teams that create software for other kinds of devices and technology in industry. For example, Ferreira et al.’s research on how to combine design work and programming practices revealed potential for miscommunication, friction, and negative effects on the overall design process and end-product due to the opposing goals of user-centered design processes and agile software development [106]: while user-centered design processes repeatedly iterate a potential design from a user's perspective before code is created, agile software development processes like Scrum aim to quickly produce code as working artifacts [106]. Consequently, oftentimes improvised negotiations were necessary to progress with the developers' work [106]. Similarly, Salah et al. report the need of establishing a shared design vision and rationale between developers and designers to prevent a discrepancy between the intended and the implemented design. This, however, requires synchronization efforts, for example, by introducing synchronization points [294] and by creating respective artifacts, such as design prototypes (see Section 2.2.2).

As designers and developers frequently work independently [228], a hand-off phase is required in which designers and developers align to turn designs into software. Maudet et al.'s multi-stage study with professional designers and developers reveal that the latter frequently misinterpret and struggle to implement a designer's original intent [228]. Further, they identify three types of *design breakdowns* – a situation occurring when a design is handed over to developers for implementation: 1) missing information as designers do not communicate required details, 2) edge cases in which designers do not consider potentially problematic situations, and 3) technical constraints of which designers are unaware when creating their designs. Further, Maudet et al. reveal an increase in workload and redundancy due to a required recreation of design documents with developer tools, as well as late involvement of developers in the design process that hinders the communication and development of complex and custom interactions. Finally, a *lack of shared vocabulary* or *vocabulary misuse* increase the difficulty of communication between designers and developers [228].

As listed above, existing works provide insights in interaction designers' challenges and practices in related fields of professional software development. Such issues can surface when designers hand their designs over for implementation [228]. However, as XR faces a tool gap that hinders designers to efficiently create respective design artifacts or prototypes[248, 11] for developing and communicating design visions

[294, 109], the question arises how XR interaction designers approach this need. Further, it is unclear if the challenges known from software development in other domains are equally faced by interaction designers working in the field of XR, or if they encounter amplified or different obstacles due to the emerging character of XR technology. This gap will further be addressed by this thesis. However, to complete the current state of the art, Section 2.3.2 introduces the latest research activities regarding XR interaction design practices, and Section 2.3.3 summarizes recent advances in prototyping tools research and development for XR in research and practice.

2.3.2 Understanding XR Interaction Design Practices

Latest research activities describe XR as an emerging field that faces several challenges which are not simply limited to technical or work-oriented issues. As an emerging field, it is taught and executed by people who originate from other fields of software creation [110], such as game development, architecture, and general software engineering, and, consequently, incorporates a conglomerate of diverse approaches, methods, tools, knowledge, and expertise. Lately, this lack of coherence became apparent in regards to the concept of mixed reality [325] as well as the more recently coined acronym *XR* and its meaning (see Section 1.3). Additionally, only few studies with a specific focus on XR prototyping examine creational processes of XR interaction designers based in practice. This can be ascribed to them often focusing on the evaluation of a specific authoring tool [200] or neglecting the larger context of prototyping and interaction design (see Section 2.2). This situation leads to a scattered picture of how XR interaction designers and their professional development teams approach their design challenges.

One of the few XR specific studies was published by Gandy and MacIntyre in 2014 [123]. Based on DART, their toolkit created to support media designers in transitioning their 2D storyboards into 3D animations, Gandy and MacIntyre discussed challenges and visions for XR authoring tools with eight creators [123]. Aligned with recent studies (e.g., [248, 11]), they emphasize the the necessity of providing authoring tools for designers without dedicated coding skills.

Another study that focuses on the challenges occurring with today's design tools for novice XR designers was published by Ashtari et al. [11]. They interview professional designers, domain experts, and hobbyists to identify approaches and provide insights in how current design and prototyping tools are applied. Ashtari et al. manage to identify eight hurdles when designing for XR, ranging from finding a starting point and difficulties to design for physical aspects, to user testing and evaluation. They also report that traditional design tools like "flat storyboarding" [11] reach their limit when it comes to designing for specific user interaction due to the "unlimited nature of immersive experience[s]" [11] and the accompanying loss of control over the user's potential actions. Finally, role-playing is reported "as a more effective, faster, and easier way to portray [the designer's] thought" [11]. However, current tools and methods are reported as being ineffective because they fail to simulate the real experience regarding, for instance, lighting conditions and audio [11], or do not provide expected and needed guidance for XR.

Further, Speicher et al. survey 30 AR creators and users to evaluate two AR development scenarios. This study results in six challenges for AR development: cross device and/or cross platform communication, mapping the environment, the devices' obtrusiveness, gesture recognition, tracking, hardware limitations regarding a field of view's narrowness, and the immersive scaling and sizing of AR objects [326]. Nebeling and Speicher also indicate that the current tool landscape requires XR creators to change or adapt their design approaches [248]. This aspect is further detailed in Section 2.3.3.

When observing these current challenges faced by XR creators, similar problems and approaches can be seen with challenges and approaches in other domains, especially if user interfaces have to be created for emerging technologies, a custom application has to be developed for an otherwise standardized and established technology, or the software requires specific types of interactivity. For example, similar externalization practices focusing on the design of (spatial) experiences are reported by Dow et al., who investigate design approaches for ubiquitous computing systems based on a study with eleven designers. They describe *prototyping by example* [85] as a fall-back approach to overcome tool limitations. Similarly, Leiva et al. report the *enactment of interactions* during the design process for prototyping and developing custom interactions [210]. Here, enactment was perceived as being easier to communicate compared to creating dedicated artifacts to explain a system's behavior [210]. Also Myers et al. reported challenges for interaction designers who prototype and iterate a system's interactive behavior because respective tools do require programming [242]. Oftentimes, designers fall back to more convenient approaches that further create issues with validity and misunderstandings, such as annotated story boards or textual descriptions [242]. As XR lacks standards and guidelines [11] and many tools require programming skills [248, 11]), this may lead to the conclusion that prototyping several, if not the majority of interactions in XR resemble the development of custom interactions as reported by Leiva et al. [210] or interactive behavior as described by Myers et al. [242]. However, more insights into actual XR prototyping and interaction design practices are required in this regard, which are provided in this thesis.

2.3.3 XR Prototyping Tools in Research and Practice

This section summarizes the current tool discourses in XR interaction design and prototyping research to provide a holistic overview of current challenges faced by XR creators. Prototyping in and for XR is an active research area that focuses on the development of tools to ease the creational process for both experts and novices. As such, available tools and hardware are frequently and rapidly changing and standards regarding display technology, interaction metaphors, and devices as well as respective hardware requirements are slowly developing as more applications are being built. However, some kind of stability in this regard is beneficial for refining concepts and establishing respective tools for supporting both creators and users [241].

In the continuously changing XR tool landscape, several authoring tools for XR have been developed in scientific and industrial communities [248, 146]. DART [221], as one of the early toolkits for AR authoring, supported media designers in transitioning their 2D storyboards to 3D animatic actors without requiring programming skills. More recent tools propose a variety of alternatives for XR creators, for example, physical prototyping [247, 246, 327], immersive authoring [201, 372, 271], video editing [208, 211, 209], live sharing [381, 345], and asynchronous or asymmetric collaboration [346, 245].

Commercial tools include game engines like Unreal Engine and Unity, as well as development toolkits and interfaces like ARKit, ARCore, A-frame, ARToolKit, or WebXR. Tools addressing less technical creators are, for example, Adobe Aero, Tvori, ShapesXR, and the now discontinued tool Microsoft Maquette, which enable XR prototyping using a what-you-see-is-what-you-get (WYSIWYG) editor. However, such tools are often too restrictive regarding their functionality and fail to support creators' needs - the tradeoff between *threshold* and *ceiling*, meaning between how difficult learning a tool is compared to what one can do with it [241], is not sufficient.

Despite these advances, XR creators still face challenges [11, 248]. To further investigate the issue of a lack in tool support, Nebeling and Speicher study prototyping software, cluster them regarding the produced artifacts' fidelity, and identify three main challenges [248]: Firstly, the available tool landscape is massive and complex for creators to capture. Secondly, tool chains to support prototyping processes and the fidelity-wise evolution of ideas and artifacts need to be rebuilt for every XR application due to technical challenges and a simultaneous lack of technical skill. Thirdly, design iterations are not sufficiently supported by available tools due to a lack in compatibility and a general optimization of tool-chaining towards higher fidelities.

To conclude the aspects and current advances of XR interaction design related research and practice, this section provided insights into challenges faced by interaction designers in multidisciplinary teams (see Section 2.3.1) as well as XR interaction design practices (see Section

2.3.2) and tool research (see Section 2.3.3). In addition to the tool gap [248] and a lack of standards [326, 11], the required technical skills to operate existing tools increase the barrier for inexperienced and non-technical designers [11]. Further, existing prototyping tools like storyboarding fail to sufficiently address the increased complexity of 3D applications situated in a physical world where users can roam freely and environmental factors, such as lighting conditions, cannot be controlled [11]. Finally, due to the emerging character of XR technology, tools and hardware change and advance rapidly which results in a difficult to grasp situation for designers [11, 248]. Existing work, so far, has not yet focused on emerging practices in industrial and multidisciplinary settings nor investigated in approaches to overcome the challenges summarized above, especially from an interaction design perspective. However, those insights are required to reduce the potential of the theory practice gap [132] in XR tool research and XR design practices. This gap is addressed in this thesis and analyzed through a practice theory lens. Concluding the related work overview, the following section introduces the practice theory fundamentals according to Shove [314] as an analytical lens for empirical work provided in this thesis.

2.4 Social Practice Theory as an Analytical Lens for Interaction Design Practice

To this point, the presented related work took a scientific design perspective to provide the fundamentals of interaction design in Section 2.1, theories about prototyping and prototypes in Section 2.2, and known challenges for XR interaction designers in Section 2.3. Further, Section 2.1.5 introduced the theory-practice gap as one of the central motivators for this thesis. In this regard, Kimbell, who argues for applying tools from social practice theory to understand design practices, criticizes that literature in design research lacks a respective lens and fails to put the rich body of analytical tools created by social practice theory into use [178, 176].

Following Kimbell's critique, this work also takes a practice-theoretical perspective on interaction design and attempts to offer a more holistic approach to understanding professional XR interaction design practices. As this thesis focuses on understanding XR interaction design practices, respective relevant principles of praxiology will be discussed in more detail in the following sections. However, this thesis does not expand praxiological perspectives or contributes to this particular theory; rather, it utilizes a subset of concepts to further analyze XR interaction design and its current challenges, specifically prototyping for XR systems in a professional environment. This subset of concepts is introduced below and mainly based on Shove's works [314].

2.4.1 The Praxiological Perspective

Goodman et al. elaborate that the underlying meaning of the term *practices* highly depends on the observational perspective [132]. In their work, Goodman et al. differentiate between a colloquial meaning, i.e., the activities performed to create commercial software, and a social sciences perspective, which provides a rich and more diverse notion of practices [132]. However, practice theory is not a unified concept; instead, praxiology offers a collection of different lenses one could apply to understand social and organizational phenomena [252, 299].

In general, "practices are the mundane activities that make up most of what people do in their daily lives" [190] and "can be understood as the regular, skilful 'performance' of (human) bodies" [276].

To further understand practices, how they come to existence, and how they cease to exist, Shove et al. lay out a framework based on the three elements *materials*, *competences*, and *meanings*[314]:

Materials address all required artifacts needed to perform a practice and incorporate "objects, infrastructures, tools, hardware, and the body itself" [314]. Materials are ambiguous when used in the broader context of design. For example, a material might refer to the matter or substance used to fabricate a design artifact, such as wood, paper, clay or software. However, through the praxiological lens, material in the practice of designing refers to a broader set of items, such as tools in the form of pencils and brushes, computers, guidelines, methods, the designer's body, and infrastructural artifacts like electricity.

Competences describe different aspects of practical knowledge and understanding [314]. This includes both formal or explicit knowledge (e.g., knowing a design process model) and tacit or implicit knowledge (e.g., knowing how to apply a design process model). Competences required for designing are, for example, the knowledge about which technique, method or tool to use and how to apply them in an appropriate way to solve a design problem, skills like sketching or programming, or having a sense of using the right color, proportions or lighting.

Meanings combine Reckwitz' descriptions of mental activities, emotion, and motivational knowledge [314] associated with the practice itself or any element that is being part of it. Meanings can be rooted in both society and the individual. In the context of interaction design, meanings could, for example, be attached to the set of tools a designer applies. For example, following a user-centered design process is generally associated with building potentially more usable and relevant designs for target user groups.

Practices, according to Schatzki, can be observed from two different view points: *practice as performance* and *practice as entity* [300, 298]. While the former denotes the observable individual instance of a practice [330], the latter depicts a practice's rooting in socially shared meaning, competences, and materials [314, 330]. This means that elements existing in the praxiological entity are dynamically integrated each time a practice is performed [314], and therefore recursively reproduce and shape the practice as entity.

Praxiological frameworks and concepts have been applied frequently in HCI studies for analyzing behavior and designing interfaces in the context of sustainability and consumption (e.g., [196, 313, 190, 330]). However, due to the central aspect materials play in some strands of praxiology [190] and the respective analytical frameworks and lenses, social practice theory can also be beneficially applied to understand and describe the practices of designers [177, 178] in fields of emerging technology and practices. This is the perspective taken by this thesis.

2.4.2 Emergence, Stabilization, and Demise of Practices

This thesis applies practice theory as a lens to analyze and describe the current change happening in interaction design of commercial applications through the emergence of XR as a market-ready medium. As a showcase, prototyping practices and their design artifacts – in this case prototypes – are observed because the latter carry meanings in an organizational context as well as a designer's rationale, skill, approach, and interpretation of a certain design problem (see Section 2.2). The main focus in this work lies on understanding how XR interaction designers cope with the tool gap in XR application creation and development based on their knowledge and experience and potentially establish new forms of interaction design practice for an emerging technology. Therefore, this section introduces elements of change and dynamics in practices following Shove et al.'s line of thought.

When turning towards the question how practices emerge, change, stabilize, and get abandoned, Shove et al., provide the concept of *links*. Links are interdependent and dynamic relations between the three elements materials, competences, and meanings, that are dynamically created when a practice is performed [314]. These linkages describe how a practice comes into existence, stabilizes, changes or is abandoned [314]. As long as linkages are not yet established, one can address existing materials, competences, and meanings as *proto-practice*. Consequently, *ex-practices* denote materials, competences, and meanings between which links are no longer made, resulting in a practice to be abandoned. Only if links between materials, competences, and meanings are established through repeated integration of these defining three elements, a practice can be addressed as such. Shove emphasizes that links have to be renewed "time and again" [314] through integrating similar defining elements of a practice in specific configurations for stabilization and routinization. Therefore, practices “should be understood as ongoing accomplishments in which similar elements are repeatedly linked together in similar ways” [314].

Further, practices can change over time with the evolution or transformation of the three elements of practice. For example, design practices underwent a transformation with the introduction of computers and corresponding software tools. Hand-drawn sketches and paper or clay models lost their significance in tasks like 3D modelling with the continuous evolution of 3D modeling software due to reduced costs and increasing flexibility when designs had to be reworked. Nevertheless, sketching and modeling with physical materials are still tools designers use and competences that are taught and required, hinting towards an aspect of *continuity in practices*. Shove et al. showcase this in the context of driving, when material configurations were shifted with the course of time to make driving more affordable with respect to required skills and financial wealth [314]. Such change often happens after a *disruptive moment* like major advances in technology innovation, infrastructure, or social meaning, that introduces new or altered materials, competences, and/or meanings. The current advances in XR technology as well as the increasing demand for respective software can be considered as such a disruption in existing commercial design practices. Consequently, change destabilizes existing practices and restabilization requires the ongoing integration of new and the adaptation of existing elements. Therefore, elements of practices are not only interdependent but also shape each other [314].

3 Research Design and Methodology

The empirical work in this thesis presents a *research into design* approach following Frayling's classification of design research [112] by utilizing both a *scientific design* lens as well as a *social practice theory* lens. To address the knowledge scarcity regarding professional design practices in XR interaction design through empirical investigation, this thesis utilizes a mix of predominantly qualitative methods. In four studies, the complexity of XR interaction design is approached from the following perspectives: a user-centered design case study in Section 5, two investigatory designer-centered studies in Section 6, 7, and a theory-practice focused study presented in 8. While Section 6 and 7 present studies conducted with professional XR designers working in XR software companies in North America and Europe, Section 8 tends towards a potential gap existing between research outcome and practitioners' needs. This combination of multiple perspectives allows a deeper understanding of interaction designers' challenges and increases the rigor and validity of the presented insights. Based on those, this thesis addresses the following two research questions in an explorative manner:

RQ1 What are interaction design practices and challenges in professional XR application development?

RQ2 What are design implications for XR prototyping tools based on professionals' XR interaction design practices?

The respective studies are presented in Part II of this thesis and contribute to answering those two research questions as follows (see Figure 3): Section 5 reports on a design case study of an XR application built in a collaborative research and design project for medical workers in a controlled hospital environment. It provides insights into collaborative design practices, prototyping processes, artifact evaluation, and impact of XR applications on users based on a user-centered design process. Further, it presents a sample design process for an XR application. Section 6 deepens the challenging aspects of professional XR design practices surfaced in Section 5 by focusing on professionals from the industry who collaborate on interdisciplinary teams. This section further provides insights into roles, tool usage, design challenges, and designers' counter measures as well as differences of interaction design approaches for 2D compared to 3D. Section 7 focuses on prototyping as an activity and prototypes as design artifacts to further investigate tool use, design practices, idea externalization, and design challenges in relation to a design goal and a project context. Finally, Section 8 turns towards a specific set of tools – design guidelines – to further investigate the lack of guidelines [11] highlighted in Section 1.1. Consequently, Section 5 predominantly contributes to RQ1 and Section 8 to RQ2. Sections 6 and 7 provide relevant information for both RQs.

Finally, to complete this section, the following paragraphs introduce the main research activities conducted over the course of this dissertation: *design case study* applied in the study presented in Section 5, *iterative literature review* as utilized in Section 8, *semi-structured interviews* conducted in both studies described in Section 6 and 7, and *artifact analysis* as utilized in the study presented in Section 7. Their exact implementation can be found in the respective publications detailed in Part II. Table 1 provides an overview of the conducted research activities.

3.1 Design Case Study

Design case studies are "an action research methodology" [370] framework that can be fruitfully applied to practice theory-based research [370, 371]. As such, design case studies support understanding the entanglements of social practices and design spaces for IT artifacts as well as their appropriation and respective change through usage of such artifacts after they have been rolled out [370].

According to Wulf et al., ideally, such studies consist of the three phases *empirical pre-study*, *technology design*, and *evaluation* [370]:

Empirical Pre-Study observes and analyzes the usage of existing tools and media to understand existing user practices and a potential

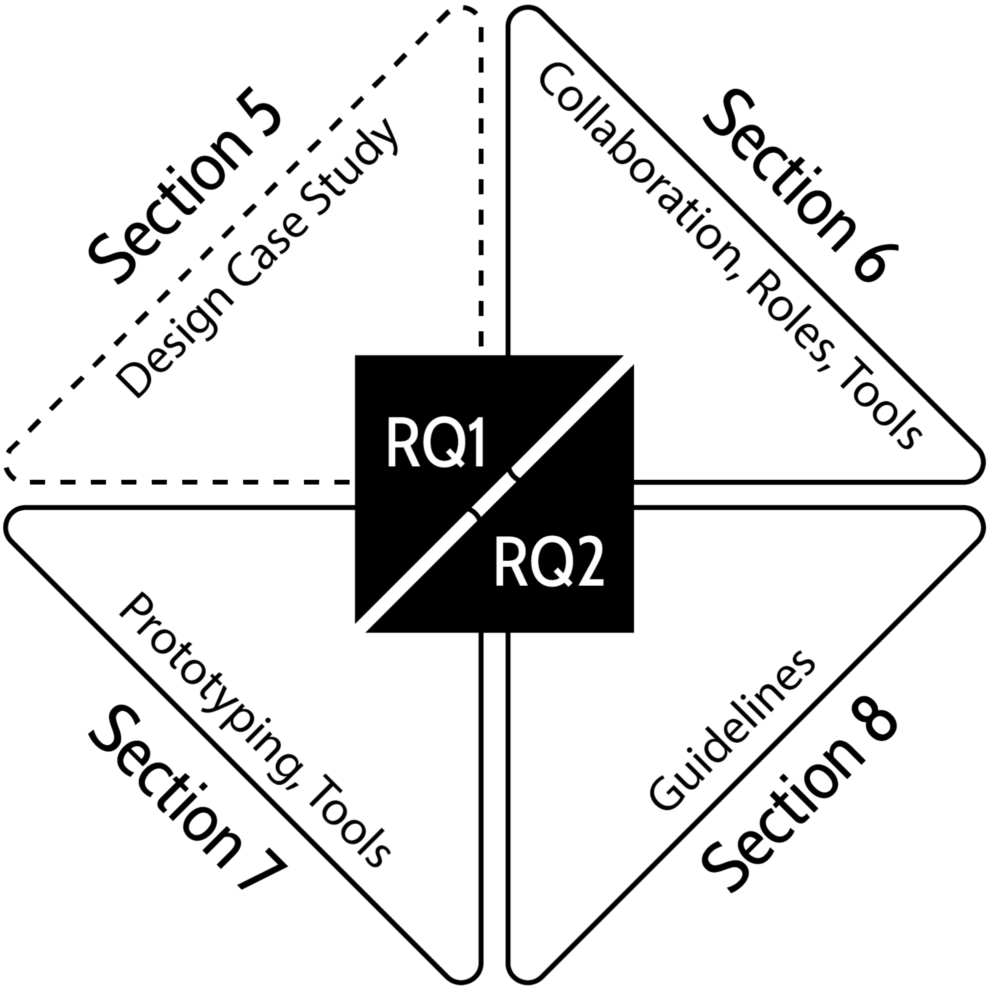

Figure 3
Relating research questions to thesis sections. While Section 6 and Section 7 add to both RQ1and RQ2, Section 5 predominantly relates to the former and Section 8 to the latter.

design space for to-be-designed IT artifacts. The emerging design problem, requirements, and user needs act as input for the technology design phase.

Technology Design focuses on transferring and refining the learnings from the empirical pre-study into IT artifacts through user involvement.

Evaluation takes place in real world scenarios and aims to test out an IT artifact in a praxiological context – ideally over a longer period of

Table 1
Details of the conducted research activities. Since Section 5 is a sumamry of a three years project, no further details regarding the applied methods are given in this section because it would go beyond the scope of this thesis.

Section	Name	Research Activities
5	Supporting Medical Auxiliary Work	*Empirical pre study:* 4 on-site observations 5 contextual semi-structured interviews with employees 1 focus group involving 12 stakeholder representatives *Technology design:* Interdisciplinary co-design sessions *Evaluation:* 12 semi-structured evaluation-interviews (paired with quantitative methods based on standardized questionnaires and an observational user study)
6	Current Practices, Challenges, and Design Implications	26 semi-structured retrospective interviews
7	Elements of XR Prototyping	17 semi-structured retrospective interviews artifact analysis based on 15 interviews and 26 project descriptions
8	Research and Practice Recommendations	literature review based on 89 scientific papers and 6 publications of XR hardware companies

> time. Consequently, users are asked to appropriate an IT artifact and incorporate it in their practices. This generates both insights about how adequate the artifact is for the intended design goal and space as well as how it impacts and shapes existing practices and vice versa.

Similar to the design process models previously described in Section 2.1.2, the phases of a design case study are not traversed linearly but iteratively.

The work presented in Section 5 describes the summary of a three years collaborative software design project and provides an overview of the design process, the applied methods and prototyping approaches, the final software artifact as well as interim and a final user evaluations. This reported project was conducted as a design practice research approach (i.e., activities performed by the researcher that are similar or identical with the activities performed by an interaction designer [104, 105]) and provided first-hand insights into design processes using XR technology. The overall project followed the user-centered design methodology as described in the ISO 9241:210 [159]. Nevertheless, in this thesis, the paper is discussed as a design case study. However, applied methods are only discussed on a surface level since incorporating and reflecting on the full range of this three-years project would be out of scope for this thesis. Consequently, no further methods like the applied standardized usability questionnaires are introduced in Section 3 for this study. However, Section 5 provides more insights and a deeper introduction of involved approaches and methods.

3.2 Semi-structured Interviews

Interviews are a well-known and frequently applied method in qualitative research [155] and “good for getting subjective reactions, opinions, and insights into how people reason about issues” [195] as well as “needs, practices, concerns, preferences, and attitudes” [199]. Interview studies are common practice in both general interaction design and specific XR interaction design research. For example, Goodman et al. [132] interviewed eight commercial interaction designers to gain insights into their practices. Also, Stolterman et al. conducted an interview study with nine interaction designers to learn about their tool relationship and usage [334]. Studies addressing XR specific interaction design topics are, for example, Ashtari et al.’s interview study with 21 XR creators [11] or Gandy et al.’s [123] insights when discussing their tool with eight former users.

While interviews offer great flexibility and opportunities to gain deep insights [199], a major drawback is the deviation of what people say compared to what they actually did based on what they remember [293]. This problem of recall originates from the timely and often also spatial separation of inquiry and performance [199] and can be accounted for by combining interviews with more situated techniques, such as observation [199] or artifact analysis (see Section 3.3).

In general, there are three different approaches to structuring interviews [199, 115]: *Fully structured* interviews follow a fixed order of questions arranged in a script. *Semi-structured* interviews allow to deviate from the script, providing an opportunity to ask for more detail and explanations of the participant's answers. Finally, *unstructured* interviews represent an extreme of gaining additional insights as the researcher is free to explore topics predominantly based on the interviewees' answers. Consequently, unstructured and semi-structured interviews foster a more exploratory and open-ended discussion, allowing for spontaneous responses and unexpected insights to emerge [199]. All three types have benefits and disadvantages. For example, following a strict guide and conducting structured interviews simplifies the evaluation due to the fixed order of questions and the expected topics and answers [199]. On the one hand, this structure limits exploration and the emergence of new and related topics of interest. On the other hand, having less or no structure to allow for more exploration lacks the consistency of having asked each interviewee the same questions and affords more resources for the analysis [199]. To ensure a high quality and consistency of collected data, semi-structured questions need to ensure that a specific set of topics is addressed with each interviewee to simply the analysis. In addition, they need to be formulated as openly as possible to enable deviations and further explorations of participants' answers [155].

As the work presented in this thesis requires an explorative approach due to several unknowns regarding interaction design practices in XR, semi-structured interviews were applied. To collect empirical data about work practices of professional creators in XR industry, this interview method is applied in the studies presented in Section 6 (26 interviews) and 7 (17 interviews). Insights of both studies address RQ1 as well as RQ2.

3.3 Artifact Analysis

The term artifact, in the context of this dissertation, is frequently used as a synonym for prototypes produced during the creation of (XR) software. The paper presented in Section 7 adapted a form of artifact analysis to learn about the purpose, creation, use, and materialization of prototypes as artifacts of design processes. In total, artifacts from 26 projects of 15 XR interaction designers from the industry were analyzed. The respective insights address both RQ1 and RQ2.

The analysis of artifacts considers artifacts as outcomes of human actions and sees their production and usage as interwoven with their respective social context [280].The core idea of artifact analysis according to Lueger and Froschauer is that each artifact that comes to existence opens up and closes opportunities, gains meaning, gets manipulated, and adds to society [220]. Usually, artifacts analysis is structured by applying a form of framework that might be either reapplied from related fields of research (see, e.g. [36]) or created on the spot to answer specific research questions [259]. Following Odom et al.'s argumentation, the outcomes of such an analysis are critical and theoretical in the sense of challenging the understanding of an artifact as well as offering the potential of asking new questions by "more precisely defin[ing] artifacts and their qualities" [259]. Lueger and Froschauer's concept of artifact analysis aims to answer four key questions [220]:

Why does an artifact exist? Artifact creation might happen on purpose or as a byproduct of human activity – the latter is also referred to as *traces*. To learn about an artifact's reason for existence, the analysis considers, for example, the artifact's utility or social ties – respectively, its materialization and social context. [220]

How do people create an artifact? According to Lueger and Froschauer, per definition, artifacts have to be constructed or produced. This renders them to be externalized and materialized objects of action in a respective context [220]. This question investigates how an artifact was produced or constructed, focusing on the production preconditions, required competencies and knowledge as well as coordination of activities [220].

What do people do with an artifact? This question addresses the appropriation, assignation of meaning, and integration of artifacts in daily practices and routines [220].

What does an artifact do with people and society? Finally, artifact anal-

> ysis investigates how artifacts support, influence, form and potentially change society and their users' behavior and intention [220].

In interaction design research, artifact analysis was used, e.g., to identify differences and similarities of terms and practices used across closely related design disciplines combined with an analysis of a designer's values incorporated in respective artifacts [36]. Further, Odom et al. applied an artifacts analysis approach in the context of learning about and defining slow technology (i.e., technology aiming at reflection rather than performance) in a research through design approach [259]. A less strict approach of analysing artifacts created during a design process was applied by Dow et al. [85], who investigated how designers of ubiquitous systems approach the challenge of lacking tool support.

3.4 Iterative Literature Review

"A literature review seeks to uncover the sources relevant to a topic under study and, thus, makes a vital contribution to the relevance and rigour of research" [356]. According to Cooper, literature reviews are grounded in primary or original (scientific) work and "describe, summarize, evaluate, clarify, and/or integrate" [63] respective content. Literature reviews are frequently conducted at the beginning of a research project, for example, to identify a research gap and further research questions or investigating the interpretation of research community concepts (e.g., Speicher et al. [325]). However, literature reviews can also be applied to summarize the published findings of a specific field to verify or falsify hypotheses about a research community or the body of published work, as it was applied in the work presented in Section 8.

In their work, vom Brocke et al. propose a framework for rigor literature search, analysis, and documentation [356]. This framework emphasizes the iterative characteristics of narrowing down a search process, or, as stated by Baker and cited by vom Brocke et al., the "circularity that exists when defining a topic and undertaking a literature review" [17]. The five proposed steps to be followed in an iterative manner by vom Brocke et al. are:

1. Definition of the review scope and flavor: As reviews can have different tonalities and purposes, vom Brocke et al. propose to draw on Cooper's taxonomy [63] consisting of 1) *focus*, e.g., research outcomes or theories, 2) *goal* in the sense of integration, criticism or central issues, 3) *organisation*, i.e., historical, conceptual, methodological, 4) *perspective* such as neutral representation or advocacy of a position, 5) *audience* in the regard of specialized or generalized scholars, practitioners/politicians or the general public, and 6) *coverage*, e.g., exhaustive, exhaustive and selective, representative, or central/pivotal [356].
2. Conceptualization of the topic: According to vom Brocke et al., definitions of key concepts and terms of interest should be provided based on existing literature and identified relevant items. Such definitions and terms can be identified and created, for example, based on concept mapping [356].
3. Literature search: Further, the search process includes relevant databases, respective querying based on keywords, search strategies like backwards and forward search, and continuous evaluation of the identified sources regarding quality and topic fit [356]. According to vom Brocke et al., it is generally advised to rely on peer-reviewed sources such as high-quality journals and conference proceedings [356].
4. Analysis and synthesis: Identified literature has to be analyzed and synthesized, for example, by using a concept matrix [356].
5. Resulting research agenda: The analysis and synthesis of identified literature finally leads to refining the research agenda and related research questions [356].

Finally, vom Brocke et al. emphasize that literature reviews require rigor also in documenting the single steps to allow fellow researchers to assess the validity of the presented insights against the given body of existing work as well as potentially extend it. In conclusion, a literature review does not have to assess and review all existing sources – it rather has to be clear and specific regarding search parameters and processes as well as inclusion and exclusion criteria [356].

The paper presented in Section 8 uses an iterative literature review approach to analyze the body of published design guidelines, design principles, and design heuristics for XR in both academia and industry based on vom Brocke et al.'s framework [356]. In the respective study, 89 scientific publications suggesting design guidelines as well as publications originating from six market leading XR hardware companies were analyzed following this methodology. The respective insights address RQ2.

Part II

Empirical Investigations of XR Interaction Design Practices

4 Introduction

The next four sections illustrate the research activities performed and outlined in Section 3 to address the research questions RQ1and RQ2.

This part predominantly utilizes the scientific design perspective described in Section 2.1 to analyze and report on interaction design practices as performed by professional XR creators. As such, Section 5 reports on a collaborative AR application development project conducted in five central sterile services departments. The focus lies on the design process as well as the final user evaluation of the created AR application. The remaining three sections directly connect to the related work set out in Section 2, specifically research conducted to investigate (XR) design approaches ([11, 123, 210, 132]), prototyping and prototypes ([215, 85], and design tools ([334, 244, 248]) and guidelines [355]).

Finally, the respective results are summarized in Section 9. The main contributions are insights into collaborative application creation practices, prototyping practices in XR as well as design implications for prototyping and design tool creation with a specific focus on design guidelines.

5 Supporting Medical Auxiliary Work: The Central Sterile Services Department as a Challenging Environment for Augmented Reality Applications

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Abstract

This paper reports on the central sterile services department (CSSD) as a potential new design space for future research in Human-Computer Interaction (HCI) and Augmented Reality (AR). Within the last 2 years, we explored processes, tools and user needs in this field to identify use cases with the capability of enhancing everyday work using AR head-mounted displays (HMD). The conducted research was focused on the potential of applying AR technology as a proof of concept in which 8 problem-driven use cases were identified. These use cases enable interesting aspects for future investigation and utilization of new technologies. In addition to that, this paper describes the insights into user groups, their tasks, challenges, and needs for work support in this specific domain. Furthermore, a sample application is introduced which demonstrates the possibilities of HMD-based AR in the CSSD.

5.1 Introduction

AR, as defined by Milgram and Kishino [236], describes the enhancement of the real-world environment through the addition of virtual information. In the medical field, this technology "takes its main motivation from the need of visualizing medical data and the patient within the same physical space" [316]. Whereas the majority of AR applications in medicine addresses surgery [55], the medical environment offers various other use cases focusing for example on medical staff and their daily working environment which should not be neglected. Such support, be it training, education or logistics, can be a valuable aid for health personnel in complex areas outside the operating room. One of the often invisible areas of demanding medical work, is being conducted in the CSSD, where used operational tools and implants are being washed, disinfected, packed, sterilized and stored for future reuse. The CSSD is part of the low-wage sector, including employees who often work in three-shift systems with a focus on late and night shifts. Organizationally, the CSSD is anchored between the surgical department of both hospitals and private medical practices, and the storage department in which operational instruments are placed into stock.

In the project smartZSVA [163], we investigated in application scenarios and use cases in which workers of the CSSD can be supported with the help of HMD-based AR in order to enhance their current working situations as well as reduce the health-risk for patients. Following a user-centered design (UCD) approach, we conducted on-site observations paired with contextual interviews and discovered 3 major challenges also supported by Brooks et al. [47] and Alfred et al. [3]:

First, the lack of the visibility and acknowledgment of the department and the workers causes an underrepresentation in innovation activities carried out by research and modernization projects in those facilities, which in return results in a lack of appropriate tools for workers in the CSSD. The current work place design around touch-based interaction, stationary information displays and hand-operated input devices requires multiple attention shifts between the task and supportive displayed information or input devices, which provokes untrained employees to lose their context and make mistakes.

Second, the CSSD is a highly controlled and physically demanding environment. The need to comply to specific safety rules and legal regulations require staff members to wear safety gear to protect against sharp tools and potentially infectious material as well as minimizing the risk of recontamination of disinfected and sterilized instruments. Machinery used for washing, disinfecting and sterilizing operational tools exposes employees to high levels of noise and humidity. This does not only result in mental and physical exertion of workers, it also challenges supportive software and hardware regarding noise levels, light reflections, safety regulations and reliability. The basic prerequisite demands that surfaces, devices and tools can be disinfected simply by wiping them down. In addition, medical workspaces, products and services have to comply with legal requirements and specifications of standards, such as the ISO 13485 [162].

Third, the demand of training and process support is high due to frequent fluctuation in personnel and the complexity and amount of handled tools and sets combined with often changing working instructions. As a result, all CSSD employees need to be continuously trained on the job regardless their experience. In the following sections, our UCD approach in investigating the CSSD with the aim of supporting workers with AR is set out. With the above in mind, we identified 8 use cases reported in Section 5.3.2 that describe how workers and the overall CSSD department can benefit from AR-based support. For the evaluation of use cases described in Section 5.4, we implemented an AR prototype detailed in Section 5.4.1 and conducted an on-site user study described in Section 5.4.2. Finally, we discuss our approach and present future work in Section 5.5.

5.2 Related Work

Compared to other clinical topics, the CSSD is a “neglected area of infection control systems of a hospital” [19], even though it plays an important role in the overall process. The main focus on conducted research in this domain lies on quality assurance, enhancement (e.g. [20, 362, 32]) and error prevention through instrument tracking [91, 380]. In their study focusing on describing the CSSD and revealing factors that impact the performance of staff members, Brooks et al. [47] involved 22 employees from 12 hospitals. Their data revealed 4 key factors that have a direct impact on the CSSD’s work quality [47]: (1) Role and visibility within the hospital, (2) relationships and communication with operating room staff, (3) staffing and management, and (4) technical problems and solutions.

This indicates that supportive tools and processes should be designed in an all-embracing way and also keep the overall organizational structure in mind. Alfred et al. performed a work-system analysis in a 700-bed academic hospital [3] with the goal of identifying factors that affect the quality of the CSSD employees’ performance. They point out that patients’ and staff members’ safety “requires improved design of instruments and the decontamination area, skilled staff, proper equipment maintenance and effective coordination of reprocessing tasks” [3]. Further challenges are introduced by the working environment and the task's nature itself: besides challenging working conditions regarding noise, temperature and humidity [141], the amount of individual surgical instrument types available in a large hospital might get up to 250,000 [3]. It is highly unlikely that even skilled and experienced employees can remember the required steps for each tool during the sterilization and repacking process [3, 141].

In their work, Ruether et al. [292] describe a support system for workers in the decontamination area. The tool was designed to decrease the errors during the preparation of instruments before the actual cleaning. The projection-based interface empowers the user to request further information for a tool using its RFID tag. If the user scans the tag, the system can provide additional disassembly information, issue reporting functions, or reclamation features for example. Aside from that, related work focusing on AR-based employee support in the CSSD is scarce.

The absence of related work investigating in AR in the CSSD might be due to the fact that the overall topics addressed in this context are similar to those from other domains, such as training of inexperienced employees or logistic use-cases involving picking and packing tasks in hospitals (see [18, 278, 254]) or industry (for example depicted in [126, 308, 361]). There, the potential of HMD-based AR has already been demonstrated. However, even though the use cases are closely related, the application domain differs mainly regarding domain-specific regulations, organizational structure, visibility for other domains, and limitations for technology and interaction techniques. Therefore, further investigation is required.

5.3 Contextual Analysis and Development of the Use Cases

With our research, we aimed to identify true pain points of employees in the CSSD. For this sake, we followed an iterative UCD approach, as defined by the ISO 9241-210 [159], with the goal to involve end-users as early as possible to minimize timely and costly correctional efforts. The iterative UCD process model consists of the following 4 steps (1) contextual analysis with the goal to identify user groups, tools, processes, pain points and tasks, (2) development of user requirements, (3) development of prototypical solutions, and (4) evaluation and test of potential solutions.

Our UCD approach can be split in 3 major phases: Phase 1 consists of a contextual analysis and the evaluation of identified working processes, user groups and roles, pain points and applications in use in addition to potentially new use cases introduced by HMDs and AR. It also results in the formulation of the use cases presented in Section 5.3.2. Phase 2 focuses on the formulation of user stories and the development of initial solution concepts for the identified use cases and is detailed in Section 5.4. Phase 3 consists of the iterative implementation and refinement of the AR prototype in Section 5.4.1 as well as an on-site field study for evaluation described in Section 5.4.2. Table 2 gives a brief overview of methods applied in which phase of our UCD process and who was involved as a user or expert of certain domains.

For Phase 1, we conducted 4 on-site observations paired with semi-structured contextual interviews with 5 employees from the CSSD following the DAkkS usability interview guideline [78] to get familiar with the CSSD, tools, processes, goals, organizational structures, working procedures, problems and pain points. In a follow-up focus group, we involved in total 12 stakeholders to get additional insights in the CSSD and discuss the potential of HMD-based AR support. The group consisted of representatives of the identified user groups in the CSSD detailed in Section 5.3.1 (department managers, educators, shift supervisors and workers), manufacturers of medical devices and storage systems, as well as software providers of in-use applications. Based on our observations and findings of Phase 1, we developed the use cases detailed in Section 5.3.2 and documented user roles, tasks and working processes described in Section 5.3.1.

Table 2
The methods applied during our research regarding our UCD process phase explained in 5.3, the general UCD process steps as defined by [159], involved users and experts plus data types; abbreviations for the UCD process steps: C = contextual analysis, R = requirements / user stories, D = design, E = evaluation; abbreviations for the user groups: U = employees in the CSSD as presented in Section 5.3.1, X = domain experts of the CSSD, such as software and machinery providers, P = usability professionals; abbreviations for the data type: quant = quantitative, qual = qualitative

Method	Phase	UCD Process Step	User Group	Data Type
Participatory Observation	1	C	U	qual
Semi-structured Interviews	1, 3	C, E	U, X	qual
Focus Groups	1, 2	C, R	U, X	qual
Storyboards	2	R, D, E	X	qual
Use Cases	1, 2	R, D, E	X	qual
Paper Prototyping	2, 3	D, E	P	qual
Digital Mockups	2, 3	D, E	P	qual
Wizard-of-Oz	2	D, E	U, X	qual
Expert Evaluation	1, 2, 3	E	X, P	qual
Think-Aloud	2, 3	E	U	qual
ErgoNorm	2	E	U	qual
SUS	3	E	U	quant
SEQ	3	E	U	quant
UEQ	3	E	U	quant

5.3.1 User Groups and Their Roles in the CSSD

We investigated 5 German CSSDs varying in size with a range from 1,400 beds to small limited liability companies to understand the tasks and roles of the CSSD department. The overall process in a CSSD can be summarized as follows:

Reusable contaminated surgical instruments and implants are reprocessed in the CSSD after being used on patients. As a crucial department in terms of hygiene and safety [59], the CSSD reprocesses contaminated surgical instruments and implants after their application and consists of 2 strictly physical separated sections: the decontamination area and the sterilization area. The general processes in a CSSD are described as follows and depicted in Fig. 4:

In the decontamination area, used tools are delivered, unpacked, roughly washed, disassembled, and placed on instrument trays. In-

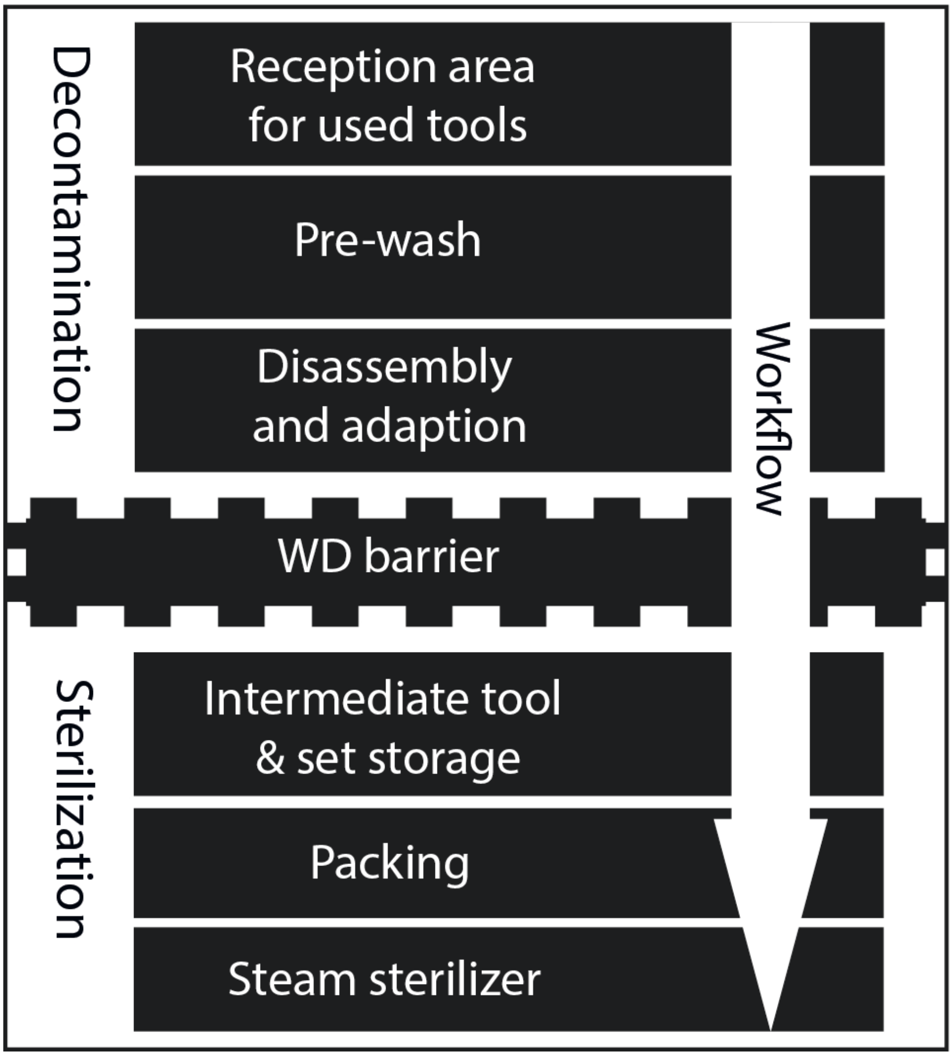

Figure 4
A schematic visualization of the CSSD department.

struments with hollow bodies have to be placed correctly on specific adapters for proper cleaning. After that, the trays are collected on stock carts and pushed into washer-disinfector appliances (WD). The WDs also function as a gate between the decontamination and the sterilization area. Since they can be accessed from both sides, carts are pushed in from the decontamination side, disinfected, dried, and pulled out from the side of the sterilization area. After an inspection, if any contaminated tools remain, the whole batch has to be washed again. Defective tools are replaced, clean tools are either stored away or directly reassembled, sorted, maintained and repacked according to detailed inventory lists. While some tools are packed individually, others are bundled according to packing lists in sets as depicted in Fig. 5. If a tool is missing or irreplaceable, the set has to be marked accordingly. After the packing process has been completed, the trays are collected on a stock cart and pushed in the steam sterilizer before being placed in stock or reused directly.

In the overall process, we observed 4 different roles regarding tasks and responsibilities. It is common that a single person fulfills multiple roles:

Department manager: leads and manages the CSSD, consultant for staff, implements and tracks the quality management, mediates between the CSSD and other departments.

Educator: supports and guides new and inexperienced workers, trains them on sets, machinery and process steps, ensures their proper qualification on the job.

Shift supervisor: deploys and supervises staff, troubleshoots in case of technical or work-related questions, mediator between workers and department managers.

Worker: personnel whose expertise ranges from inexperienced or untrained to highly skilled; tasks are unpacking and pre-washing used surgical tools and implants, deconstructing instruments, sorting goods into WDs, quality and functional inspection of tools and machinery, packing tools, updating and maintaining inventory and packing lists, sterilizing packed tools and sets, as well as reporting quality issues.

5.3.2 Identified Use Case Scenarios

Based on the previously detailed contextual analysis, we identified 8 use cases which can benefit from HMD-based AR support. Those use cases mainly focus on workers and educators, but also implicitly involve

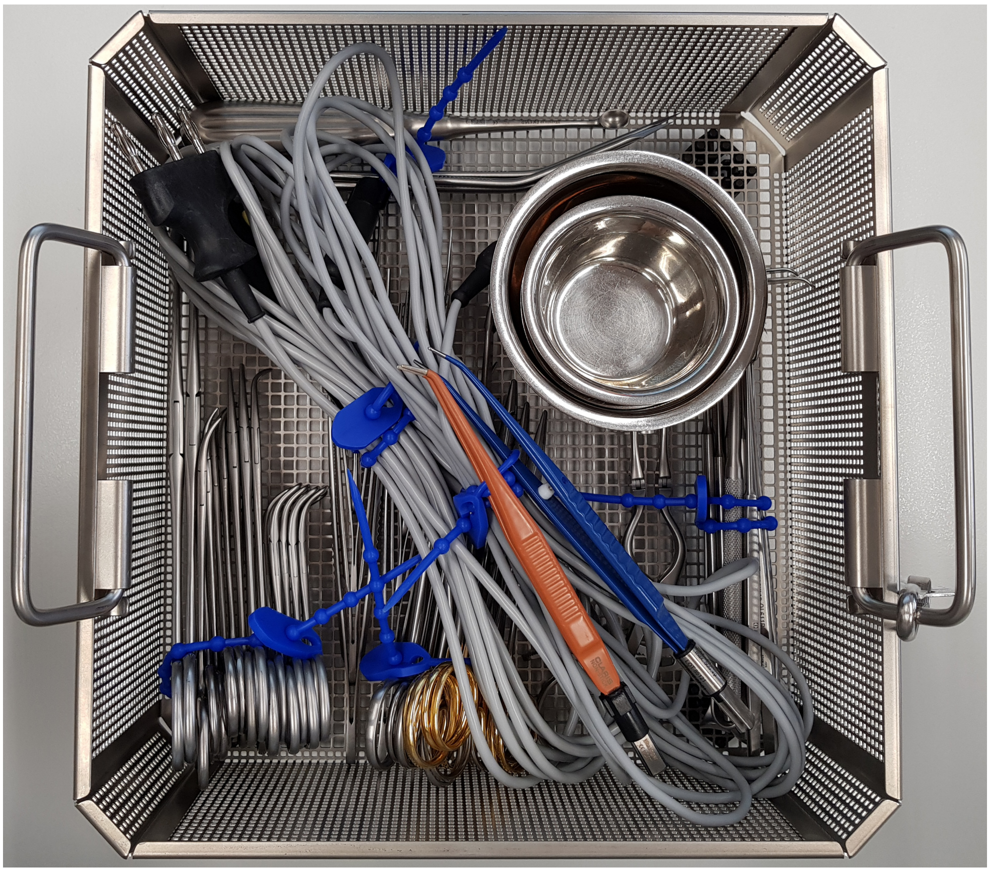

Figure 5
A simple sample set for treating wounds containing approximately 80 tools with low complexity. Complex sets might contain more than 100 intricate instruments

department managers and shift supervisors. Context analysis found that workers often need to handle multiple instruments and tools at the same time. Furthermore, the room for placing mobile devices is scarce due to strict hygiene and safety regulations in addition to a shortage of space. Future application solutions should therefore support hands-free interaction and wearable devices.

5.3.3 Storage Logistics

If an item for a set is missing, defective or can not be identified, the replacement instrument must be collected from a designated storage unit. Depending on the CSSD, these instruments can be stored in automated rotomats or regular shelves. Getting the correct instrument often requires manual work from the worker's side and is prone to errors: storage locations are spread over the CSSD and might be changed or relocated dynamically. Additionally, identifying the correct tool is challenging due to their similarity or washed-out alpha-numeric serial numbers. Finally, serial numbers often have to be written down before accessing the storage space due to a lack of on-demand displays. HMD-based and hands-free AR applications can support workers with way-finding, locating storage, tool identification and context-aware on-demand information presentation.

5.3.4 Training Content and Procedures

Working in a CSSD requires continuous training: working and hygiene instructions are always changing, the staff turnover rate as well as the complexity and variety of handled instruments are high. HMD-based AR can improve the education process by supporting the recording and playback of trainings and working procedures. Processes and handling instructions can be digitized by the educators and merged into decent spatial step-by-step guides for workers. In some cases, it could be beneficial to overlay the physical version of a tool with a virtual counterpart and highlight specific areas or handling steps. Employees later can call up these training materials via headsets or alternative devices allowing for hands-free interaction without the need for attention shifts and head rotations.

5.3.5 Packing Sets and Tools

After the cleaning process, instruments are packed and passed to the sterilization. The packing process is described in hierarchical lists on the screens at the packing station PCs or tablets with the required information and sample pictures. Usually, the instruction displays are mounted on a head-up position to keep the table free for tools and sets. This positioning requires the workers to constantly switch their view point and leads to losing the focus on the current task. Additionally, required system input cannot be provided in a hands-free manner. Using HMDs during the packing process has the potential to create a more ergonomic design for the workplace with less attention shifts and hands-free interaction. By overlaying the physical set with a digital to-be status, the possibility of skipping instruments and errors due to misplacement or forgotten tools can be decreased.

5.3.6 Remote Assistance

Workers sometimes encounter unknown process steps, unfamiliar tools or unusual signs of aging and seek for advice from more experienced colleagues. Currently, these issues are solved with face-to-face communication which requires a change of clothes and disinfection procedure if the consulted person is not present in the CSDD. HMD-based AR could improve this experience with a video chat or remote assistance function and overlaid step-by-step instructions with annotations provided by the consultant.

5.3.7 Traceability and Location-Independent Information Display of Sets and Tools

It is essential to have a continuous documentation of the process steps that have been carried out on the medical instruments for quality assurance and traceability in case of machinery failure or complaints. Additionally, some tools have an expiration date or a fixed amount of reprocessing cycles before they have to be scrapped. Right now, retrieving those instruments and sets is manual labor which is often limited to the fixed packing places. Besides those places often being in-use for packing sets, there are multiple areas in which tools are already being checked and could be sorted out if the respective information was available, for example while stocking storage shelves. The overall process could be eased with dedicated HMD-based AR interfaces that allow for the location-independent and hands-free retrieval of information about sets and tools.

5.3.8 Logging of Routine Controls

The cleanliness of the machinery and the environment is critical for fulfilling the quality management and hygiene goals and rules of actions in a CSSD. Therefore, the environment needs to be highly controlled regarding inspection, maintenance, and cleaning cycles of machinery and equipment in addition to continuous logging of performed actions bound to fixed plans. Often during inspections, the worker has to switch locations to access the maintenance information and document the process. In this case, HMDs free the worker's hands and provides more flexibility concerning tools to be used in the maintenance process. By displaying context- and location-aware information using HMD-based AR, control instructions can directly be fitted to the worker's location and context. Workers can be directed to machines that have not been controlled yet. In case of damaged or contaminated equipment, log files can be created based on the location combined with a description via speech input and graphic material like photographs or videos taken with the HMD. Workers from subsequent shifts can then be presented with the latest maintenance protocols on the machinery itself which eases the detection of additional damage or necessary maintenance steps.

5.3.9 Assembling and Adapting Tools

Tools with hollow bodies, tubes or cannulas have to be disassembled and put on specific adapters in order to be properly disinfected. If this process is not done accurately, infectious material might remain on the surgical tools and contaminate a whole batch, which might lead to a critical delay in the tool processing plan or the deformation of specialized and expensive instruments. This work is done in the decontamination area in a CSSD, where workers have to wear protective gear which hinders accessing information using desktop PCs and tablets. Workers could benefit from HMD-based AR which supports hands-free interaction for accessing additional information and presents the correct disassemble instructions paired with suggesting fitting adapters. Besides being hands-free, to handle tools, parts and fitting adapters, spatial displays have another advantage: they enable users to access the information needed ad hoc.

5.3.10 Alerts and Status Notifications

In a CSSD, machinery and equipment is spatially distributed over large areas that are often occluded by staff, carts, walls and shelves. Accessing information like the current status of the arrival area for contaminated sets and tools is often not possible without being present in the respective location. Additionally, there are several situations in the CSSD that require immediate attention, such as the arrival of high priority sets which might remain undetected. Hereby, HMDs could be useful for seamlessly integrating status updates from machinery or remote information access into a worker's information display for other cases previously listed without needing an additional device.

5.4 Evaluating Use Cases With an AR Prototype for HMDs

In Phase 2 of our UCD process, we let domain experts and department managers select the use cases which promised the most improvement for the identified pain points in the observed CSSDs. Table 2 presents an overview of the applied methods plus the collected data throughout the design process in Phase 2. Based on focus groups in which we discussed first design concepts depicted as story boards and flow diagrams with domain experts, we decided to create a training application for evaluating the use cases 5.3.3, 5.3.4, and 5.3.5. Since we prepared for agile SCRUM-based [310] development cycles which would fit the UCD process model, we documented requirements elicited from the use case descriptions as user stories following the template *[unique ID] As a [role], I want [feature] in order to [reason]* [277], for instance:

SZ-29 *As a worker, I want to know the exact location of exchange instruments in stock in order to safe search time (efficiency).*

In total, we documented 22 user stories and clustered them in fields of interests, for example privacy and security or efficiency. These user stories were further broken down to features that could be designed and implemented. Depending on the fidelity stage of the developed prototypes, different methods of visualizing and testing were applied. In the early stages of the design, we relied on paper-based sketches and interaction flow diagrams. We did switch to digital mockups only after the basic design concepts were sorted out. The early prototypes were tested with usability experts and domain experts to get rid of major interaction flaws and potential errors in the envisioned working process.

5.4.1 Resulting AR Prototype

Phase 3 of our UCD process focused on the implementation of the AR prototype and an in-field evaluation study with workers from the CSSD. The main features of the developed AR prototype are depicted in Fig. 6, which were previously presented in [187]. The AR prototype is developed for the Microsoft HoloLens 1st generation. Our iterative development process was based on the user stories defined in Phase 2 of our UCD process. When the prototypes reached a sufficient level of interactivity, we informally evaluated them with usability and domain experts as presented in Table 2, by letting them try out and comment on the application.

The AR prototype is a proof of concept for investigating the suitability of our use cases listed in Section 5.3.2. It enables workers to identify sets, access set information, and initiate the packing process. If needed, workers can let themselves guide to stock locations in addition to interrupting the packing process at any time.

For development, we worked with Unity 2017.4 [351] and Visual Studio 2017 Pro. We also applied the Mixed Reality Toolkit [234] to realize user interactions. For identifying sets, we used customized image-markers resembling the in-use barcodes from the CSSD which were handled by the Vuforia library [357], whereas QR-codes used on staff badges for employee identification were interpreted with the open source library ZXing [382].

Context-relevant information about operational sets is prompted directly over the set. Fig. 6 further depicts and explains the displayed information during the packing process. There are 3 different information groups: the set information which is fixed to the set, and the packing information which can either be pinned to a fixed location or set to a tag-along behavior following the worker's position and head rotation. Additionally, location-based information is being displayed during the storage location use case, such as navigation paths or the physical location of tools in stock. An admin interface allows us to specify these positions in various locations, which enables us to test in facilities with different spatial features. We have not integrated the application with existing systems and used locally stored JSON files based on realistic data to simulate a backend. The AR prototype also features

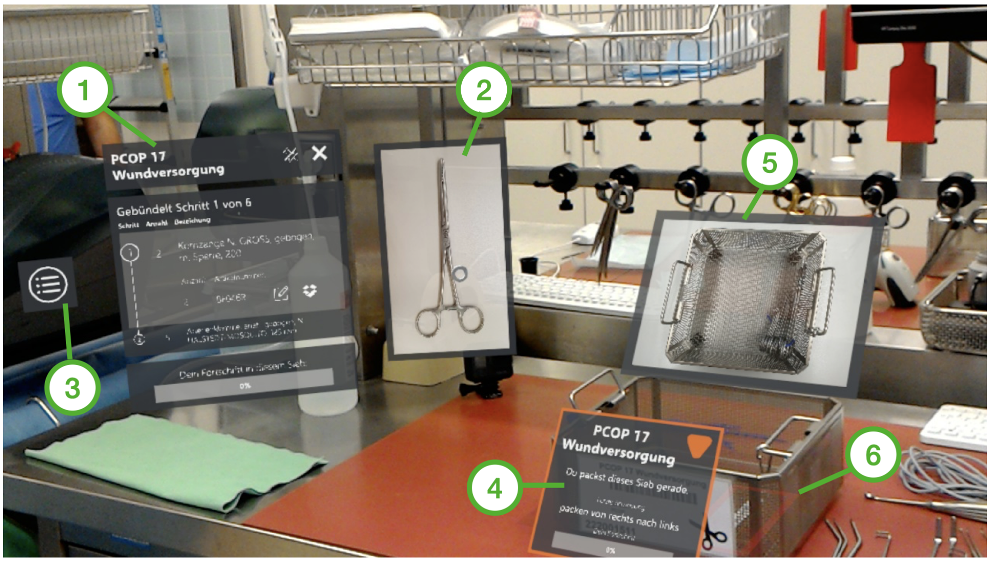

Figure 6

The AR prototype currently displaying information required for the packing process. (1): the current step the user needs to carry out (2): picture of the current tool to be packed (3): switch between the complete list and the current step (4): set identification and current state definition (5): example picture of the next state of the set after the current packing step has been completed (6): representation of where the instrument should be packed.

5 main interaction methods used for different purposes:

Speech input: activation of the admin interface; speech input is not applicable for worker related tasks due to the high noise levels in CSSDs.

Bi-directional foot switch: operating the packing list with hands-free interaction.

Air tap gesture by HoloLens: operating the remaining interfaces; also excessively used in tasks where the user's attention is required (e.g. confirmation of critical steps).

Position-based information: displaying contextual relevant information and cues when the user leaves the packing space.

Image detection: identification of operational sets.

5.4.2 User Study

We evaluated the AR prototype described in Section 5.4.1 with department managers, shift supervisors, workers and educators. Since department managers tried out the applications during pitches and project presentations, their feedback was not formally evaluated or recorded. However, we received positive comments rating the application itself as being useful and applicable. Some criticisms from department managers however, were regarding physical strain, privacy, hardware costs, hygiene, and battery lifetime.

5.4.3 Study Procedure

In our formal study, 12 workers (4f, 8m, $M = 42$ years, $SD = 11.6$) from 2 different German facilities tested our application in an on-premise think-aloud evaluation. The recruitment process was supported by the department and shift managers of facilities involved in the smartZSVA

[163] project. We had no preconditions for attendance except that participants have to fulfill the role of workers in a CSSD. Workers willing to participate were employed in the CSSD for at least a month (mean = 6.4 years). Inexperienced workers were insecure about the test situation and therefore decided not to participate. The set used for testing depicted in Fig. 5 came from a third facility and was unknown to all participants. For the study, we were introduced to the staff members and were allowed to experience up to 2 full days of CSSD work over different shifts. Since we tested on-premise, study participants interrupted their daily work for the duration of our experiment which was around 1.5 hours, whereas their colleagues continued with their current tasks. We recorded each participant using 2 GoPro cameras from different angles and the HMD's video feed.

The study procedure was as follows: at first, we asked participants to fill a survey to assess their expertise in the CSSD and their frequency of using PCs, tablets or smartphones. Then, we let them rate their currently used packing software with the System Usability Scale (SUS) [45] to create a baseline with pragmatic scales to compare our prototype. Since none of the workers were familiar with AR and the HoloLens, we included a gesture training sequence on the HMD. After that, we presented a walk-through tutorial based on printed out screens where we explained the AR prototype's main features and how to handle virtual buttons and the foot switch. The names of the distributed screen components were also explained to ensure that participants can relate interface fragments to the task descriptions. We then introduced the think-aloud method and handed them a staff badge to authenticate and log into the application.
In order to validate the software application and the appropriateness regarding the 3 selected use cases, we presented the participants a realistic introduction scenario resembling their daily work routine. We then clarified remaining questions and ensured the correct positioning of the HMD before presenting the 9 tasks:

1. Authenticate and log into the application using the staff badge.

2. Access the general set information and decide if you are authorized to pack the set and carry it to your packing station.
3. Arrange your packing station according to your needs (foot switch and application windows), prepare for packing.
4. Follow the packing instructions and mark missing tools until you reach list position 6.
5. Collect missing tools from the correct storage location (missing tools are in stock).
6. Continue the packing process and place the tools in the set.
7. Collect missing tools from the correct storage location (missing tools are absent from stock).
8. Correct the inventory on the packing list and finish the current packing block.
9. Finish packing the set and transport it to the steam sterilizer.

We used the Single Ease Question (SEQ) [297] after each task to assess the perceived task difficulty on a likert-scale with a range from 1 (very difficult) to 7 (very easy). We always discussed the reasoning behind the rating to understand the participants' motives and filter out bias introduced by the HMD. After all 9 tasks were completed, we asked the participants to assess the AR prototype using the SUS for direct comparison of the pragmatic scales with currently used packing software, and the User Experience Questionnaire (UEQ) [194, 306, 364, 365] for measuring hedonic aspects. After the completion of the SUS and the UEQ, we questioned the participants in a one-to-one semi-structured interview about insights in how they perceived the application. We specifically addressed the relevance of the prototype for their day-to-day work and if they could envision themselves using the application in the presented use cases. Table 2 summarizes the applied methods for the Phase 3 evaluation described above.

5.4.4 Results

We focused on collecting and evaluating qualitative data since we were mainly interested in the relevance of AR in the presented use cases. However, we originally intended to include a baseline for pragmatic scales using the SUS in order to be able to compare our AR prototype with currently in-use software regarding its usability. Nevertheless, we left out the SUS score benchmark because the ratings for our AR prototype were too positively biased and the results were therefore not meaningful.

We experienced negative bias due to the usability and user experience issues introduced by the HMD, for instance the limited field of view, weight, heat, reflections or pressure on the bridge of the nose. Overall, we got extremely positive feedback about the application itself. Based on the SEQ ratings ranging from 5.5 to 7 (median), the tasks were perceived as being at least more or less easy. Only few users were confused about when to use the input gesture or the foot switch due to missing or overlooked cues and unfamiliarity with the interface. However, every participant completed all tasks.

The UEQ ratings used to evaluate hedonic aspects also presented in Fig. 7 show unusually high ratings in all 6 categories. We used the UEQ benchmark tool [305] for evaluating our UEQ scores. According to Schrepp [305], it is unlikely to score above 2 (+3 relates to extremely good) or below -2 (-3 relates to extremely bad). However, our scores are above average in all 6 dimensions, which leads to the conclusion that our UEQ evaluation was positively biased, also in comparison to the UEQ benchmark depicted in Fig. 8. We scored in the top 10% of the benchmarked products, except for perspicuity.

Discussions with participants and the closing semi-structured interviews pointed towards a positive bias due to the novelty of the technology and the experienced fun, especially during way finding tasks. It might also be true that the implemented scenario and the used test set was too easy to point the workers to difficulties in the envisioned use case,

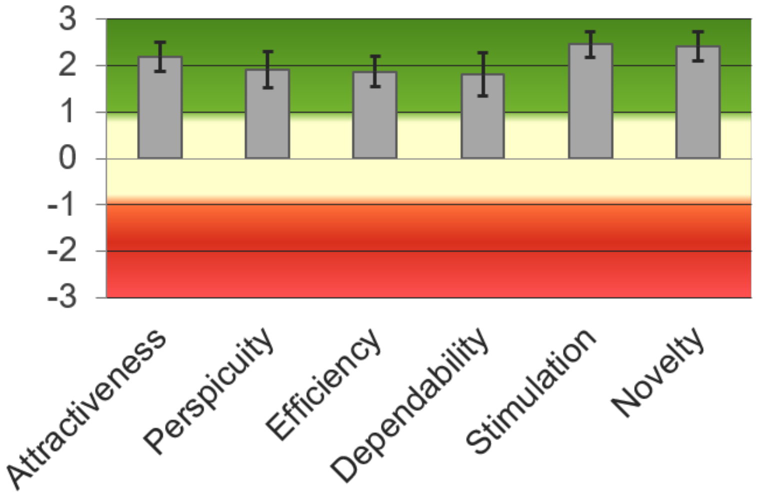

Figure 7
UEQ result for the AR prototype regarding attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. Error bars represent the 95% confidence intervals, N = 12.

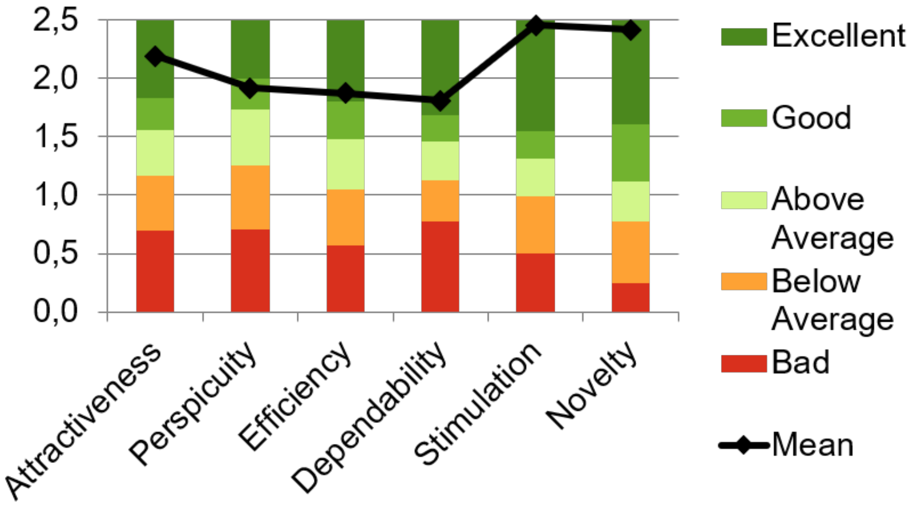

Figure 8
Exceptionally high UEQ benchmark results for our application. The benchmark is calculated based on data from 401 studies of various products and in total 18483 participants [305]

which explains the very positive ratings for the SUS, the SEQ and the UEQ.

In the closing interviews, we asked our participants about the applicability of our prototype for their daily work. Besides the overall very positive feedback, workers criticized that their working speed was slowed down. Others perceived this slow-down as a positive feature for ensuring the correctness of every process step. Also, positively mentioned were the overlaid positioning information, the tool sample pictures, and the required explicit confirmation for each packing step. However, they were missing some information concerning maintenance procedures. Finally, they could imagine this prototype being used to train inexperienced staff as an addition to already existing procedures. Some also mentioned that “this might be useful when [they] encounter a set [they] have not packed in a while”. The participants especially liked the navigation feature and rated it positively for CSSDs that are complicated regarding their spatial construction and stocking scenarios. Participants even came up with additional scenarios outside the CSSD where an HMD-based AR application could be useful, for example, during the preparation for operations.

Nevertheless, the participants were critical about the HMD concerning their privacy, autonomy and occupational status. They often asked if the department manager could “hack on the glasses and see what [they were] doing”. One mentioned that she does “not want to become a remote-controlled robot” who does not know how to think on her own behalf. Others addressed a potential decline of relevance for their job because “everyone could pack a set with such a pair of glasses”. Furthermore, they felt isolated because the HMD caused them to “be more focused on [their] task where [they] would normally joke and socially engage with [their] colleagues”. They compared the glasses with horse blinders, which they rated on the one hand as being positive concerning focus and the quality of the results, but on the other hand as being concerning regarding their social status and comfort.

5.5 Discussion

We reported on 8 use case scenarios in the CSSD which we documented based on a UCD approach involving both stakeholders and workers from the CSSD. In a study with an AR prototype that presented 3 use cases, we were able to demonstrate the potential of AR in the CSSD, even though we could not test with inexperienced workers. We aimed to filter out negative bias introduced by the inappropriateness of the HMD since we were interested in the usefulness of AR as such. While excluding the HMD as a potential source of negative bias is arguable, it was not our intention to conduct an evaluation of the ergonomics of the HoloLens. In addition, we do see the HMD as an exchangeable tool, while the concepts and workflows can be reused in future applications. Despite us testing on-premise and with actual workers from the CSSD, our results were not reliable and can be enhanced by conducting a long-term study to reduce bias caused by the novelty of technology unknown to the user group. We also recommend for future on-premise studies to consider long-term studies to receive meaningful results, regardless the domain. Additionally, the impact of introducing new technology might have on the daily routines and social interaction should be part of future evaluations. During our investigation, we encountered both support from workers who were interested and amazed by the potential of AR as well as rejection and statements of fear. We also learned that wearing an HMD affected the way of interacting with colleagues. Workers reported to be more focused on the task and be too immersed in their work which lead them to feel left-out and ignored by colleagues. This could also be part of future investigations.

Finally, we see that the CSSD can benefit from well-developed AR applications and offers many challenges for future hardware development in the medical field.

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6 Current Practices, Challenges, and Design Implications for Collaborative AR/VR Application Development

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Abstract

Augmented/Virtual Reality (AR/VR) is still a fragmented space to design for due to the rapidly evolving hardware, the interdisciplinarity of teams, and a lack of standards and best practices. We interviewed 26 professional AR/VR designers and developers to shed light on their tasks, approaches, tools, and challenges. Based on their work and the artifacts they generated, we found that AR/VR application creators fulfill four roles: concept developers, interaction designers, content authors, and technical developers. One person often incorporates multiple roles and faces a variety of challenges during the design process from the initial contextual analysis to the deployment. From analysis of their tool sets, methods, and artifacts, we describe critical key challenges. Finally, we discuss the importance of prototyping for the communication in AR/VR development teams and highlight design implications for future tools to create a more usable AR/VR tool chain.

6.1 Introduction

When Gartner removed AR and VR from its Hype Cycle for Emerging Technologies in 2019 [342], they indicated that the technology as such has reached a mature state. In fact, the market is evolving rapidly around consumer adoption as well as software and hardware [263]. In contrast, literature in science and practice understands AR/VR as an emerging technology with a variety of challenges [79] still requiring significant technical skill and knowledge, and is therefore difficult to be adopted for low-tech creators like artists and designers [27] but also for professional developers. Current research in HCI is focused on lowering the entry hurdles for non-technicians by demanding and providing authoring tools that require less to no coding skills [11, 248, 328, 205]. However, little is known about the situation for experienced professionals in this field, who have to face a melting pot of various disciplines, skills, motivations, and platforms which results in a fragmented environment of vocabulary, tools, methods, and approaches [34]. We contribute to the stream of research on AR/VR authoring tools by investigating how professional teams approach the challenge of AR/VR application creation, and how they make use of artifacts, tools and methods in their collaborative work.

In this paper, we report on the findings from our semi-structured interview study conducted with 26 professionals from the field of AR/VR application development. We aimed to recruit experienced creators with varying backgrounds and skill sets to gain broad insights into the current approaches and challenges faced by professional AR/VR application creators. We interviewed software developers, managers, Design Thinking practitioners, and user interface (UI) designers who create applications for diverse domains to gain a better overview of the current situation in practice. We specifically concentrated on the collaborative character of this interdisciplinary field: Based on the tasks and goals reported in our interviews, we condensed the 4 roles into (1) *Concept Developer*, (2) *Interaction Designer*, (3) *Content Author*, and (4) *Technical Developer*. Even though a single person often incorporates multiple roles, their created artefacts are distinct since they serve differing goals in this collaborative environment.

The workforce diversity of the development teams with regard to their skill sets and backgrounds is both a challenge and a benefit. In addition to pointing out a lack of standards, best practices, and tools combined with rapidly changing hardware and software platforms, the majority of participants voiced issues regarding a “missing common language”. This, they argue, is required for collaboration in the sense of coordination and workflow with interdisciplinary team members and inexperienced end-users / customers. Therefore, they aim to rapidly create interactive artifacts for communication. The tool sets and methods applied during this process originate from various fields, such as software engineering, game design, animation, user-centered design (UCD), arts, graphic design, and 2D user interface design. We learned that this patchwork of tools further creates challenges throughout the implementation process: from the contextual analysis phase, to the research and prototyping phase, to testing and evaluating until the final product is built.

Our work adds to the findings of Ashtari et al. [11], Nebeling and Speicher [248], and Gandy and MayIntyre [123] and contributes as follows:

1. We provide empirical insights into the collaborative work practices in professional interdisciplinary AR/VR application development.
2. We provide further details about key challenges and workarounds encountered in interdisciplinary teams working with emerging technology.
3. We provide directions as to how HCI can contribute to making AR/VR toolchains more accessible and user friendly.

6.2 Related work

We draw on prior work in the areas of AR/VR authoring tools, work practices of AR/VR developers, and communication of concepts and ideas in interdisciplinary teams.

6.2.1 AR/VR authoring tools

In research, several works exists about AR/VR authoring which target creators with different levels of skill as well as different fidelity stages of the resulting prototypes [248, 146]. Based on the current authoring tool environments, low-fidelity tools generally require less programming skills, whereas high-fidelity prototypes need to be programmed and thus require advanced programming or scripting skills [248]. In practice, commercial AR/VR game engines and software development kits such as *Unity*, *Unreal*, *ARKit*, *ARCore*, *A-Frame*, *ARToolKit*, or *WebXR* are used.

Other tools focus on supporting the low to medium fidelity prototyping stages of application development with reduced to non-required programming skills (e.g. *Pronto* [211], *ProtoAR* [248], *GestureWiz* [326], *iaTAR* [205, 203], *PowerSpace* [147], *ARVIKA* [113], *Adobe Aero*, *wiarframe*, *Microsoft Maquette*, and *Reality Composer*). However, those tools are often limited in functionality and inadequate for supporting the whole development cycle [11, 248].

The patchwork of available tools indicates that AR/VR creators have to learn multiple tools, posing questions about how they are managed and appropriated by developers [86]. However, we still lack knowledge about the practices which exist for such tool usage "in the wild". With our study, we provide insights in how professional AR/VR creators make use of the available tools in order to accomplish their goals in a collaborative and interdisciplinary environment. Additionally, we detail the challenges the creators are facing given the admixture of tools and methods. We therefore complement research by Ashtari et al. [11], who focused on the learning process and barriers of inexperienced AR/VR creators.

6.2.2 Practices and challenges in AR/VR application development

Several studies exist that include information about AR/VR creation from the creators' perspective. However, those studies are often conducted in scope of the evaluation of specific authoring tools [200] and therefore do not reflect realistic creation processes.

In a recent survey, Speicher et al. [326] asked 30 AR designers, developers, and users to evaluate 2 scenarios for AR development and highlight potential technical hurdles. Their work provides insights into 6 major challenges encountered in AR development: cross device / cross platform communication, mapping of the environment, obtrusiveness of devices, gesture recognition, tracking, narrow fields of view (FoV), and immersive scaling and sizing of AR objects.

Gandy et al., the creators of the AR prototyping tool *DART* [221], evaluated how creators used their application 10 years after publication [123] and detail the needs of non-technologists and requirements for future tools designed for supporting AR authoring. Similar to Nebeling and Speicher [248] and Ashtari et al. [11], they highlight the need for authoring tools that do not rely on coding skills.

Based on this prior work, Ashtari et al. [11] emphasize the importance of considering low-tech creators as a developing target group for future AR/VR authoring applications. In their work, they identified 8 barriers encountered by creators with low technical skills by interviewing 21 AR/VR creators with both, professional and amateur background: (1) knowing where to start, (2) making use of online learning resources, (3) lacking concrete design guidelines and examples, (4) designing for the physical aspects of immersive experiences, (5) planning and simulating motion in AR, (6) designing story-driven immersive experiences, (7) encountering many unknowns in development, testing, and debugging, as well as (8) testing users and evaluating challenges. Furthermore, they highlight potential entry points for building more accessible tools, such as integrating learning opportunities, supporting early-to-middle-stage AR/VR prototyping, personalizing authoring tools based on expertise, integrating access to learning resources, and integrating debugging and testing facilities.

We aim to extend this work by providing empirical insights in the authoring process of professional development teams of AR/VR applications, similar to the approach of Dow et al. [85], who investigated the challenges of designing for non-traditional systems, such as ubiquitous computing. We specifically target the challenges for AR/VR creators compared to designing 2D systems from contextual analysis to deployment, as well as challenges and workarounds imposed by available tools and methods in collaborative work environments.

6.2.3 Collaborative prototyping in interdisciplinary teams

Prototyping methods are widely accepted as an important part of software creation within HCI. Prototypes support the visualization of ideas and serve as boundary objects [331], enhancing learning and collaboration in the co-design projects of interdisciplinary teams with different stakeholders, such as designers and end-users [53, 84, 283, 127, 108].

Often, prototypes and their methods are differentiated regarding their fidelity and the effort necessary to create them, as well as tools applied during the creation process [229, 248]. While this alone might not be sufficient to describe the usage and application fields of prototypes as valuable communication artifacts [156, 231, 100], one might argue that detail about the characteristics and roles the prototypes play in the design phases is lacking.

In product development, prototypes are used to save time and resources during later phases of the product evolution process by exposing flaws and misconceptions while their identification and correction is still easy and cheap. However, creators have to find the balance between effort and the required realism of created artifacts. Benmahmoud-Jouini and Midler [26] address this problem of overdesigned and overtrusted prototypes by providing a framework including 3 archetypes for categorizing prototypes according to their the purpose and intended application: stimulators for exploring the user needs and their context, demonstrators for showcasing concepts and their relevance regarding the preceded specifications, and validators for testing close-to-the-market solutions. Whereas stimulators are meant for ideation purposes and open-ended thinking, demonstrators target first concept evaluations and validators allow for detailed development.

In AR/VR application creation, prototyping sessions are embedded in UCD approaches with a focus on end-user or stake-holder involvement, for example during participatory design (PD) sessions as well as co-creation and experience prototyping workshops (e.g. [43, 344, 49, 88, 95]. For instance, Brösting and Gruhn [40] developed a concept that enables developers and UI designers to collaborate on the creation of industrial AR applications. They create “Interaction Stories” as boundary objects which are modeled in-situ and transformed into code snippets. To our knowledge, besides that, the role of interactive artifacts for communicating within interdisciplinary teams in professional AR/VR creation has not yet been investigated in detail.

In our work, we provide initial results about the methods and tools used for prototyping in interdisciplinary development teams combined with the purpose and reuse of resulting artifacts. By doing this, we want to support the creation of a more user friendly AR/VR tool chain for collaborative prototyping processes.

6.3 Study design

We followed a qualitative approach to explore the field and conducted semi-structured interviews using online video conferencing tools. In total, we interviewed 26 professional user experience (UX) designers and developers who were actively working on AR/VR software creation. Along with the identification of roles and tasks as well as their interplay, we also focused on tools, methods, challenges and workarounds applied in their daily work.

6.3.1 Participants and recruitment

For recruitment, we followed a two-step approach. First, we asked creators we personally knew about their networks and platforms in order to establish contact with experienced professional UX designers and developers of AR/VR applications. Besides asking them to spread our study request to their personal contacts, we also posted the request on relevant Slack channels, Meet-ups, Twitter, Facebook, and LinkedIn groups. Second, we received support from recruited interviewees who also spread our request over their communication channels. Our aim was to sample a diverse group regarding their background, application area, target devices, and local distribution.

In total, we recruited 26 participants (f10/m15/o1) with different roles in the AR/VR application development process. Based on their skill set, we grouped them as follows: Creators with design skills (D), creators with design and coding skills (DC), creators with coding skills (C), and managers (M). Apart from the managers, all participants were experienced in 2D application development. Table 3 provides an overview of participants, backgrounds, experience on the job, their application area, and whether they received formal training for AR/VR. 15 participants had worked on applications based on actual customer requests (pull-applications). The remaining 9 interviewees were developing applications based on their own motivations and ideas (push-applications). All developed applications' technology readiness levels were above 5. We recruited interviewees without regard to their place of residence and ended up with professionals from Europe (Germany, Austria, Italy, Hungary, France, Great Britain) and few samples from USA and Canada. The interviews were conducted in both German and English. The literal transcripts were translated to English by a German native speaker with a C1 skill level in English. Our participants covered the following age groups: 18-24 (4), 25-34 (17), 35-44 (2), 45-54 (2), and 55-64 (1).

Table 3

Summary of study participants; on job (years) refers to the participant's working experience in the field of AR/VR application development

ID	Background	Occupation	On job (years)	Main topics	Had formal training
Managers (M)					
ID14	Biomechatronics	Executive Director	4	Game Design, Architecture	✗
ID22	Media Technology	Executive Director	7	Game Design, Architecture	✗
Creators without coding skills (D)					
ID2	Science	XR Experience Designer	4.5	Games, interactive Stories	✗
ID4	Graphic Design	Interaction Designer	7	Experiences for Museums	✗
ID5	Graphic Design	Design Thinking Consultant	3	Agri-Food Business, Training	✗
ID10	Service Design	UX/UI Designer	0.6	Energy, Climate Change	✗
ID13	Electronic Visualization	Experience Designer	2	Education (Space)	✓
ID16	Fine Arts	Experience Designer, Visual Artist	3	Location-based Entertainment	✓
ID25	Cognitive Science	AR UX Designer	4	Energy	✗
Creators with design and coding skills (DC)					
ID1	Human-Computer Interaction	AR Designer	4	Architecture, Manufacturing, Sales	✗
ID7	Media Informatics	Software Developer	3	Architecture, Health, Museums	✓
ID8	Industrial Design	Creative Director AR/VR	5	Virtual Environments, Art	✗

ID	Background	Occupation	On job (years)	Main topics	Had formal training
ID9	Graphic Design	Product Owner AR/VR Technologies	6	Energy	✓
ID11	Media Informatics	Software Developer	4.5	Marketing, Sales	✗
ID15	Media Informatics	Software Developer	7.5	Architecture, Marketing, Sales	✓
ID18	No higher education	Interaction Designer, Developer	1	Education	✗
ID19	Digital Media	UX Designer, Developer	2.5	Location-Based Entertainment	✗
ID20	Computer Science	Product Manager, Developer	6	Architecture, Construction	✓
ID21	Graphic Design	UI/UX Designer	5	Automotive, Remote Assistance	✗
ID23	Digital Media	UX Designer	4	Remote Assist Applications	✗
ID24	Game Design	AR Product Designer	4.5	Consumer Experiences	✗
ID26	Game Development	MR Evangelist, Dev Tech Engineer	8	Automotive, Arts, Game Design	✓
		Creators with coding skills (C)			
ID3	Computer Science	Software Developer	3	Science, Architecture, Energy	✗
ID6	Media Informatics	Software Developer	12	Exhibitions (Fairs)	✓
ID12	Media Informatics	Software Developer	7	Architecture	✗
ID17	Game Design	Software Developer	8	Location-Based Entertainment	✓

6.3.2 Study procedure

Before the interview, we discussed the details of the study and clarified remaining questions with our participants. The interviews themselves were conducted using video conferencing tools like Skype, Zoom, Google Hangouts, and Microsoft Teams, allowing participants to also show us the artifacts and tools they were using in their creation processes. In the beginning, we introduced ourselves and let the interviewees talk about their tasks, experiences with AR/VR tools and devices, their working environment including team sizes and relevant departments in addition to their employers' application domains. Furthermore, we were interested in their personal experiences with 2D application development. We then moved on to the main interview questions which we constructed based on the DAkkS usability guidelines which provide an established question catalogue for context interviews [159, 78]:

We designed the questions to investigate the full process of developing an application ranging from planning, preparation, and execution to evaluation and transfer. Since we were also interested in the types of applications our participants were building, we asked them to explain their approach based on a recent or ongoing product they were developing. During their explanations, we investigated their tool usage, created and prepared artifacts, information and inspiration sources, knowledge exchange, and collaborative development approaches before letting them point out differences to other AR/VR projects they have worked on. Furthermore, we asked them to compare their practices and tool set for AR/VR development to their experiences in 2D application design and finally voice their wishes concerning future tools, methods, and approaches for creating AR/VR applications. In the end, we collected demographic information, such as age, gender, job experience in years, and occupation.

6.3.3 Data analysis

We adopted an open coding approach much as suggested by Strauss and Corbin [336], but - because the paper is exploratory - do not seek to develop axial and selective codes to investigate roles, current practices, tools, and challenges of experienced AR/VR creators. The transcripts were organized and coded in *MAXQDA*. We developed and evaluated the coding schema dynamically on the first 8 interviews with the use of affinity diagrams created in *MIRO*. After that, we applied it to the remaining transcripts. The coding schema delivers insights into the application creation process with a focus on tools and built artifacts for communication between the different roles. Furthermore, we identified challenges and their workarounds.

The following sections present our main findings. We first introduce different roles, their tasks, tools, and the artifacts created in the process of AR/VR application development. After that, we introduce our main findings regarding challenges in an cooperative landscape encountered by AR/VR creators.

6.4 Roles, tasks, and tools in professional AR/VR creation

Our sample revealed the co-existence of at least 4 roles participating in the development of AR/VR experiences, even though roles cannot always sharply be distinguished from each other and transitions between tasks, tools, and artifacts happen fluidly:

> *"I think in AR/VR, there is less definition between the roles. Whatever needs to be done next, you just pick it up and work on it. ... There is no point where my responsibility ends." (ID24-DC)*

Often, a single person incorporates multiple roles, depending on the team's size and complexity of the experience in development. In our sample, teams ranged from 1 to 10 creators working on the same project with a diverse composition of skill sets. 3 of our participants worked as a freelancer, 10 were part of a mixed-skilled core team who hired freelancers if a specific expertise was needed. 1 worked in a design department of a company, 1 was part of a software development department, and 11 worked in teams with mixed professions who did not hire freelancers. Dedicated designer roles existed, but sometimes suffered from a lower standing in the department compared to colleagues with a mixed skill set or the role of a technical developer when it came to hardware and tool availability:

> *"[A head-mounted display] is still expensive. ... From some companies' perspective, [designers] are not the ones who produce, so giving your HoloLens to developers for testing their code makes sense. Giving a HoloLens to designers for them to play with it and try random things, that's another topic." (ID25-D)*

On the other hand, our participants valued the fact that there are many skills required to create outstanding applications:

> *"You are just one person, you cannot do everything. Compared to big companies like Microsoft, where there is a dedicated designer for everything, our applications are good, they still work and people like it, but they do not have those crazy wow-effects, properly cast shadows, highlights, ambient sound design because there was a dedicated sound designer involved." (ID23-DC)*

> *"You cannot be an expert in everything. It requires collaboration. ... The need for collaboration in AR/VR is greater because of the complexity and the need for a number of different assets." (ID13-D)*

The roles we could identify based on our data set are not correlated with the ones detailed in Table 3 since several of our participants shared similar tasks regardless of their expertise and skill set and therefore incorporated multiple roles. We identified the four roles: (1) concept developer, (2) interaction designer, (3) content authors and (4) technical developer:

Concept Developers (22 of our 26 participants) typically focus on creating the first concepts and drafts of an application, ideally by ignoring technical limitations and focusing on the problem to be solved. This might happen based on concrete customer or user-needs, in which case they also act as mediators between end-users or customers and the remaining AR/VR creation team. Concept developers usually work with technology agnostic methods based on the UCD process, for example applied in contextual analysis:

> *"If the use case is not yet clear, we usually start with investigating in the problem and decide afterwards which would be a fitting device. It could also be that the use case itself is already clear and limits the selection, for example if some hands-free*

> *interaction is required. ... We want to find a good and logical use case that is not only based on a technology hype."* (ID5-D)

It could also happen that application concepts are developed from scratch based on ideas and fictional use cases, for example for location-based gaming:

> *"We want to teach people about the development of technology in the near feature and its impact on society. We think it is important that people do learn about the danger and challenges they will be facing in the future. We want to do this based on a games approach because technology is complex and it should not be boring to learn about it. ... AR/VR is also part of this technology and will have a huge impact on society." (ID16-D)*

Concept designers often produce artifacts for the sake of documenting, such as video protocols of reenacted scenes in which the application concept is fictionally put to work, photo diaries, user needs and requirements, or other system specification documents, roles, and application environments.

Interaction Designers (23 of our 26 participants) handle the mechanics and interactivity of the application, usually on a conceptual level. They design for locomotion, navigation, and input / output, as well as the interplay of various modalities used in AR/VR systems. They research similar projects and solutions or novel approaches for interaction design on social platforms, app stores, movies, books, and in AR/VR communities:

> *"For example, if I would design some sort of medical application, I would download all the medical applications I could find for AR/VR and observe the interactions other people have been creating. ... This is for opening up your mind because every designers is at the same spot in a way that there are not many standardized patterns, so everybody comes up with novel approaches. ... Sometimes, somebody has come up with*

> *a really neat solution that also works well in your application." (ID1-DC)*

Interaction designers mainly produce artifacts that aim at communicating and evaluating ideas regarding interaction, information architecture, information flow, and structural issues, such as interaction flow diagrams, storyboards, and wireframes.

Content Authors (10 of our 26 participants) focus on the creation of animations, 3D models, visuals like shadow casts, textures, and color schemes, or sound design such as voice overs and music. Depending on the application, they also design 2D-screens or 2D elements, for example for AR applications that run on mobile phones and tablets, or text-based annotations. Unfortunately, our sample only included 2 content authors with a self-reported dedicated skill set in 3D modeling. The majority of our participants described themselves as having only basic knowledge. Therefore, they used pre-built assets or outsourced their creation:

> *"Some other people help with the UI design, like there is one person that mainly does the art and the graphics for stuff. He is the one that models [the 3D assets] and adds all of the cool effects to them. And in his case, I'll just graybox[1] it or draw a super simple thing in my [3D modeling software] and describe what I want and he'll get it right." (ID18-DC)*

Content authors produce continuously enhanced artifacts with the goal of reaching a final state. Final artifacts are then used as content in the resulting application. Intermediate states of those artifacts are used for communicating and evaluating their approaches.

Technical Developers (15 of our 26 participants) do not only produce code and develop features. They often provide consultation regard-

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[1] Gray boxing is a prototyping technique in which the designer uses gray boxes as place holders for 3D models in the virtual environment; this method is applied when the focus lies on spatial interaction, positioning and scaling without the influence of visual effects and representations and was reportedly executed in Unity. The gray boxed application is then deployed on the target device and tested.

ing the technical feasibility and practicability of concepts and therefore know about current hardware, development frameworks, techniques, and limitations. Besides that, they conceptualize and build the applications and implement custom interactions, image recognition, and positioning. Additionally, they provide support when it comes to hardware selection, software framework selection, tracking techniques, development environment, plug-ins, libraries and network related problems such as cross-device application development. Finally, they combine inputs from concept developers, interaction designers, and content authors and influence major design decisions regarding their technical feasibility. Artifacts produced by technical developers are mainly interactive or working AR/VR prototypes of different fidelity levels as well as custom software and script snippets, for example for gestures.

AR/VR creators apply a mix of various tools and methods to reach their aims. This process results in a collection of artifacts that are similar for the roles and, based on their purpose, independent of applied tools and methods. Only Unity is an exception, since all of our participants' teams developed their products using this game engine.

Besides that, there is no software-based tool that was favoured for prototyping. Sketching and wireframing were the methods that were mentioned most often.

6.5 Challenges for AR/VR creation in interdisciplinary teams

AR/VR has a unique set of challenges for creators due to the three-dimensionality and novelty of the medium. We asked our participants about the barriers they perceive as being the most important ones compared to 2D application creation and identified 3 major areas: (1) team-internal misconceptions about the medium, (2) lack of tool support and appropriate methods, and (3) the absence of a common language.

Table 4
Summary of challenges, solutions, and created artifacts

Key challenges	Problem	Solution	Artifact examples
Misconceptions about the medium	Overestimating hardware and software performance, being unaware of hardware specific limitations, overestimating the robustness of sensory input regarding surrounding environmental factors, projection incompatible experiences from 2D design	Creating awareness via demonstration and experience sessions, creating quick and dirty evaluation artifacts, involving technical creators as feasibility evaluators throughout the design process	Mood boards, working applications
Lack of tool support	Missing a spatial environment for designing or testing, prototyping AR/VR-specific system behavior to get a working prototypes without coding, lacking a full integration into the creator's workflow (e.g. missing design specs), creating inaccessible artifacts for creators with a non-overlapping skill set, finding tools, using prototypes as final product, causing a decline in code quality and reusability	Teaching each others tools (e.g. paired programming), creating physical prototypes in co-creation sessions, falling back to robust prototyping techniques and doing joint explanation sessions	Physical prototypes, annotated information flow diagrams, sketches, wireframes
Missing a common language and shared concepts	Sharing precise descriptions of system behavior and design ideas, creating unsatisfying artifacts due to inappropriate fall-back options (e.g. designing in 2D)	Doing joint prototyping sessions (e.g. live coding), creating interactive or animated artifacts	Video clips, animations, gray boxing

6.5.1 Challenges caused by misconceptions about the medium

AR/VR creation is challenging because it requires the creators to have a mix of knowledge regarding the functionality of AR/VR software and hardware as well as design practices and skills. In interdisciplinary teams, there are roles that focus more on the design aspects, whereas others are more engaged with technical limitations. In particular, creators who do not have a technical background often have unrealistic expectations about what AR/VR can or cannot provide. For them, it is difficult to differentiate between renderings for marketing purposes or actual applications which can lead to an overestimation of hardware and software performance, which might result in costly adaptions to already matured design prototypes:

> *"I had too many lights and it was using too many resources, so the frame rate was very low for the [device]. We had to iterate through that a lot. ... I also had some problem with transparencies which caused a jitter and I had to work on that a lot." (ID2-D)*

Other participants reported trouble that was caused by being unaware of hardware limitations like only having specific input devices or modalities, or a narrow field of view:

> *"The field of view is very important. My first experience with the Hololens1 was that I could not really understand the field of view in Unity." (ID23-DC)*
>
> *"... but [the device] doesn't have an amazing field of view. ... They have to reconsider all of their design thoughts." (ID26-DC)*

In addition to that, the robustness of sensory input like image recognition and image detection regarding environmental factors is often overestimated. This regularly results in the need to design around hardware limitations when features do not work perfectly, such as tracking in varying lighting conditions:

> *"You can't always predict how the lighting conditions are going to be [in the target environment], and you can't always control everything. [When I am asked if the tracking will work a 100%,], I'm like 'I don't know. It might not be'." (ID11-DC)*

Some creators mainly working on design tasks also reported that they tried to simply transfer their experiences from the 2D design spaces to spatial interfaces and failed. While information is typically conveyed using specific output devices and fixed locations for 2D applications, AR/VR embraces the 3D environment which is challenging when it comes for example to positioning UI elements:

> *"... and then we realized that sometimes you have some content that is facing you, but then you will look somewhere else and then you lose where your content was. And it's like we really realized all the difficulties to have 360 degrees interfaces instead of just one in front of you because people tend to lose their screens everywhere." (ID25-D)*

To cope with the problem of misconceptions, teams came up with collaborative solutions. In their understanding, it is not necessary that all involved parties know exactly how AR/VR works on specific devices in particular environments. It is more valuable to create awareness that limitations exist and then to communicate and validate ideas to minimize the amount of wasted efforts:

> *"Usually, you make prototypes to pitch an idea. The whole purpose is to show "Wouldn't this be so cool?", but you also need to present a realistic idea. You need to make sure that your idea is good both in a use case and in realism, like it can actually be implemented." (ID24-DC)*

Some teams also involved both developers and concept designers from the beginning on to validate ideas before they evolved into prototypes by using previously created artifacts:

> *"[Me and the developers] went to the company and experienced the workflows on premise. ... What we always do in our workshops: Everybody has to use [AR/VR] at least once. ... We use showcases from the developers. Those are applications they developed before and ideally demonstrate both their skills and what has been done in the domain. It is impossible to understand and feel [AR/VR] if you have not used it at least once." (ID5-D)*

One participant provided insights into later design phases, when user needs get broken down into concrete features and design ideas:

> *"Developers are involved to tell the [Product Owner] or SCRUM Master if this feature is feasible or not. ... During design, there is always a developer next to me. And I tell him or her that I am designing this interaction and I ask them if this is possible. They will say: Yeah, it's ok, you can go on. Or: No, there are some technical limitations." (ID23-D)*

Another way of handling misconceptions is to create quick and dirty artifacts that are just meant to validate the technical feasibility of ideas in team-internal sessions:

> *"... We have a product owner with no technical skills. However, she is aware about the AR subject and that there are constraints she does not know. She creates lots of mood boards with visuals, and asks: "Hey, this might look cool!", and the developer does then evaluate if the concept works or if it does not work, if it needs to be adapted, etc." (ID4-D)*

The content of those mood boards is manifold but easy and fast to provide and share. They consist for example of sketches, photographs, screenshots from video games, video snippets, link collections, and animations.

6.5.2 Challenges caused by a lack of tool support and fitting methods

Experienced creators select more advanced tools like *Gravity Sketch*, *Microsoft Maquette*, or *MRTK* based on their past experience. However, the short lifespan of today's tools and the fast pace of the hardware development makes it difficult to reuse previously created artifacts and forces creators to continuously learn new tools (e.g. ID1-DC, ID8-DC, ID23-DC). It is also worth mentioning that some participants reported being limited in their tool choice due to the companies' policy or practice of having a set of paid tools which needed to be learned by their employees (eg. ID1-DC, ID23-DC). Sketching and creating graphs for explaining how the envisioned application should behave are methods our participants used mainly if they were not directly jumping to Unity for creating their prototypes. Using those "classical design tools for designers" (ID8-DC) works well as long as applications are not too complex and ideas are still rough. When it comes to spatial distribution, the task of designing AR/VR applications gains complexity:

> *"You mostly want to explain the ergonomics of the application, the layout of your UI elements, for example where is this button, where is this asset, where is the position of this map." (ID23-DC)*

Participants report that available tools often lack the 3rd dimension either in the design space or the test environment:

> *"I think the biggest [problem] is the jump between 2D applications and the fact that we actually design 3D environments and spatial interfaces. ... The missing depth is the most obvious one. Having to constrain [the design] to a 3D plane instead of actually having a spatial environment that is then shown on a screen which is also not a spatial environment feels more like doing photographs about 3D trying to tell the reader how it would look like if it would be in 3D." (ID1-DC)*

> *"If you use [tools like Unity], you are still trapped in your 2D screen. And this is the whole point: It's always good to put yourself in the shoes of the user [and their context]." (ID23-DC)*

Even though there are many tools, less technical creators feel they do not match their needs since there is a trade-off between easy-to-use and effective tools. Our participants reported, that besides lacking depth as information, interactivity, animations, and story telling are also difficult to prototype. They therefore have to use a mix of tools in order to get specific about details like interactivity, spatial distribution, orientation, and scaling:

> *"The tools are either too complex, so you need to know how to develop the application [because they are frameworks for*

> *developers]. The applications that have been designed for designers do not handle how to get a working prototype. They are too simple feature wise." (ID1-DC)*

> *"Sometimes, it is very difficult to put the animation into work. So I sometimes use Adobe After Effects just to show the animations." (ID23-DC)*

Our participants reported using a mix of 2D design and mockup tools like *Adobe XD*, *Figma*, *balsamiq*, but also more advanced software such as *Doodle Lens*, *Tilt Brush*, *Gravity Sketch*, and *Microsoft Maquette*. However, the mix of tools is not well integrated into their workflows:

> *"If we mockup [the application], there are no super good tools. Microsoft Maquette is the most advanced one, but then it is difficult to get your design specs out of it." (ID1-DC)*

Therefore, less technical creators require the help of developers to move their prototypes and ideas to the 3$^{\text{rd}}$ space in order to evaluate "simple" things like scaling, positioning, and interaction:

> *"[F]or me, really the biggest problem is that once we want to prototype interactions like gestures and the 3D thing, I have absolutely no tool to do that. So I really have to rely on the developers to code something so that we can test it, because otherwise there is no way." (ID25-D)*

> *"At the moment, [the biggest hindrance] is the problem of not easily being able to test out these different interactions I have on my mind, like: ... Should [the asset] follow me with ... slight delays, should it turn when the head goes outside the UI? And then I might not be able to test it out before it goes into development. So I might need the help of a developer to test out those kind of basic spatial UI things that are common. I think in [Microsoft Reality Toolkit] (MRTK), there might be scripts, but I cannot use MRTK in my current assignment because [the device is not compatible]." (ID1-DC)*

However, transferring the artifact into an environment where it becomes inaccessible for alterations executed by the low-tech creator causes conflicts:

> *"For example, for UI layout, I would just code everything. I would think it is super smart, but it's not because then the designer would have less access to changing things because he wouldn't know how to change it." (ID11-DC)*

On the other hand, it also happens that technical creators with little design knowledge sometimes have to take over the role of content creators and interaction designers:

> *"It's not like in normal mobile development [where] UI/UX designers do the big part of the design. In [AR/VR], it is mixed and developers also have to do a bit of the design, which is a very hard task because we are not designers and we have to find tools that can help us designing." (ID3-C)*

One participant reported that their team addresses this tool gap by teaching each other the use of different instruments to lower the barrier and keep artifacts accessible:

> *"On my team, right now everybody knows how to use Unity. ... We did a lot of paired programming to show [the inexperienced creators] how it works. So we just kind of teach each other all the time. And that has evolved into everybody knowing Unity, and as a programmer, I should also know a bit of the design side, so I'm also learning Figma (the tool designers use) in order to understand each other better. I'm not a pro on that, but it is enough to do at least basic things if I have to substitute [the designers]." (ID11-DC)*

Other teams use physical prototyping in collaborative sessions, where developers and designers jointly work on mimicking interactivity, positioning and scaling to better understand the overall application:

> *"It helps to understand the physicality of the experience. Because you are surrounded with all elements that do exist in real life and it's hard to imagine that when you're just looking at the screen or just a paper." (ID25-D)*

> *"It is to make sure that your design will actually make sense. So I started with a little bit of role playing and putting stickers on top of each other. I used transparent papers for holograms and put something on top, for example for spatial annotations. I was doing these kind of things to really feel if the interaction metaphor could really work in space." (ID23-DC)*

> *"Especially the developers were positive about physical prototyping in 3D, because they usually only get those descriptions and then it is difficult for them to imagine how the application should behave." (ID3-D)*

However, physical prototypes can become really complex when multimodality has to be modeled, such as spatial sound which has then to be played by other designers or participants (ID5-D). Besides that, there are other hindrances:

> *"[Physical prototyping for AR/VR] has a lot of constraints because you cannot do it remotely and since the environment where the application should be used is in our case difficult to be replicated in an open office space, it would not work." (ID25-D)*

Physical prototypes take time to be constructed and are therefore only feasible if the project budget and resources allow it. In order to save time, participants reported that their team prototypes directly in Unity:

> *"Eventually, the working prototype is actually the application itself and is created by developers, this is why I just stick to UX*

> *writing based on this information flow diagrams* [2]*."* (ID23-DC)

> *"For 2D, it is much simpler because you can just draw on your whiteboard to show what you want to say. In AR, people have to think about it in 3D which is quite challenging to understand. Also, for 2D ... realistic prototypes can be done very easily, for example with [drawing software], but for AR, at least right now, you have to go through the development process."* (ID7-DC)

Additionally, participants reported that they had trouble in getting rid of artifacts which were no longer needed, because they had to put a lot of effort in constructing them:

> *"If you have very complicated prototypes, such as programming your own hand gestures, you want to keep using it which might be problematic: If you spent a lot of time on it you do not want to scrap it. This is always a problem with AR prototypes. If you spent time on it, you built something like an emotional bond."* (ID7-DC)

In fact, several participants reported that an artifact originally developed as a prototype was shipped as the final product due to time and budget constraints, and a lack of understanding from the customers' side for necessary code refactoring "because the prototype already looked so good" (ID6-C). This caused problems regarding code readability and code reusability in addition to an increased amount of necessary work with respect to future changes and maintenance.

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[2] ID23-DC creates graph-based visualizations of the application logic and adds annotations to describe the interactivity and application flow similar to information flow diagrams [102] or user flow diagrams [218]

6.5.3 Challenges caused by missing a common language and shared concepts

Our participants mentioned that a missing common language and shared mental models often cause confusion and leave uncertainties about design ideas and implementation tasks. Developing a common understanding of how the envisioned AR/VR application should behave and what they look like requires knowledge exchange via artifacts [62, 84] that can convey envisioned concepts as precisely as possible:

> *"We think that the interactions are the most important part of an AR Game because it adds to the immersion. If you have good interaction, it feels natural. ... It is often that if you talk about something, everybody imagines it in a different way and there is always a difference between my interpretation and my second programmer's understanding. We had a lot of problems in the beginning of people implementing things in a wrong way and then having to scrap it completely. In order to cope with that, we decided to be exact about our interaction types and make them to become manifest." (ID17-C)*

Furthermore, people bring the vocabulary and concepts from their field of expertise and sometimes have to fall back to a common ground of knowledge as a workaround. This results in artifacts that cannot hold up to the creators' expectations:

> *"In the beginning, we [developer and designer] did not have the same language. This is why we went for 2D prototyping instead of 3D prototyping – we might have found something better if we would have had the same language." (ID7-DC)*

As reported in Section 6.5.2, AR/VR is difficult to explain and talk about when using still images and sketches due to the complexity of the applications without at least some sort of interactivity:

> *"If you show moving pictures or simple animations, you can see how people better understand the point you want to make." (ID8-DC)*

However, doing animations is expensive and time consuming due to the skills required for producing animated artifacts which provide enough interactivity to explain the intended behavior of the design. Our participants reported also falling back on more robust and fast approaches, for example sketching, and providing interactivity by explaining the ideas in face-to-face sessions:

> *"[We communicate with the developers through] speaking and sketching. [This is] the cheapest, quickest way. When it's something a bit complex that needs to show some interaction, for instance, and it requires a really clear sketch, I do a wireframe. Otherwise, we simply discuss together and sometimes [the developers] do live coding [where we can directly assess the changes]." (ID25-D)*

Other participants went for creating visual artifacts like storyboards and interaction flow diagrams with precise, annotated descriptions of how the system should behave. However, AR/VR lacks a standard set of interaction patterns [11] which makes it difficult to depict interactive and animated system behavior:

> *"... it's more due to the understanding people have or do not have of what AR is. A 2D prototype for a 2D UI is still an approximation. No matter how polished it feels or looks, you still have to imagine transitions between screens and the state of buttons if they are not present in the prototype, but because you used a lot of those apps or websites, you can fill in the gaps with your internal libraries. This still sometimes leads to misunderstandings, but at least there is a shared library of how things work or knowledge that can be used to fill in the blanks. In the case of emerging mediums like AR, people do not have this internal library. ... It is even more complicated with spatial sound. ... You cannot expect people to understand such a medium by just talking about it." (ID4-D)*

An approach reported by participants who possessed coding skills involved a combination of programmed artifacts with limited interactivity and "acted out" system behavior to demonstrate envisioned applications. This approach is also known as gray boxing:

> *"We used a marker as anchor point to provide first impressions and check if we were talking about the same things. It was not beautiful and consisted of simple [virtual] boxes and spheres that were anchored on the markers just to see potential interactions. ... We also showed that one could now go to the left or the right and also perform other movements. We documented some of the findings afterwards as bullet points [in written form]. Others were implemented based on our memory because it would be intricate to describe exactly how the interaction behaves." (ID6-C)*

6.6 Discussion

Our findings add to the work of Ashtari et al. [11], Gandy and MacIntyre [123], and Nebeling and Speicher [248], and provide insights into the current practices, challenges, and workarounds of professional creators of AR/VR applications. Based on the reported artifacts and tasks, we identified at least 4 roles (detailed in Section 6.4) involved in collaborating on the creation of AR/VR applications in the professional field. Furthermore, we highlighted 3 key challenges, workarounds, and the resulting artifacts (summarized in Table 4) which surfaced during our interviews. We now want to discuss how our findings add to previous studies for enhancing future tool-support in AR/VR authoring.

6.6.1 Similarities and differences between end-user developers and professional AR/VR creators

To complement Ashtari et al.'s findings [11], we want to discuss our key challenges regarding similarities and differences between professional creators and end-user developers upon their tool usage and encountered problems. Following Ko et al.'s explanation [180], end-user developers differentiate from professionals regarding their priorities.

Whereas professionals are being paid, end-user developers aim to support goals from their own field of expertise through the creation of software, such as hobbies or their jobs. For our comparison, we focus on 6 of the “8 Key Barriers in Authoring AR/VR Applications” [11], since we did not provide further detail about findings regarding testing and evaluation. Generally, we found that both groups have similar issues and needs when it comes to AR/VR application creation.

The first 3 key barriers *(1) Difficult to know where to start*, *(2) Difficult to make use of online learning resources*, and *(3) Lack of concrete design guidelines and examples* strongly overlap with our findings as reported in sections 6.5.1 and 6.5.3. As we reported, professional creators with few technical skills have trouble understanding the medium and its limitations regarding hardware and software and therefore risk developing designs that are difficult or even impossible to implement with current technologies. It also turns out to be difficult to discuss ideas and approaches with their more knowledgeable team members because, unlike in 2D development, there is not yet an established set of guidelines and standards. Our participants also reported on the broad tool landscape and, in case they were not restricted by their companies’ policies anyways, the difficulty in finding sufficient tools (also reported by Nebeling and Speicher [248]). Here, the problem was mostly that many lacked spatial placement and interactivity features, and were either too simple or too complex for the creator’s needs.

The findings detailed in Section 6.5.2 conform with Ashtari et al.’s key barriers *(4) Difficult to design for the physical aspect of immersive experiences* and *(5) Difficult to design story-driven immersive experiences* [11]. Similar to end-user developers, professional creators reported a lack in tool and production workflow support. We learned that creators with little or no programming skills are highly dependent on creators with a sufficient technical background to create working interactive prototypes. On the other hand, creators with few to no design skills rely on collaborators with content creator skills in order to fill the application with life and ensure a good user experience.

The main difference that we noted between end-user developers and professional creators is their access to expertise. Interdisciplinary teams came up with collaborative solutions to work around the challenges imposed by the AR/VR development landscape and found ways of drawing from their collaborators' skills. Whereas we acknowledge that it is important to lower the entry-barriers for low-tech creators by designing new and easy-to-use tools based on their needs, we see that future tool development could beneficially draw on established approaches, workarounds, and communities present in the professional AR/VR development field. We provide further detail on this finding in Section 6.6.3. In addition to that, tools supporting the collaborative prototyping of creators with different skill sets and knowledge could also ease the appropriation of AR/VR as a complex medium.

6.6.2 Emerging roles of AR/VR creators due to specialization of skills and their impact on future authoring tools

We developed the role definitions based on existing tasks and goals in the AR/VR development cycle reported by 26 practitioners with a broad set of skills. Our participants worked on projects with varying levels of complexity and collaborated in teams of different sizes and with divergent levels of specialization. While this blurred the lines between already existing roles in our data set, we were able to identify four preliminary roles emerging from our pool of participants: Concept developers, interaction designers, content authors, and technical developers (see Section 6.4). Collaboration as a concept for AR/VR tool creation has been around for some time, for example Schmalstieg et al.'s Studierstube [301]. More recent AR/VR prototyping tools, such as XRDirector [245], additionally incorporate roles based on tasks or interdisciplinary collaboration [40].

However, the roles proposed in Section 6.4 are still at a high level and not yet unique to AR/VR teams as they can also be found in other software and game development teams. Based on our findings, we expect an increasing specialization for AR/VR designers and developers as well as the development of new roles and processes for application development as the field matures. Gandy and MacIntyre already indicated an expected “movement toward specialization among contributors” [123] for AR/VR application development. This increasing specialization also requires tools that support collaboration in interdisciplinary teams to cope with the medium’s growing complexity.

A common way of handling complexity on the coding side is through convention over configuration (COC). This was introduced to web-development in 2004 through the Ruby on Rails framework and subsequently inspired many others. Initial authoring tools for AR/VR like AMIRE implemented a visual programming paradigm to support graphical designers [140] but were described as too complex for them and not domain-specific enough [146]. The TOTEM framework implemented a template-based approach to content creation for location-based games inspired by COC. It also described three distinct roles and their responsibilities in the development process: game designer, content creator, and programmers. The assumption was that developers were needed anyway and already got first class support with rapidly developing IDE’s. The benefits of decomposing systems into modules for separation of concerns have been advocated since the 1970s [262] and are part of the state of the art in object oriented programming. To support collaboration however, the programming could be separated from the content and design-related roles (although they would sometimes be held by the same person) through the tools that helped in creating structured data and exporting it in standard formats [366]. This is much like in traditional GUI programming, where widgets could be visually placed and stubs to be filled with interaction logic are automatically created. For Mixed Reality experience design, the placement and arrangement of the widgets in 3D space should be possible, maybe like in a collaborative version of the classic Tinmith mobile Augmented Reality modeling system [265].

As showcased in our study and also supported by literature [48], multi-disciplinarity and a broad skill set are needed in order to create usable experiences. However, it also comes with the pitfall of having to overcome diverging concepts, expertise, and incomplete individual knowledge, also known as “symmetry of ignorance” or “asymmetry of knowledge" [107, 285] in PD and computer-supported collaborative work (CSCW).

Our participants reportedly experienced this when designers without programming background discussed their artifacts with technical developers and vice versa and realized that their individual knowledge was not sufficient to solve a given design problem due to the specificity of their skills. In addition, AR/VR is a medium that is still developing at a fast pace which renders it difficult for a single person to keep track of the most recent developments. Both experienced and novel users and creators face a landscape of hardware, software, and tools that keeps evolving with a few standards and guidelines slowly emerging[11, 248].

Therefore, one can view designing AR/VR systems themselves as being a wicked design problem [48] which requires "a greater diversity of knowledge and technical skill than any one practitioner can provide [...] for finding solutions" [165]. In her work about interdisciplinary team development for designing a platform for computer-supported collaborative play, Jennings emphasizes that multi-disciplinarity requires each team member to be "equally valued" and able to participate in the design process [165], much like Ehn and Kyng also described in the UTOPIA project [94]. Furthermore, interdisciplinary teams need well-constructed boundary objects for internal communication [53, 84, 108]. As our study and previous work [11, 248, 123] demonstrates, this is not yet possible in creating AR/VR systems, or requires additional efforts to come up with workarounds.

Another potential approach to breaking down and distributing work among interdisciplinary team members working on complex software is the creation or implementation of dedicated software engineering processes - corresponding to game and classical software development. In line with Musil et al.'s prior research about similarities and differences between game and software development processes, we see that AR/VR development teams might benefit from dedicated engineering processes to cope with challenges surfacing due to the diverse background and roles of team members [240]. While we did not specifically focus on already in-use formalized software processes in our study, we noted that the approaches described by our participants are apparently similar to agile methodologies which are also strongly driven by incrementally evolving artifacts. Additionally, some of our participants reported that they successfully implemented SCRUM or at least follow a SCRUM-based development process. Be that as it may, McKenzie et al. investigated anticipated and practical application of agile frameworks in the game industry in New Zealand and observed that studios unintentionally diverge from the formal process without it being realized [230]. We therefore want to emphasize the need for further research to provide more detailed insights into applied development processes in AR/VR development and their analogies to game development and classical software engineering methodologies in order to improve how already existing or potentially new approaches can support interdisciplinary AR/VR development teams.

We also see that future tools for AR/VR creation could benefit from following a PD approach to better design for the needs of both, creators and end-users in AR/VR system development as well as provide support for the various roles in their development process. Ens et al. already argued that Mixed Reality (MR), and thereby AR/VR, are becoming commonplace and therefore one can "focus deeply on the nuances of supporting collaboration, rather than needing to focus on creating the enabling technology" [99]. The important point to note here is that now that MR is leaving the lab and entering workplaces and homes, it can finally be seen as an evolution of (2D) groupware and therefore lessons learned from over 30 years of CSCW studies can be applied and evolved. This includes the common ground of the development processes and CSCW [264], as well as the intersection of code and design in cooperative processes. However, one has also to consider Brooks' humbling notion of seeing our work as that of a toolsmith, who is designing a tool that is set out to make a task easier [46]. And when doing so remembering Culkin's famous quote that "we shape our tools and thereafter our tools shape us" [72].

6.6.3 Design implications for future prototyping and authoring tools

Given the fact that over the course of the last few decades a lot of prior research has already focused on AR/VR authoring and how such tools should be designed in order to support creators and developers, the question remains why those approaches are not yet established in tools in current use. In this regard, we argue that firstly, the field is relatively young and has not yet been fully adapted by the consumer market. While tools and hardware continue to rapidly evolve, a so-called killer use case is still missing. Additionally, standards have yet to be established. Therefore, it is a financial risk to invest in commercially developing authoring tools.

Secondly, research about the actual needs of design and developer practitioners from the field of AR/VR is scarce. With this work, we intend to close this gap by providing insights into the challenges, approaches, and needs of actual practitioners in this specific field. As pointed out by Dow et al. [85], it is crucial to focus on actual practitioners as well as the tools used in line with their strengths and weaknesses in order to push the development of future tools for non-traditional design environments - in this case AR/VR - in a promising direction.

Finally, we want to discuss design implications towards more usable development tools as suggested by prior work [11, 248, 123].

Use simple tools developed based on tasks and goals. As our study shows, practitioners favor quick and easy tools which help them to effectively, efficiently, and satisfyingly reach their goals. This is a classic usability engineering problem [159] and there is a large pool of methods to draw from, for example by applying PD in tool development. However, we experienced that AR/VR authoring tools in practice do not necessarily differentiate between roles, tasks, and goals, but are rather feature-bound and end up being either too complex or too simple in addition to not supporting crucial elements of creative work, such as the possibility of evaluating ideas and exchanging artifacts.

Draw from existing methods, approaches, and workarounds. Participants from our study came up with a variety of workarounds to overcome the obstacles imposed by their tool sets. Since AR/VR creation unifies several disciplines and design approaches, it makes sense to make use of the complete set of already existing methods and find practical ways of adapting or redesigning them to the new medium, or supporting them in their appropriation [86]. In addition to approaches from classical UI development and filmography (e.g. [248, 245, 211]), we encountered gray boxing, a method applied in game design for creating low-cost prototypes to construct spatial layout and scaling properties. This bears striking similarities to the use and study of prototyping in systems design, as described by Floyd to include widget toolkits, very high level programming languages, and database-systems, in order "to make effective work possible" [109], generate human-feedback, and "keep trying until you get it right" [54]. Our participants also voiced the usefulness of physical prototyping because it has a realistic view point, features spatiality, physicality, and real-life scales as well as enables easy interdisciplinary collaboration due to a low to non-existing learning curve of required tools. On the other hand, it has too many drawbacks, such as construction time, transferability, potential complex workarounds for interaction and multi-modality, and the restriction to a certain physical space.

Create well-built artifacts for interdisciplinary communication. A common approach to interdisciplinary team work is the communication via artifacts or prototypes to establish a common ground of knowledge. Design patterns as introduced by Alexander[2] were developed for this purpose and got adopted in other application fields, such as software engineering, collaboration [121, 307, 64, 279], HCI [38, 142], game-design [31, 368], AR [222, 373], and interaction design [22]. Therefore, design patterns could be an appropriate approach to establish a common language for AR/VR development if the field has matured to an extent where it is possible to draw from a rich pool of applications and experiences. However, as and when the field matures to such an extent, patterns require team members to be aware of them, learn and use new vocabulary, and might therefore be difficult to apply in practical AR/VR experience creation.

We suggest to focus instead on the creation of interactive and adaptive artifacts. As we saw in our study, available tools impose their limitations on the production workflow and the resulting artifacts or AR/VR application creation. We encountered various artifacts that were built based on the need to overcome those barriers and noted that even static artifacts like user flow diagrams required some sort of superimposed interactivity to be understood by team members due to the complexity of interaction, spatiality, and multi-modality in AR/VR. Based on that observation we conclude that future tools should facilitate the creation of artifacts with animations, interactivity, and flexibility to be collaboratively assessed, adapted and refined. Since our participants reported that their artifacts resulted from workarounds of tool limitations, we recommend analyzing the reason behind the creation of the artifact rather than simply what they show or do not show [156, 231, 100]. Having such collaborative Mixed Reality artifacts ready-at-hand during the design process of a diverse team would allow for mutual learning and languages games in a Wittgensteinian sense of language as action [93], i.e. giving the words a meaning in their use context, and thus allowing the grounding of the design in the work tradition.

Make use of all three dimensions. As reported by our participants and also detailed in literature, designing for 3D in a 2D environment or on a 2D screen is cumbersome and feels unnatural. However, based on our findings, this differentiation between design space and application space is still imposed by authoring tools used in practice. In contrast to that, current trends in AR/VR authoring tool development, for example Nebeling et al. [245] and Leiva et al. [211], follow the "What You Experience is What You Get" (WYXIWYG) Editor principle from Lee et al. [205, 203, 202], who proposed an immersive authoring tool for concurrent content creation and validation in the application space. WYXISWYG leans on the "what you see is what you get" approach of todays' graphical user interface editor prototyping tools. In their work, Lee et al. describe immersive authoring as beneficial when it comes to specifying spatial arrangements and behavior [202] because the resulting design can be evaluated while being created without the need of switching between a 2D content creation environment and a 3D application execution environment. Immersive authoring can therefore reduce the entry barriers to AR/VR creation for inexperienced designers and increase the efficiency of AR/VR application developers without programming skills. This is inline with findings from the field of location-based experiences and ubiquitous computing, where the need of in-situ authoring for appropriate ideation, reflection and rearrangement of content was described [363].

Finally, it is important to note that immersive authoring is not always the best fit for approaching design challenges, especially when the design of abstract problems such as programming logic is required [202].

Allow for interdisciplinary, collaborative creation. As highlighted in our study, compared to end-user developers who tend to work alone, professional AR/VR creators benefit from having access to experience beyond their skillset. There are many ways one could adopt to establish a collaborative setting in an interdisciplinary field, starting from creating more accessible communities by embedding social networks like Slack, Facebook, and Twitter, allowing for easier asset exchange by basing new tools on existing standards and incorporating known platforms, out-sourcing the challenges to more experienced creators (e.g. [138, 130]), or by ensuring that tools are backed by an active user community that is able to provide support if needed[123]. The crucial part is to empower creators to design decent artifacts that are efficient, effective, self-explanatory, goal oriented, and could be easily shared between and accessed as well as altered from the different roles in an interdisciplinary setting [165, 331].

6.6.4 Limitations

We acknowledge the dominance of lab studies in our related work as a potential limitation of this paper. The majority of our participants used Unity as integrated development environment. While for some of our participants this reflected the market situation, by its very nature of qualitative study, we have no statistical data with which to make strong claims about representativeness.

6.7 Conclusion

As our findings illustrate, tools which were previously developed in lab-scenarios, resulting from specific end-user development application areas or created by re-using already existing frameworks from other application areas might not fully satisfy the needs of practitioners in the field and therefore require designers and developers to come up with creative workarounds.

We have presented insights into current challenges, practices and design implications for professional AR/VR creators based on a study with 26 AR/VR designers and developers. Our findings add to existing work from the field of HCI tool research for spatial application authoring by presenting 3 key challenges for professional creators and how interdisciplinary teams solve them: (1) Misconceptions about the medium, (2) lack of tool support, and (3) missing a common language and shared concepts. In addition, we identified 4 roles involved in AR/VR creational processes, namely concept developers, interaction designers, content authors, and technical developers. We think that taking approaches from practice as a base for developing authoring tools is beneficial when it comes to the applicability and usefulness of the results. In addition to that, the interdisciplinarity of AR/VR application creation affords collaboration. Future authoring tools should therefore focus on supporting the construction of well-built boundary objects for communicating ideas, concepts, and approaches.

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7 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.

7.1 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 [248] 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 [221]. With industry practitioners' increased adoption of XR, current research efforts are focusing on supporting non-technical designers, hobbyists, and end-user developers [11]. 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 [185].

XR still has to come a long way to accomplish standardized tool chains, development processes, user interface design conventions, or good design practices [325, 186]. 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 [169]. We follow an expert designer-centered approach to boost the currently under-represented 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 [225, 317]. Where required for clarification, we explicitly use AR, VR, or MR, following Milgram and Kishino's [235] definitions.

In line with previous work into ubiquitous computing and interaction design [85, 334, 333, 374] aiming at supporting the development of compelling user interfaces and creativity [169], we investigate industry practitioners' prototypes as a *"core means of exploring and expressing designs for interactive computer artifacts"* [156]. Since prototypes are used as aids in thinking [257] and communication of ideas and concepts [85], 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[334]; 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.

7.2 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.

7.2.1 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 [221], 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 [123] 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 [247, 246, 327], immersive authoring [201, 372], video-based editing [208, 211], live sharing [381, 345], and asynchronous/asymmetric collaboration [346, 245].

Despite the advances in tools research, designers are still facing many challenges. Nebeling & Speicher [248] 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 [241]. Ashtari *et al.* [11] 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 [325] 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.* [185] 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 [85, 334, 374]. 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.

7.2.2 Prototypes in Interactive System Design Research

Prototypes play an important role in designing software applications in general [109, 156] as well as in research of relevance to interaction design practitioners [85, 215]. 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 [282, 291], and mixed-fidelity prototypes [229]. 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 [282, 291]. Mixed-fidelity describes how prototypes can have aspects of varying fidelity and therefore do not match the definition of low- or high-fidelity [229]. In the context of prototyping, fidelity is also associated with methods [224, 343] used for creating prototypes, such as paper prototyping [282] as a low-fidelity method. Furthermore, fidelity is aligned with the skills and resources required to operate prototyping tools [248].

Over the past decades, several attempts have been made in interactive system design to create taxonomies of prototypes. Floyd's "three E model" [109] 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 [109]. 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 [21].

Other approaches support a broader perspective. For instance, Houde and Hill [156] argue that everything could be a prototype depending on how a designer uses it, even a brick [156], and call for shifting attention towards the *purpose of a prototype* rather than the prototype itself [156]. 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"* [24], which also *"supports creativity, encourages communication, and permits early evaluation"* [24]. They further propose four dimensions to analyze prototypes: *representation*, *precision*, *interactivity*, and *evolution* [24]. 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 [49] (e.g. Wizard-of-Oz [137]).

Instead of focusing on how prototypes are being used in a design process, Lim *et al's* metaphor of filters [215] 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 [215]. 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 [215].

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.

7.3 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 7.7) 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.

7.3.1 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 5).

Table 5

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

ID	Occupation	XP (years)	Background	Project	Platform
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

7.3.2 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 5. 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 7.7). We structured the main portion of the interview based on an established question catalog [78, 159] 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.

7.3.3 Data Analysis

To analyze the data, we organized each interview individually on a virtual whiteboard using Miro (e.g., Figure 9). 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 9). Descriptions, statements, opinions,

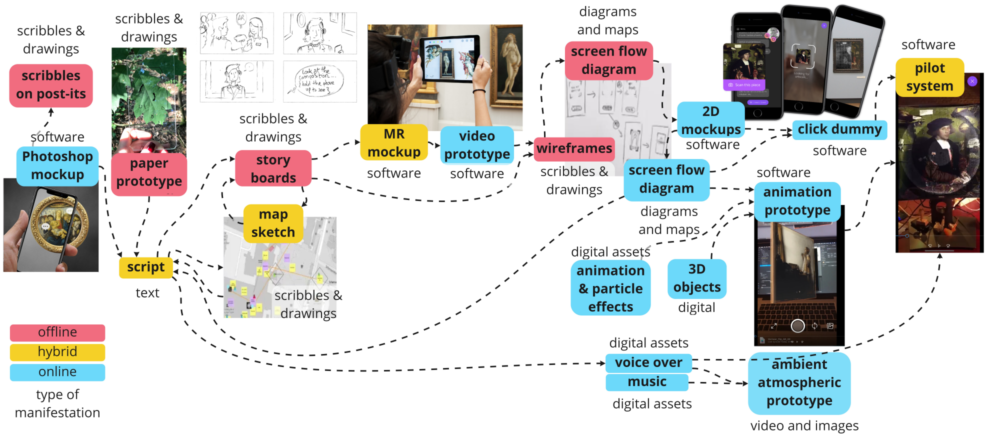


Figure 9

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.

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 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 [65], 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 7.4.

7.4 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 6 summarizes our specific observations in this regard. The respective findings are discussed in Section 7.6.1.

Table 6
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 7.6.1.

	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

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.

7.4.1 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 [24]. 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 are applied or transformed. We call this analysis **structural analysis** and describe the respective results in Section 7.4.1.1. 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 7.4.1.2. This analysis enabled us to understand the challenges in XR application design and how prototypes support overcoming them.

7.4.1.1 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 7.

Table 7

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 10.
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 11; 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 15 (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 13; recreating an expensive X-ray device as wooden prop to prototype the mapping of physical and virtual properties (P17).

Manifestation	Type	Description	Example
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 [49] using Wizard-of-Oz or demonstration by example [85], 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 12, walkable scenery models (P06, P13) in Maya or Blender, VR prototypes in Microsoft Maquette (P15).

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 10). 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 7.4.2, 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

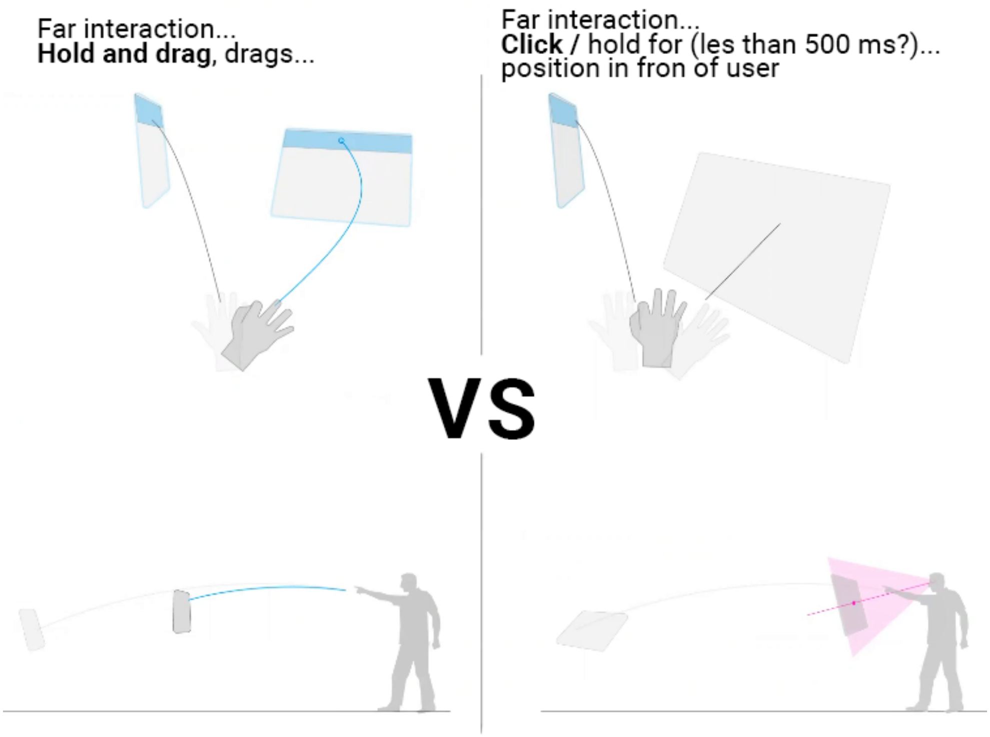


Figure 10
Representation of a sketch created in Figma, provided by P06. The sketch depicts two alternatives of interacting with distant window panels: hold and drag (left) vs. click (right). This sketch depicts various elements, e.g., spatiality by showing different perspectives (top: ego perspective; 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.

manifestations can also negatively affect a prototype's fidelity, as discussed in Section 7.4.2.

7.4.1.2 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 8 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

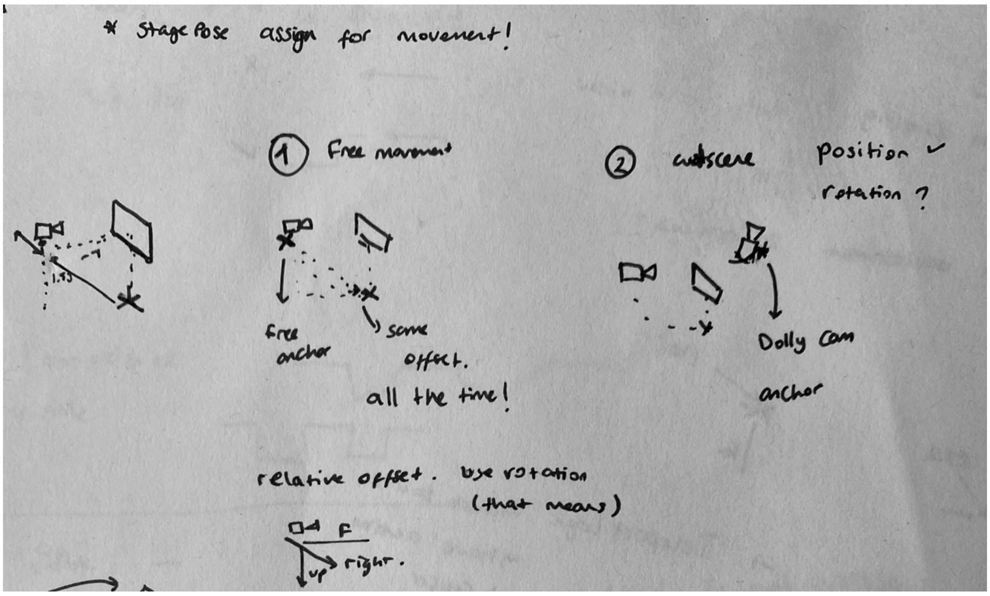


Figure 11
Diagrams and sketches depicting camera movement and transitions provided by P06 to answer cinematographic questions.

requirements. For example, Figure 12 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.

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 12 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 13 shows the evolution from sketch, to a placeholder prop, to the final physical model. Rep-

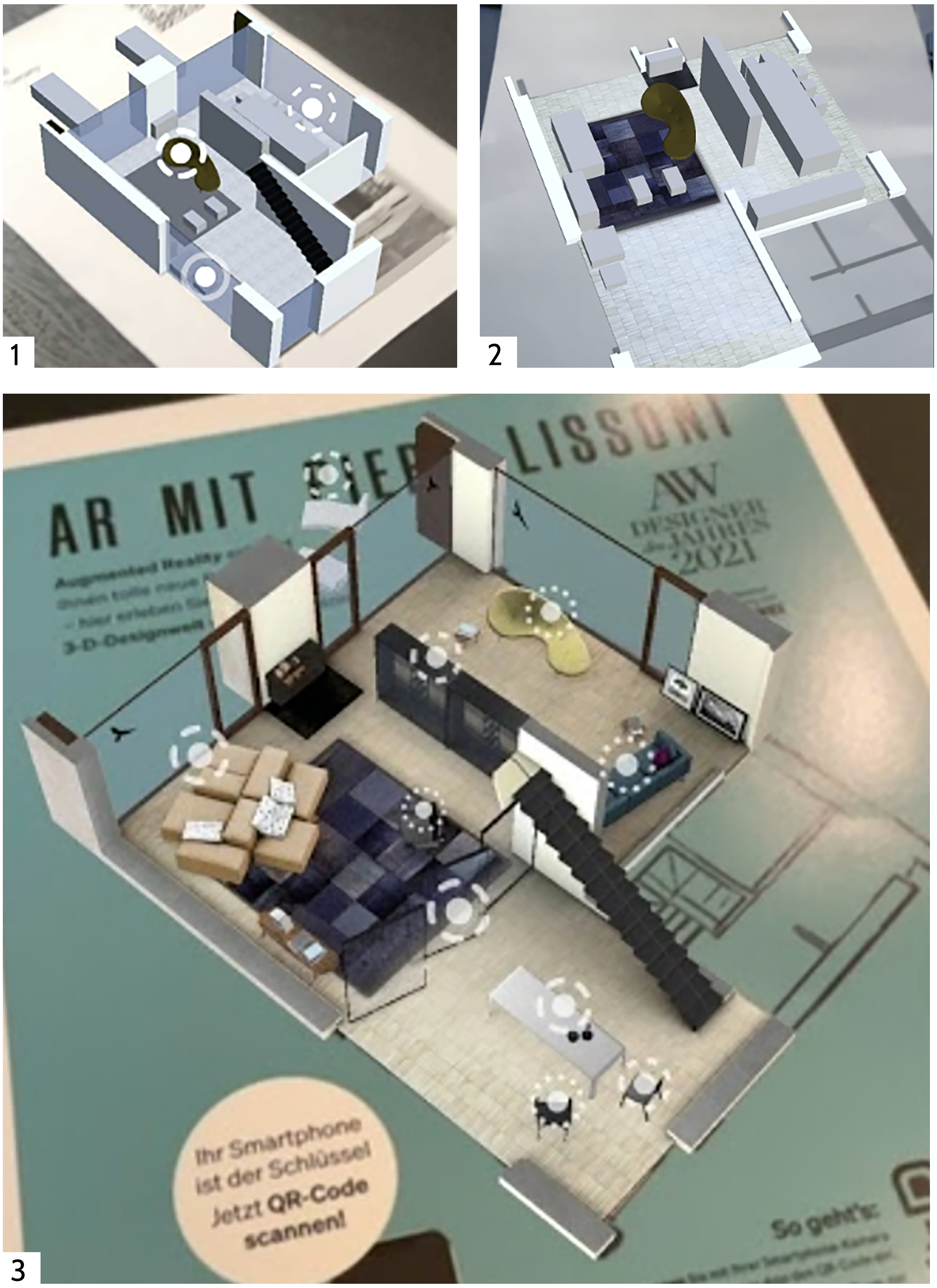


Figure 12
Evolution of an application from an initial grey-boxed layout (1) to the final product (3) (P12)

Table 8
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, gray-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

resentative 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).

3) World-building is a concept from fiction and describes "the process of building a fictional world" [150]. 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

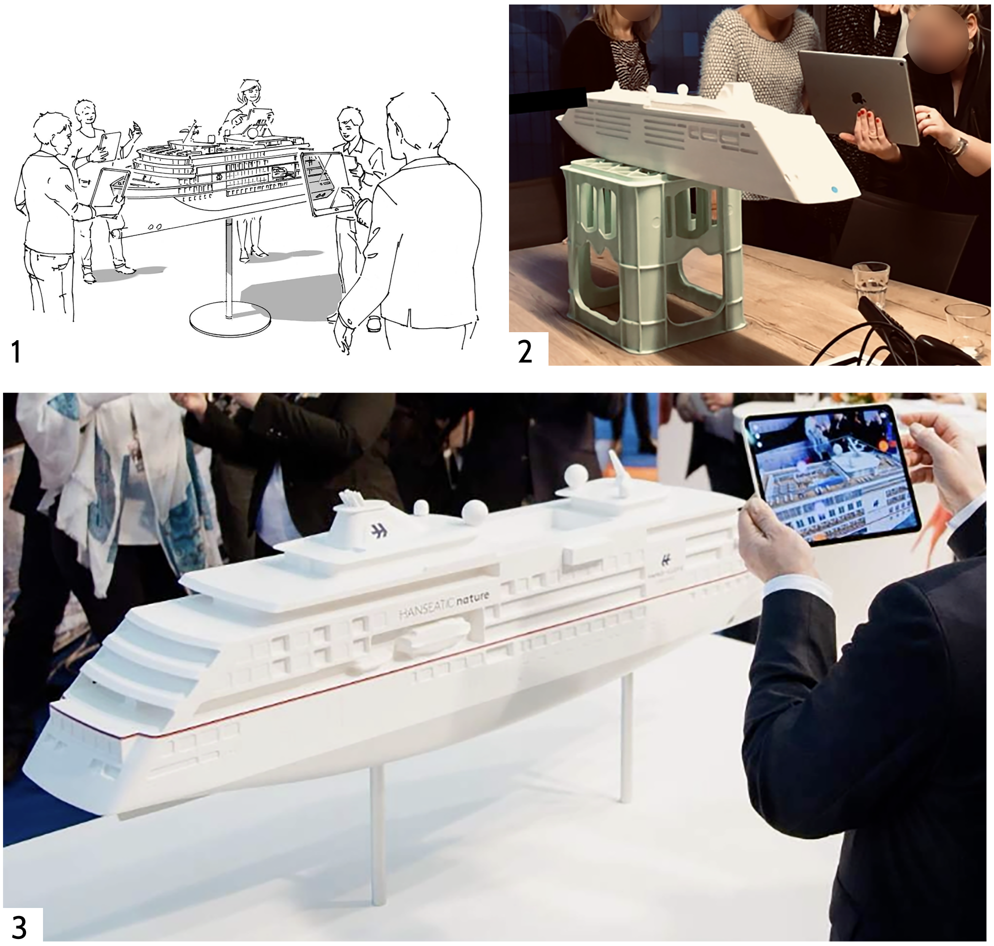


Figure 13
Evolution of an application featuring a physical model in a handheld application on iPads: From (1) sketch over (2) substitution prop to the (3) final physical model (P12).

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 10). There were also sketches and ray-cast 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.

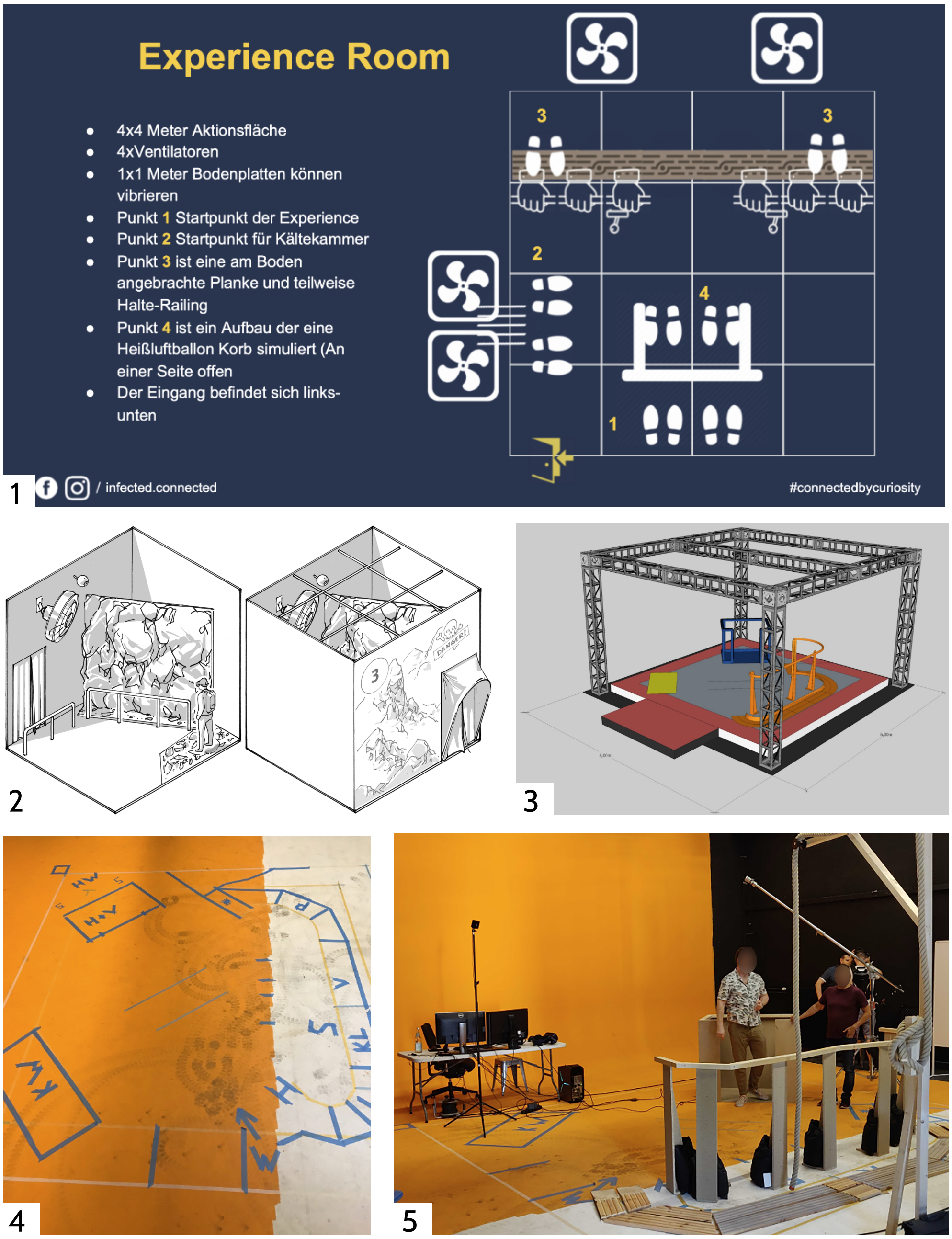
9) Cinematography describes and investigates cinematic elements such as camera angles, camera movement, scenery, and color. The reported prototypes addressing those features were sketches drawn in perspective, diagrams detailing camera movement, or experience scenery models.

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 7.5.

7.4.2 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.



Experience Room

- 4x4 Meter Aktionsfläche
- 4xVentilatoren
- 1x1 Meter Bodenplatten können vibrieren
- Punkt 1 Startpunkt der Experience
- Punkt 2 Startpunkt für Kältekammer
- Punkt 3 ist eine am Boden angebrachte Planke und teilweise Halte-Railing
- Punkt 4 ist ein Aufbau der eine Heißluftballon Korb simuliert (An einer Seite offen
- Der Eingang befindet sich links-unten

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Figure 14
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).

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 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 7, 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 15).

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 15

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 6). 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* [267] are discarded after they have fulfilled the designer's intention.

In practice, both approaches of evolutionary and throw-away prototypes were combined. Figure 9, 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 9, 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.

7.5 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.

7.5.1 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 [248] 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.

7.5.2 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 [11, 185], 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 16. 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.

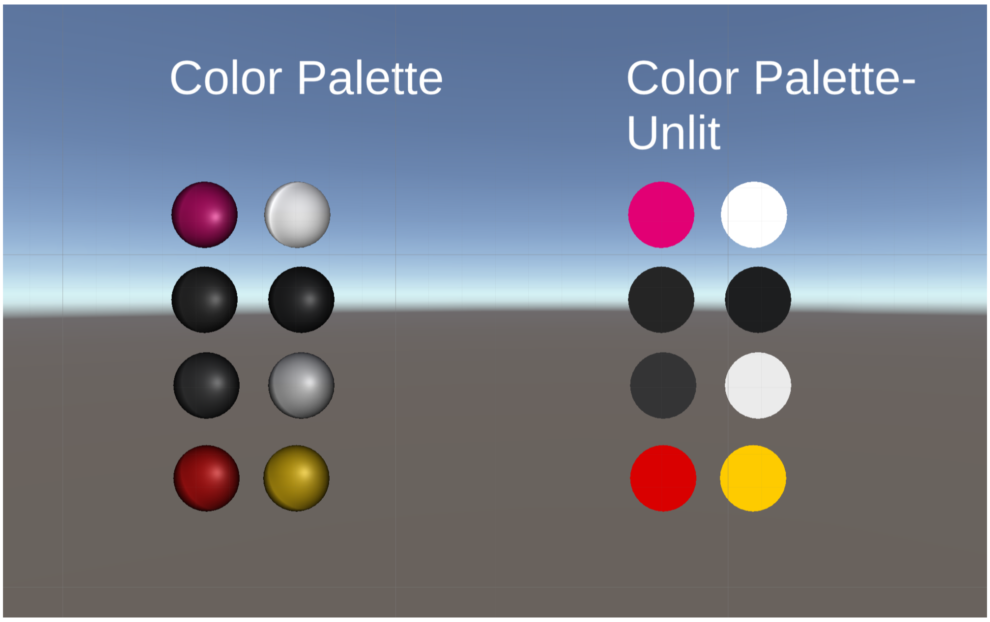

Figure 16
Color palette tests in the Unity Emulator (P04). Due to the three-dimensionality and light effects, color palettes defined by corporations do not reflect the intended color. Furthermore, when displayed on the target device, additive screens tamper with colors in AR applications.

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.

7.6 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 dataset was rich in the variety and complexity of XR prototypes. As a summary of our work, we answer our research questions from Section 7.1 and discuss existing and potential future work.

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

We highlighted in Table 6 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 [156, 193, 61, 185]. 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 [11] or the need to create adaptive and interactive artifacts [185]. 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 [325].

In line with prior work [156], 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 7 and ten elements of XR prototypes, detailed in Table 8 to form our taxonomy. In line with Lim*et al.'s* notion of prototypes as filters [215], 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" [215] and enable a more effective use regarding creation and communication [156]. 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 [53], 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 [156].

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.

7.6.2 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 [215]: *"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"* [215]. Our participants also often reported using ephemeral prototypes that do not have a persistent form but rely on internal libraries of experiences, mental imagery [12], 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 [185]. However, expressing interactivity requires time, effort, and a certain skill level in operating high-fidelity tools [11, 185, 248]. 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 [49], 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 [85, 49] 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 [267].

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 [215] and the tool gap [248], 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.

7.6.3 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 downsampling. 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 [86, 332]. 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 [334]: 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 [326] or reactive path-based programming [378]. 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.

7.6.4 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 [317]; 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 [325, 186]. 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.

7.7 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.

Acknowledgements

We thank our participants for their time, effort, and willingness to share their work with us.

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 7.3.2.

7.7.1 Opening questions

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

7.7.2 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, . . .)?

7.7.3 Prototyping process & tools

7.7.3.1 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?

7.7.3.2 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?

7.7.3.3 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?

7.7.3.4 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?

7.7.3.5 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?

7.7.3.6 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?

7.7.4 Closing questions / reiterate

1. Do you always follow the same approach as described in your sample project? What are the differences?
2. Do you always face the same problems?
3. Do you always create the same deliverables?
4. Do you always use the same interfaces to other divisions?

5. What takes the most time during prototyping/development (regarding tasks)?
6. What is the biggest hindrance you were facing in other projects?
7. How long does the overall process take in general?
8. In case they have experience with 2D prototyping: What are the differences between WIMP and XR prototyping?

7.7.5 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?

8 Research and Practice Recommendations for Mixed Reality Design – Different Perspectives from the Community

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Abstract

Over the last decades, different kinds of design guides have been created to maintain consistency and usability in interactive system development. However, in the case of spatial applications, practitioners from research and industry either have difficulty finding them or perceive such guides as lacking relevance, practicability, and applicability. This paper presents the current state of scientific research and industry practice by investigating currently used design recommendations for mixed reality (MR) system development. We analyzed and compared 875 design recommendations for MR applications elicited from 89 scientific papers and documentation from six industry practitioners in a literature review. In doing so, we identified differences regarding four key topics: Focus on unique MR design challenges, abstraction regarding devices and ecosystems, level of detail and abstraction of content, and covered topics. Based on that, we contribute to the MR design research by providing three factors for perceived irrelevance and six main implications for design recommendations that are applicable in scientific and industry practice.

8.1 Introduction

As the diversity of devices such as smartphones or tablets increased, novel research fields appeared. Emerging spatial technologies like augmented reality (AR), virtual reality (VR), and mixed reality (MR) afford new requirements and interactions while they also include the actual environment as such in the interaction itself. Although spatial technologies have been researched for decades, it was not until the second wave of VR brought new devices to the mass market that research was refueled.

Recent work reports different kinds of design practices and lessons learned for UI design, for instance, in the shape of design principles, guidelines, heuristics, or recommendations [97, 355]. Those are supposed to support designers in creating usable interfaces with reasonable time and effort [323]. Spatial media research also includes the elicitation and publication of case studies and practices (i.e., [97, 355, 79, 42]).

In this context, current research reports that both researchers and practitioners perceive the present situation in MR development as lacking relevant, practical, and applicable design guides [11, 185], if they are easily accessible at all.

In this paper, we examine the current use and applicability of design recommendations with a particular focus on MR design in practice [185, 132]. We compare design recommendations for MR systems originating from both scientific research and industry practice to answer these questions:

RQ1 What are the differences between research and practitioner recommendations for AR user interfaces?

RQ2 What factors contribute to them being perceived as relevant or irrelevant for application development?

RQ3 What can we learn from those differences for future work on design recommendations for spatial user interfaces?

In a literature review, we analyzed design recommendations from 89 scientific papers and compared them to those published by Apple, Google, IBM, Magic Leap, Microsoft, and Spark AR. We compared the recommendations regarding four key issues: Focus on MR unique design challenges, abstraction regarding devices and ecosystems, level of detail and abstraction of content, and covered topics. We further formulate—based on our findings—three reasons for the perceived irrelevance of design recommendations for MR and six implications on how to create meaningful design recommendations for both practitioners and researchers.

8.1.1 Terms and Concepts in this Paper

The data set of our analysis contains work that focuses on augmented reality but also includes other types of mixed reality media as defined by the reality-virtuality continuum of Milgram and Kishino [235]. Throughout this paper, we will address the type of media as MR and switch to a more specific differentiation of AR or VR if needed. Furthermore, we differentiate between spatial- and non-spatial media as types of user interfaces (UI). Spatial media consists of UIs that involve spatial components like MR, tangible UIs, or ubiquitous computing. In contrast, non-spatial media encompass more classical UIs, such as command-line interfaces, desktop applications, or systems for mobile devices and tablets following the Windows-Icons-Menus-Pointers (WIMP) paradigm.

8.2 Related Work

8.2.1 Designing Interactive Systems

Among insights from user-based experiments, resources such as informal and adopted design guidelines as well as standards play a central role for designers working to develop usable interactive systems (see Figure 17). In 1976, Cheriton proposed design guidelines for time-shared computer systems with the goal of standardization to *"[decrease] the effort required for users to change systems"* [60]. Other guidelines exist to provide system designers references to reduce well-known errors because *"[most errors] are system induced, a result of inappropriate system design"* [256]. Over the last 50 years, the design research field used different terms like design principles, guidelines or heuristics for these proposals. A well-accepted definition for the terms is hard to find. According to Fu et al. [114], these and more terms are part of knowledge explications. Based on a literature review, Fu et al. synthesize the following definitions [114]:

Principle: A fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, that provides design process guidance to increase the chance of reaching a successful solution.

Guideline: A context-dependent directive, based on extensive experience and/or empirical evidence, that provides design process direction to increase the chance of reaching a successful solution.

Heuristic: A context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, that provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution.

Furthermore, design principles are formulated more general to "*outlast the technological demands of the moment*" [255, 160]. According to Preece et al., guidelines and heuristics are strongly related because design guidelines can be transformed into heuristics for evaluating systems [267]. Without guidelines for specific applications or technologies, designers tend to adapt guidelines from other contexts to new technologies. This bears the risk of neglecting unique features of new technology. User-based experiments help to validate designs and to inform design activities in the early stage of an emerging technology. With further contributions from the community, collections of informal guidelines appear and may evolve into more formal guidelines or standards [117] (see Figure 17). Sometimes, established guidelines are incorporated into design tools that can enforce consistency and ensure reasonable designs of systems [255].

8.2.2 Design Recommendations for MR

MR is an emerging medium slowly being adapted for mass marketing. As general consent, MR design practices diverge from non-spatial media in presenting and interacting with content. Therefore, this medium requires its own design rules, tools, and practices. Due to its early stage of development, we can observe the evolution of guidelines for designing systems. Endsley et al. [97] investigated 137 statements from AR and related fields and classified them in an iterative process. The result of their work was nine heuristics to be considered by AR designers (see Figure 18). Vi et al. [355] extended Endsley et al.'s work by developing eleven design guidelines for extended reality applications with a focus on head-mounted displays (HMD). In addition to the guidelines from

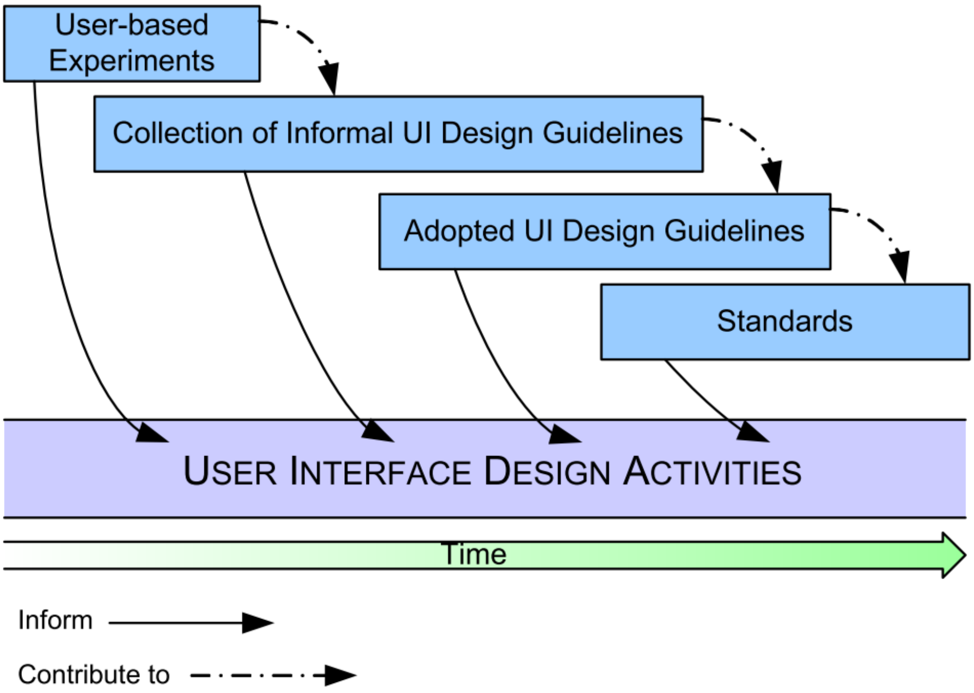

Figure 17
Development of guidelines [117]. © 2008 IEEE

research, they also considered guidelines from the web, including documentation from companies like Google, Leap Motion, or Oculus, as well as blog posts from individuals on platforms like medium.com. The created guidelines are mainly based on online sources and cover both AR and VR. However, due to the popularity of VR at the time of that study, few guidelines were elicited for AR. Both sets bear a likeness to each other (see Figure 18) and to well-known guidelines or heuristics such as Nielsen's 10 usability heuristics [253] for non-spatial interfaces. However, Endsley et al. and Vi et al. provide additional guidelines for AR, such as the three-dimensionality of the medium and a more profound connection of virtuality and reality. Because MR is a body-centric technology, special physical safety and comfort guidelines were added, focusing on ergonomics. Concluding our literature review, there were no further attempts to classify existing design recommendations for MR to the best of our knowledge.

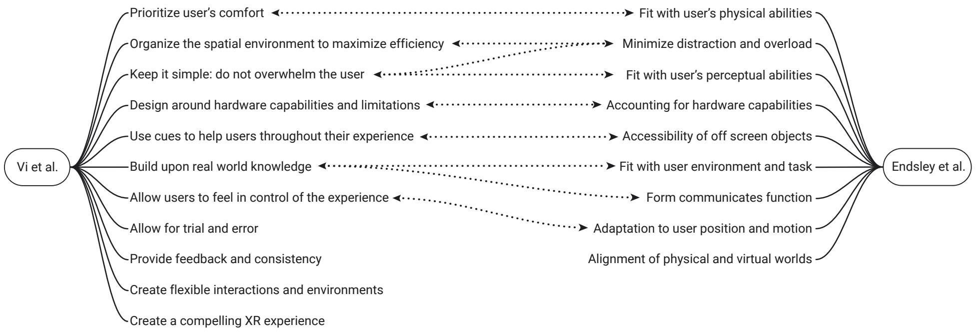

Figure 18

Proposed guidelines and heuristics from Endsley et al. [97] and Vi et al. [355]. The dotted lines show similarities between the guidelines.

8.3 Research Approach and Methods

We conducted an iterative literature review oriented on the approach of vom Brocke et al. [44] to answer our research questions (see Section 18). After identifying key concepts and terms, we defined our search terms. As the terms "design guidelines" returned too few results for a proper analysis, we added "design principles" and "design heuristics." The resulting query was:

```
("Augmented Reality" OR "AR") AND ("design guideline(s)" OR
"design principle(s)" OR "heuristic(s)").
```

We used the Scopus database and searched titles, abstracts, and keywords. Without restricting the period, we received 519 published papers between 2000 and the day of our search, April 17, 2020.

In the first iteration, we removed 34 anthologies and duplicates. The remaining 485 papers were checked for relevance by reading the title, abstract, and conclusion. Papers should mention the design of an AR application or the development of design guidelines or recommendations for AR. As a result, we further excluded papers in which our search terms were used in different contexts (also see Section 8.1.1) or had a different meaning. We also discarded non-English papers or those that did not have a full-text version publicly available. We kept results stating MR design recommendations instead of AR. Finally, we considered 89 papers for a full-text analysis (see Appendix 8.7). From these papers, we extracted statements that can guide the design of an MR application, such as design principles, guidelines, heuristics, or less formally formulated design recommendations. We will further refer to the extracted information used in our analysis as "statements."

In total, our team of three researchers collected 374 statements on a virtual whiteboard in MURAL and sorted them following an iterative, bottom-up approach into an affinity diagram [153]. We followed an open coding approach described by Strauss and Corbin [336]. Our goal was to elicit common topics regarding design recommendations in MR research. Therefore, we built clusters based on a design recommendation's purpose deduced from each statement. If the purpose was unclear, we clustered regarding a statement's proposed action. Each statement was discussed before we arranged it on the whiteboard. Due to the ambiguity of some design recommendations, the resulting clusters were not mutually exclusive. Hence, we sorted statements that could belong to multiple clusters into the best fitting one based on already arranged statements and our discussions or created a new cluster if none of the arranged statements matched. After all statements had been arranged, we appointed names deduced from a cluster's content before arranging them under matching umbrella topics. We will address those statements and clusters as "Scientific Design Recommendations" (SDRs) in the remaining sections of this paper.

To complement our scientific literature review, we considered design recommendations of companies actively developing MR hardware and software. In October 2020, we queried the websites of six market-leading, AR-related companies Apple [8], Google [133], IBM [157], Magic Leap [223], Microsoft [233], and Spark AR [101]. We extracted design recommendations that we will refer to as "Practitioner Design Recommendations" (PDRs). We analyzed them in line with our approach for SDRs and built clusters by common topics without considering the cluster names from the SDR affinity diagram. Even though some companies already provided a categorization, we followed our bottom-up approach described for SDRs to ensure comparability. This separate affinity diagram has 501 statements from Apple (59), Google

(115), IBM (20), Magic Leap (135), Microsoft (103), and Spark AR (68).

8.4 Description of the Data Set

In the following, we describe the features of SDRs and PDRs in detail. Summaries of the affinity diagrams are depicted in Figure 19 for SDRs and Figure 20 for PDRs.

8.4.1 Scientific Design Recommendations (SDRs)

Elicited recommendations either explicitly address hand-held devices (n=297; 79.4%), HMDs (n=42; 11.23%), or did not specify the target device (n=35; 9.36%). The affinity diagram of 374 statements resulted in seven main topics, which we will further detail. As depicted in Figure 19, each of the main topics consists of several clusters containing mixed statements regarding target devices.

The topic **Design Principles (inspired from non-spatial)** contains eight clusters and 58 statements (15.51%) addressing themes known from traditional non-spatial UI design, such as *Personalization*, *Guidance* in the sense of tutorials, *Learnability* in the context of providing manuals, help, and other supportive information to grasp the application, *Task appropriateness*, *Privacy*, and *Laws* such as Hick's Law [151] or the Law of Practice [249]. Furthermore, we grouped statements that vaguely mentioned the adaption of existing guidelines, principles, or heuristics in the cluster *Adaption of other heuristics and principles*, for example, Shneiderman's design guidelines for desktop application [74, 312] or Nielsen's 10 usability heuristics [350, 164] in *General Nielsen Heuristics*.

We identified 86 statements (22.99%) literally quoting or paraphrasing Nielsen's 10 heuristics [164]. Those statements were sorted in the topic **Nielsen Heuristics** and grouped in the 10 clusters *Visibility of system status and feedback*, *Match between system and the real world*, *User control and freedom*, *Consistency and standards*, *Error prevention*, *Recog-*

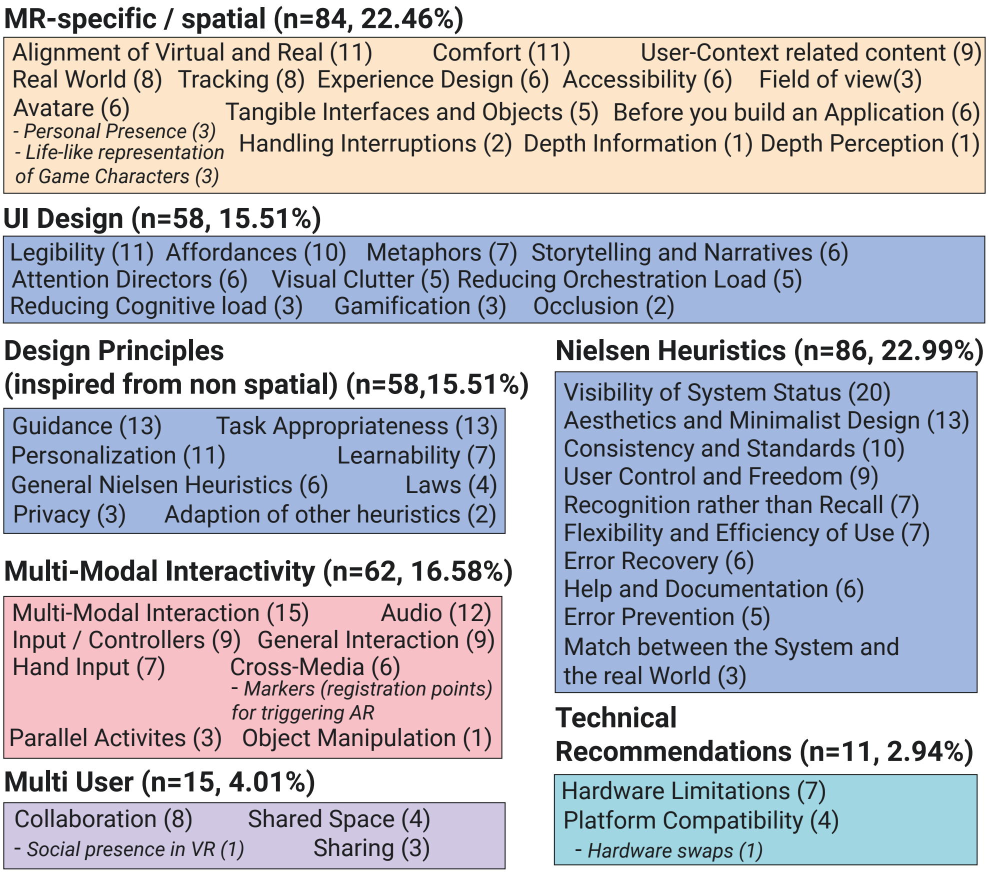

Figure 19

Affinity diagram of scientific design recommendations. Each box represents a topic written as headline that contains multiple clusters. Same-colored boxes are closely related regarding their topics. Cluster names are written inside the boxes, and their sub-clusters are denoted in italics.

nition rather than recall, *Flexibility and efficiency of use*, *Aesthetics and minimalist design*, *Error recovery*, and *Help and documentation*.

Our SDR data set revealed statements addressing **Multi-User Experience**, from which we built four clusters with 15 statements (4.01%). The clusters *Collaboration* and *Social presence in VR* are related based on the statements' content. We divided clusters regarding the defined type of media. For instance, *"Encourage more communication and interaction during the task"* [80] specifically mentioned the design of VR environments and was therefore sorted into the cluster *Social presence in VR*. In contrast, *"Effective tangible AR interfaces can be developed using the design principles learned from tangible user interfaces. The basic prin-*

ciples of TUI include [e.g.] Collaboration between multiple participants" [28] address AR systems and were, therefore, assigned to *Collaboration*. The cluster *Sharing* focuses on aspects of sharing interfaces and experiences other than *Shared spaces*, which contains statements about movement, user positioning, and placement of shared content.

In **Multi-Modal Interactivity**, eight clusters structure 62 statements (16.58%) focusing on the themes *Parallel activities*, *General interaction* like *"Creation of appropriate interaction techniques for AR applications that are as intuitive as possible"* [171, 379], *Multi-modal interaction*, *Object manipulation*, *Hand input*, *Input and controllers*, *Cross-media*, and *Audio*. The general topic addresses interactivity, either in combination of multiple modalities, spatial interaction, or audio. For instance, *Multi-modal interaction* combines several modalities like *"Gesture-based or verbal speech controls, could also be beneficial"* [82].

UI Design addresses more general design recommendations for interface design. Those are closely related to the statements in the topics Design Principles and Nielsen Heuristics. We found 58 statements (15.51%) and grouped them in 10 clusters. In addition to *Occlusion*, *Attention directors*, *Gamification*, *Visual clutter*, *Affordances*, and *Metaphors*, themes like *Reducing cognitive load*, *Legibility*, *Storytelling and narratives*, and *Reducing orchestration load in teaching environments* emerged.

The topic **Technical Recommendations** with three clusters and 11 statements (2.94%) concentrates on hardware-induced limitations and cross-device approaches for system development. The clusters are *Hardware limitations*, *Platform compatibility* and *Hardware swaps*.

Finally, the topic **MR-specific/Spatial Design** consists of 84 statements (22.46%) grouped into 16 clusters: *Field of view*, *User-context related content*, *Experience design*, *Handling interruptions*, *Tangible interfaces and objects*, *Real world*, *Life-like representation of game characters*, *Personal presence*, *Avatars*, *Alignment of virtual and real*, *Tracking*, *Depth perception*, *3D depth information*, *Comfort*, *Accessibility*, and *Before you build an application*. This topic is mixed regarding covered themes but is similar regarding the focus on MR-application-specific features rather than generic recommendations.

8.4.2 Practitioner Design Recommendations (PDRs)

Elicited design recommendations address specific devices, such as handheld (Apple, Google, Spark: n=243; 45.5%) and HMDs (Microsoft, IBM, Magic Leap: n=258; 51.5%). We created 13 main topics for PDRs through affinity diagramming.

In the topic **Interactivity**, we sorted 67 statements (13.37%) into 11 clusters. Interaction with objects is often mentioned. We divided these statements into clusters such as user initiated *Object placement*, *Scaling*, *Rotation*, *Translation*, *General manipulation* and *Visual cues for object manipulation*. We found eight statements regarding the *Affordance*. Statements about rather passive interactions with virtual objects are collected in the cluster *Reactive content*, like statements about attentive holograms. The cluster *Encourage to move* also emerged, and we collected four statements about the use of *Animations* and three statements about the proper introduction of new content to the user in the *Content spawn mechanic* cluster.

Statements about how the interactivity is implemented are collected in the topic **Input Modalities** with 68 statements (13.58%) in eight clusters. Four of these clusters—*Modality change*, *Gaze input*, *Voice commands* and *Cursor*—are dominated by statements from Microsoft's Mixed Reality documentation and Magic Leaps' design guides because they address specific design aspects for HMDs. We gathered statements about eye-gaze as well as head-gaze in the cluster *Gaze input*. We also created a cluster for statements that can guide the *Selection of the interaction modality*. Statements like *"Ensure controls and gestures are ambidextrous"* [223] are grouped in the cluster *Hand and finger gestures*. More specific statements about gestures for object manipulation can be found in the *Manipulation gestures* cluster. Also closely related to that is the cluster *Fitt's Law for touch interaction*. Close touch input to manipulable objects should be assumed to be input for the object to facilitate interaction with it.

The topic **Environment** contains 49 statements (9.78%) in five clusters focusing on the surrounding space. We created the clusters *Space*

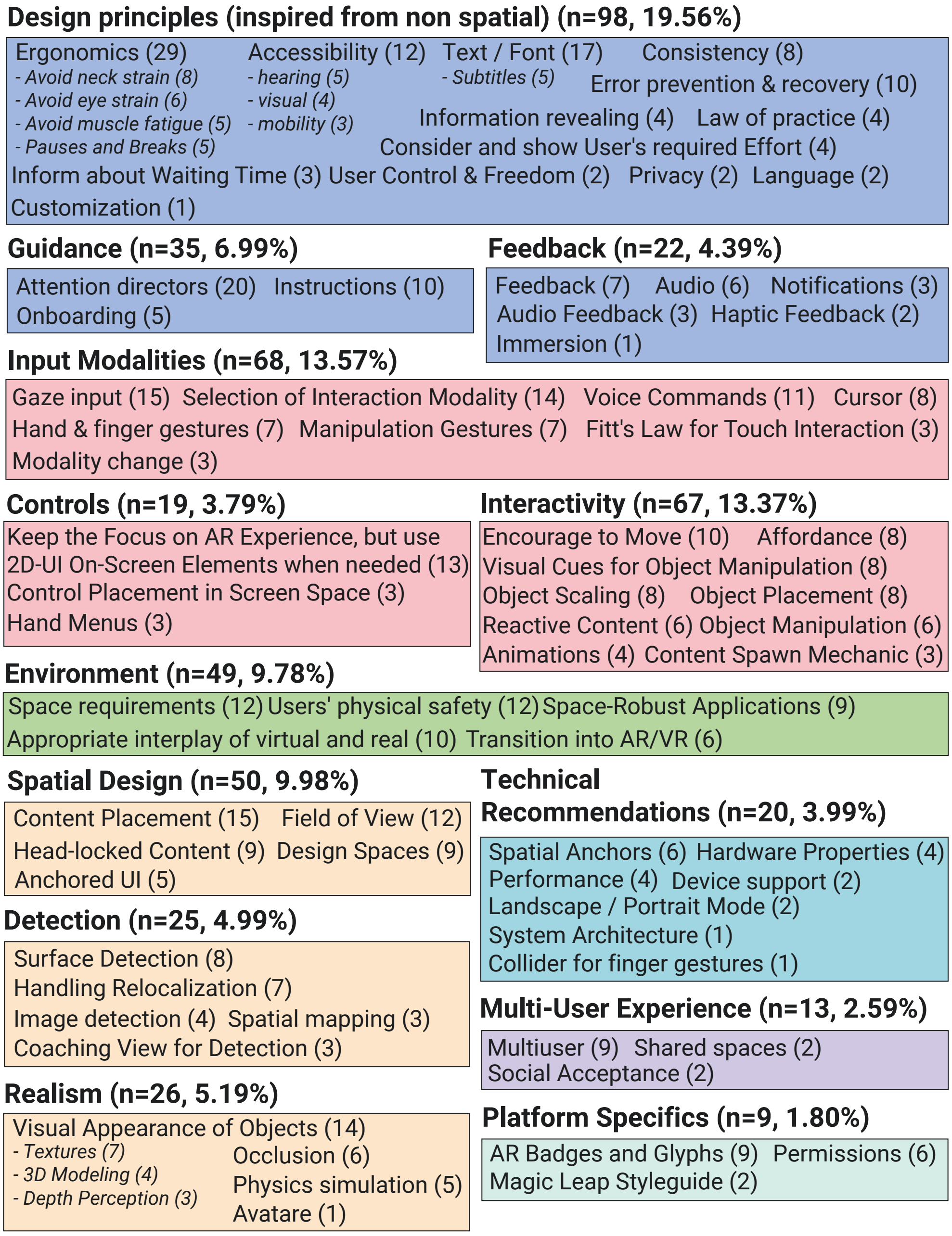

Figure 20

Affinity diagram for practitioner design recommendations. Cluster names and topics are denoted as described in Figure 19.

requirements considering the needed space for the experience, *Space-robust applications in dynamic environments* with content about designing for different physical environments, and *Users' physical safety* with statements like *"Help users move safely in their space. If people are ex-*

pected to move during the experience, remind them to make space before they make the movement" [101]. Because AR is embedded in the real world, an *Appropriate interplay of virtual content and physical environments* as well as the *Transition into AR/VR* are essential.

We found 26 statements (5.19%) divided into four clusters focusing on **Realism**. The biggest cluster is *Visual realism and appearance of objects*, which contains three sub-clusters about *Textures*, *3D modeling* and *Depth perception*. *Occlusion* is used to provide additional visual feedback and increases the perceived realism. The cluster *Physics simulation* with statements like *"By having your digital objects respond to basic physics in the world, you firmly ground them in reality"* [223] is related to the previous cluster. Also connected is the cluster *Avatars* with one statement from IBM: *"Use unrealistic avatars. Realistic avatars can fall into the uncanny valley."*

Similar to our SDR data set, we found statements that are related to design principles from non-spatial design. These statements are more general and not directly connected to AR but should also be considered. Overall, we found 95 statements for the topic **Design Principles (Inspired from Non-Spatial)** that we put into 15 clusters (19.56%). Because most users are not familiar with AR, *Error prevention and recovery* is important, and *Consistency* will increase the learnability. The companies mention different aspects of accessibility when creating an inclusive AR application. For example, there are 12 statements about the legibility of *Text/font* with five additional statements for *Subtitles*. We found more statements regarding accessibility

and made clusters for *Hearing*, *Visuals* and *Mobility*. Directly connected to those is the cluster *Ergonomics* with sub-clusters about avoiding *Eye strain*, *Neck strain* and *Muscle fatigue* as well as including *Pauses and breaks*. Other clusters in this topic are *Consider and show user's required effort*, *Law of practice*, *Information revealing*, *Inform about waiting time*, *Language*, *Privacy*, *User control and freedom* and *Customization*.

Different **Detection** techniques are used to register digital content into the real environment. We grouped 25 statements (4.99%) into five clusters related to detection like *Image detection*, *Surface detection*, and more techniques like *Spatial mapping*. Other statements like *"Show users how to find a surface using their phone. Use illustrations or animations to show users how to scan properly"* [133] can be found in the *Coaching view for detection* and *Handling interruptions/relocalization* clusters.

The topic **Guidance** collects 35 statements (6.99%) in three clusters. The biggest cluster is about *Attention directors* with 20 statements because the combination of the limited field of view and the three-dimensional characteristic of MR makes it necessary to help users find offscreen elements. Another aspect of guidance is *Instructions*. They should be clear and fit the media, *"[f]or example, if you want users to swipe, give them an arrow or a hand icon rather than showing the word 'swipe'"* [133]. The last cluster is about *Onboarding* in an MR application.

We put 13 statements (3.99%) that mentioned other people—either actively participating in the experience or passive bystanders—in the topic **Multi-user experience** with three clusters named *Multiuser*, *Social acceptance* and *Shared spaces*. We also found 20 statements about **Technical recommendations**. We built the following clusters: *Spatial anchors*, *Performance*, *Hardware properties*, *Device support*, *Landscape/ portrait mode*, *Colliders for finger gestures* and *System architecture*.

22 Statements (4.39%) like *"A sound effect or bump sensation is a great way to confirm that a virtual object has made contact with a physical surface or other virtual object"* [8] are part of **Feedback**. We created a cluster for more universal *Feedback* statements but also for specific feedback like *Haptic feedback for phones* and *Audio feedback* besides *Audio* in general, *Notifications* and *Immersion*.

Nine statements (1.8%) are *Platform Specific*, such as Apples' *AR badges and glyphs*, *Specific Magic Leap style guidelines*, and *Permissions*. Statements about elements to control the flow in the application or to open a menu are collected in the **Controls** topic. There are 19 statements (3.79%) in the clusters: *Keep the focus on AR experience, but use 2D-UI on-screen elements when needed, Control placement in screen space* and *Hand menus*.

The topic **Spatial Design** consists of 50 statements (9.98%) in four clusters. The cluster *Content placement* includes statements about how to arrange content spatially. Due to technical limitations, the *Field of view* needs to be considered. The cluster *Anchored UI* collects statements like *"VR and AR experiences should typically attach UI elements to the environment, a tracked controller, or the user's body. 'Anchored' UIs provide higher cognitive ease and require less time to learn."* [157], but they have to be separated from statements about *Head-locked content* because *"Implementing 1:1 HUD rotation and translation relative to the user's head motions should always be avoided"* [233]. Different spaces like intimate, social and public spaces are considered in the *Design space* cluster.

8.5 Similarities and Differences between SDRs and PDRs

Our analysis indicated four dimensions of differences and similarities that we will discuss in detail.

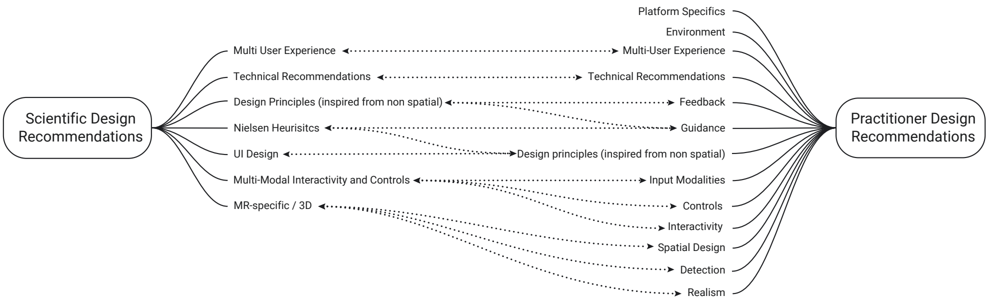

Figure 21

Topics of both SDRs and PDRs and their inter-cluster relationships

8.5.1 Focus on MR Unique Design Challenges

The SDR data set reflects that it is popular in MR research to apply the design heuristics from Nielsen [253]. As these heuristics originate from usability problems of non-spatial systems in the 90s, an appropriate adaption of their for spatial systems is at least questionable [76]. Nevertheless, statements oriented on either Nielsen's heuristics or other concepts from non-spatial UI design comprise most of the SDR data set. As a result, those proposed recommendations are too generic. Design recommendations should refer to cognitive abilities and human perception [170] and require being unspecific to a certain extent. Therefore, overlap with existing recommendations from classical UI design is likely. However, the statements contained in SDRs appear to be less applicable and relevant in the context of spatial UI design due to their lacking focus on spatial features and issues, such as environment, user orientation, movement, and position in space. Statements considering spatial aspects are also present in SDRs but less dominant than in PDRs.

That becomes more tangible by analyzing clusters of similar topics in SDRs and PDRs, such as ergonomics. As MR systems enable whole-body movement and display spatially distributed information, the physical and mental strain tends to be higher than in non-spatial systems. Therefore, specific recommendations for ergonomic use are indispensable. In SDRs, they are often derived from design principles or heuristics for non-spatial UIs. Those statements remain on a superficial level, for example, *"Consider usability and comfort. If a long-term usage is desired, take a comfortable interface for the user into account and consider human factors*" [191]. Even more specific formulations are stated without further detail: "*Consider the natural viewing angle*" [373]. PDRs consider ergonomics from more diverse perspectives, resulting in a larger span of recommendations regarding ergonomic issues caused by spatial activities such as muscle fatigue, eye strain, or neck strain. For instance, Microsoft provides a detailed design recommendation for HMDs: "*To avoid eye and neck strain, content should be designed so that excessive eye and neck movements are avoided. Avoid gaze angles more than 10 degrees above the horizon (vertical movement). Avoid gaze angles more than 60 degrees below the horizon (vertical movement). Avoid neck rotations more than 45 degrees off-center (horizontal movement).*" In conclusion, SDRs focus less on MR-specific design features and often remain on a superficial level compared to PDRs.

8.5.2 Abstraction Regarding Devices and Their Ecosystems

SDRs are mostly device agnostic and do not emphasize the need to comply with device limitations, hardware properties, or ecosystems. In contrast, several PDR statements guide compatibility with the devices' hardware features, software platforms, and respective ecosystems. For example, Magic Leap published guidelines for dealing with platform limitations and conventions: "*Certain control actions must be familiar, intuitive, and adhere to platform conventions*." Similarly, Apple's guidelines contain the use of their AR badges and glyphs to trigger the start of an AR experience: "*Keep badge placement consistent and clear. A badge looks best when displayed in one corner of an object's photo. Always place it in the same corner and make sure it is large enough to be seen clearly (but not so large that it occludes important detail in the photo)*."

Other statements address hardware properties and how to apply them in usable and compelling experiences. Those properties are, for instance, Magic Leap's controller with defined button actions and their use. Similarities exist regarding device-specific hand-tracking gestures or design recommendations for hand-menus (Microsoft), which are missing in SDRs. Additionally, technical limitations and how to avoid them are essential aspects of PDR. For instance, we found recommendations for solving technical procedures like spatial mapping (Microsoft) or texture resolutions: "*To let your scene load faster, don't make textures too large. Their resolution should be 2k at most*" [133].

Finally, there are also firm guidelines regarding publication in app stores. One example provides the Magic Leap documentation: "*Ensure your immersive app presents a clear exit or quit option when users tap the Home button. In the future, failing to enable this will cause your app to fail the submission process*." It seems apparent for companies to explicitly address hardware features and platform conventions to establish standards for their ecosystem. These standards will lower the entry barrier for users and require less effort when learning how to use such applications. Additionally, it makes sense that design recommendations originating from human–computer interaction (HCI) research focus on the medium rather than specific devices because HCI research is not bound to ecosystems or hardware. Therefore, we assume that SDRs are, in general, device agnostic and explorative regarding applied technologies or mixed hardware approaches, whereas PDRs are device- and ecosystem-specific and focus on establishing standards. However, PDRs contain several design recommendations that are neutral regarding hardware, platforms, and ecosystems and hold in a broader context of MR design. Such topics are, for instance, realistic appearance of objects, recreation of real-life physics, designing for dynamic environments, and object manipulation. Therefore, we can say that statements in SDRs focus on a subset of PDRs regarding design recommendations.

8.5.3 Level of Detail and Abstraction of Content

Design recommendations require a certain abstraction level to be used in diverse contexts. For example, recommendations might have a too-narrow scope if they are based strictly on layout choices for unique application settings rather than cognitive abilities and limitations. However, design recommendations need to provide context to evaluate their relevance, adapt them to a broad set of UI designs, and allow designers to understand their purpose.

Our analysis reveals the amount of information given with a design recommendation and the type of their abstraction as the main differences between SDRs and PDRs. SDRs tend to be of high abstraction regarding intended use and effect and give few explanations. That requires rereading parts of the statement's source to understand its potential for designing a system. At the same time, that level of abstraction leaves room for interpretation and experimental approaches. For example, Youm et al. formulated six design recommendations through their experience in mobile AR game development, such as: "*Provide useful interactions with the AR content: Provide information related to the product or object that empowers the user interaction and experience*" [377]. It is unclear what "useful interaction" means, how it affects the experience, and under what circumstances such information should be provided. Hence, this needs to be explored.

That lack of context makes SDRs appear theoretical and difficult to apply without experimenting. However, scientific papers describe detailed contextual information regarding the specific use cases and consider that also in the recommendations, for example, "*AR design content should be based on the curriculum, and the time used for AR-based teaching should not be longer than that used to teach the same content with conventional teaching model*" [212]. Such context information cannot be found in PDRs.

Furthermore, authors of SDRs rarely provide categories for thematic clustering. Those that do provide thematic clustering often refer to theoretical frameworks, abstract mental models, or ongoing research discourses, such as Ko et al.'s usability grouping system with classifiers like "User-Information", "User-Cognitive", or "User-Interaction" [181]. That categorization abstracts design recommendations from the intended use and effect but supports the identification of existing concepts in HCI research. In contrast, PDRs use categories regarding their context or intention from a developer's or a user's perspective, such as Google's AR guidelines with categories like "Environment", "Movement" or "Realism." Furthermore, PDRs abstract from the application context rather than the intended use and effect: "*Let the user select a virtual object to identify, manipulate, and interact with it. [...] Use color combinations, glowing outlines, or other visual highlights to let users know. This is especially critical in apps where multiple objects can be selected*" [133]. Additionally, PDRs often present concrete solutions for usability issues and include examples and illustrations to facilitate their design recommendations. Consequently, PDRs leave fewer open questions and encourage application rather than experimentation.

We conclude that SDRs mainly foster experimentation through abstracted design recommendations from the intended use and effect. Furthermore, they reflect ongoing research discourses and provide general applicability without giving concrete examples. In contrast, PDRs are formulated from a developer's or user's perspective, abstracted from the application context, and provide examples of intended use and effect. While they usually do not restrict experimentation, they emphasize good practices.

8.5.4 Covered Topics

The topics and clusters emerged from the recommendations' content following a bottom-up principle. The identified topics and clusters can be used in future work as a reference to evaluate new recommendations for semantic similarity and to identify gaps in thematic coverage. In comparison, SDRs and PDRs share similar concepts and topics (see Figure 21) on a divergent level of detail, such as statements regarding general design principles from non-spatial contexts, multi-user experiences, and technical recommendations.

Furthermore, the data sets differ regarding their variance of topics. For instance, we identified MR-specific statements in both data sets dealing with the interplay of virtual and real content, but only a few statements in SDRs address this topic. In contrast, PDRs consider a broader spectrum of issues such as the environment (e.g., space requirements, users' physical safety, dynamic environments, and design spaces), the detection of images and surfaces, visual realism, physics simulations, head-locked content, and general anchored UI elements.

Given the differences regarding the level of completeness and pervasiveness of topics in both data sets, we conclude: SDRs provide a horizontal, framework-like coverage of topics, including experimental areas like tangible AR. PDRs focus on horizontal and vertical topic coverage to ensure applicability with a greater level of detail. We argue that this is related to two factors: The first factor is the availability and applicability of mass-market-ready hardware. Hardware is rarely at a high level when research begins to investigate a topic. Therefore, it is challenging to formulate detailed design recommendations beyond interaction paradigms and frameworks. In contrast, PDRs explicitly investigate the applicability of existing hardware in realistic scenarios to minimize the entry hurdle for practitioners. That leads to better coverage of subtopics and edge cases, including observations from applying technology in the wild, such as dynamic environments, users' physical safety, and accessibility issues. The second factor is that long-term studies in HCI are rare, and evaluations are often part of short-term user studies or lab work [79, 182]. That leads to relatively small and potentially biased data sets due to the limited time users are given to adapt to new systems. Hence, a topic can only be investigated in-depth if new work focuses on applying existing design recommendations to adapt and refine them. Nevertheless, we found only a few papers experimenting with the adaption of previously defined design recommendations and publishing their results, such as Endsley et al. [97] and de Almeida Pacheco et al. [76]. However, companies can evaluate their existing hardware and applications in realistic settings or draw from a vast set of applications published by the community or created by their developers. That leads to a faster, many-faceted, and consistent, in-depth analysis of potential and applicable design recommendations matching platform and medium-specific topics.

8.6 Discussion

The following discussion addresses our results in the context of our stated research questions. Because we described our findings regarding RQ1 in Section 8.5, we concentrate on RQ2 in Section 8.6.1 and RQ3 in Section 8.6.2. As detailed in Section 8.5, the main differences between SDRs and PDRs relate to four dimensions: Focus on design challenges unique to MR, abstraction regarding devices and ecosystems, level of detail and abstraction of content, and covered topics. In addition, design recommendations have at least two target groups: researchers and practitioners. Consequently, recommendations serve different needs and purposes and require a clear distinction regarding their intended use and effect.

8.6.1 Perceived Relevance and Irrelevance of Design Recommendations

The issue with design guidelines being perceived as irrelevant has been reported in recent XR-focused work [11] and for design recommendations originating from practice. Beck and Ekbia investigated reasons for the perceived irrelevance of scientific output for practitioners and identified three potential reasons: the problem of communication, abstraction, and research-induced bias [25]. Building on that work, we identified three more factors potentially contributing to perceived relevance or irrelevance for design recommendations in research and practice:

The terms "design principles," "design guidelines," and "design heuristics" are regularly used as synonyms However, as pointed out in Section 8.2.1, they are not the same [114, 255, 160, 267]. Hence, published design recommendations add the problem of ambiguous wording, which leads to search results containing design recommendations of varying abstraction levels with different purposes. Based on our findings, the levels of detail and abstraction regarding devices, application, and context are crucial for serving the needs of the target group and therefore add to perceived relevance or irrelevance. Consequently, resolving ambiguous wording requires specifying the target group and the application context, as discussed in the next section.

Design recommendations fail to state their intended use, goals, and target group. Design recommendations address different target groups with different types of information. Whereas scientific recommendations aim for divergence through experimentation, practitioner recommendations provide greater detail for guiding application and aim for convergence [286]. As a result, the latter is perceived of lesser relevance in a scientific context, whereas design recommendations providing superficial guidance require specification effort to be applicable in practical scenarios [41, 125, 154]. It helps to decide if a design recommendation can serve one's needs by explicitly stating the target group and the intended use. Nevertheless, this is insufficient if design recommendations are excluded from search queries due to prejudices against their publication channels, as we will discuss in the next section.

The medium of publication denotes who perceives design recommendations as being relevant. Our SDR data set contains design recommendations targeting practitioners and researchers. However, as we know from literature, practitioners rarely consider scientific databases or attend conferences such as CHI [50, 340]. This means that design recommendations for practitioners are most likely not seen if they are published exclusively in academic media due to a biased assumption of irrelevance. Beck and Ekbia also suggest that inaccessibility feeds this prejudice because scientific publications are often hidden behind paywalls [25]. As a consequence, design recommendations for scientific purposes are well-placed on scientific platforms, whereas design recommendations for practitioners are a good fit for respective platforms like Medium, YouTube, and Stack Overflow [11].

8.6.2 Towards establishing good design practices

Creating and defining good design practices require both scientific and practical exploration and application of design recommendations. Based on our study, we would emphasize the following six implications:

Investigate, validate, and adapt existing design recommendations. Ideally, focus on the context of intended use and effect for spatial system development as well as the recommendations' impact on design and user appropriation. The key to providing relevant and applicable design recommendations is their grounding and validation in well-executed user studies combined with a diverse pool of data sets. Hereby, long-term user studies should be preferred to minimize bias, such as the novelty effect [304].

Build recommendations on reliable and transparent data; share experiments and practices. Defining design recommendations requires experience and appropriate data. Hence, recommendations should build on distinct and implemented designs. This could also be achieved by considering high-quality data sets published by the AR/VR community, which provide essential metadata regarding design decisions, potential design patterns, good practices, and their evaluation, including the process of requirements elicitation, demographics, study design and procedure, environment, and a detailed application description. Finally, stating how a design recommendation can support a researcher or practitioner and enhance the application's usability and user experience eases assessing a design recommendation's relevance.

Recommendations for research need to foster experimentation and strive for generating knowledge (divergence) [286]. Design recommendations for research should aim to build a thematic framework that could be explored and specified through application, observation, and evaluation. This explorative approach enables researchers to identify several potential solutions, to experience conceptual failures and working solutions and generate knowledge about a design space's specific challenges and rules. Such design recommendations should be grounded in and discussed regarding existing discourse and established concepts, paradigms, and theories. Finally, design recommendations for exploration aim for generalization and abstraction from context, domain, and user intent. This makes them difficult to apply in practice [286], which requires more specific recommendations.

Recommendations for practice need to guide the development of usable systems (convergence) [286]. Design recommendations for practitioners must guide system development, ideally supported by detailed explanations and examples showing the effect of use. Those examples need to enable creators to learn about and understand both the opportunities and limitations of designing for spatial media and its implications for users using the resulting application. Contrasting design recommendations for research, they foster design synthesis [286] and can take hardware specifics into account.

Be clear about intended use and effect, user groups, and wording. Due to the ambiguous use of design principles, guidelines, and heuristics, communicating the intended use and effect of design recommendations is difficult solely based on the wording. While it is desirable to better differentiate between the types of design recommendations for minimizing confusion, it is unlikely that new or enhanced definitions will be adopted likewise from science and research in the near future. Therefore, we suggest including details about the intended usage and context of design recommendations. Following this suggestion, recommendations need to be formulated accordingly to fit the needs of the target group. This includes matching publication and distribution channels of such recommendations.

Aim for a clear distinction of design recommendations and their purpose in research and practice. As we noticed, there is no well-adapted definition of design principles, design heuristics, and design guidelines. While existing work describes their derivation and transformation [267, 312], the current state of the art lacks a proper differentiation and its adoption. However, providing guidelines for formulating appropriate design recommendations requires dedicated research building on existing work such as [114]. When working towards more distinct definitions, potential factors are (1) intended use and effect, like divergence and convergence and (2) level of abstraction regarding domains, devices, and user intent.

8.6.3 Limitations

We started with investigating AR design recommendations but diverged to VR and finally MR. The mixture of those terms in literature makes it difficult to differentiate our findings because AR and VR are not interchangeable. However, only a few guidelines from SDRs were explicitly created for VR applications. When creating PDRs, we excluded VR-specific guidelines from Google and LeapMotion to ensure comparability. We focused on recommendations of six market-leading AR-related companies. However, there are additional sources for guidelines from practice, for instance, blogs like Medium or less known companies. Including their recommendations warrants a deeper study. In contrast to design guidelines from scientific literature, practitioner design recommendations are constantly being updated. Hence, the design recommendations used in our analysis might have been updated or removed by the time this paper was published. Furthermore, it is known that MR also combines several other disciplines, such as game design and tangible interfaces. We did not perform an explicit search in those areas due to the scope of our research questions. This might exclude potentially applicable design recommendations.

Finally, there might be scientific work that does not focus on formulating design recommendations but still publishes good practices. As a common limitation of literature studies such as ours, those types of publications were not considered because the papers did not contain our search terms.

8.7 Conclusion

We investigated the current state of existing design recommendations for MR applications. The literature review examined 89 scientific publications and documentation from companies actively participating in AR and MR development (Apple, Google, IBM, Magic Leap, Microsoft, and Spark AR). In total, we extracted 875 statements from the materials that can meaningfully guide MR application design into two separate data sets based on the source of the statement. We analyzed these data sets through independent affinity diagrams to find common topics in both areas to further investigate different and similar recommendations for MR design. We were able to demonstrate the differences between design recommendations from science and practice. Our findings present insights regarding four key aspects: the focus on design challenges unique to MR, an abstraction regarding devices and ecosystems, the level of detail and abstraction of content, and covered topics. Finally, we deduce six implications for future design recommendation work regarding appropriate adaptions of existing design recommendations, a call for more exploration in MR design, sharing current experiences and practices with the community, appropriate definition of the target group, the intended use of context and formulation of recommendations to guide the development of usable MR systems and a clear distinction of design recommendations and their purpose in design research and practice.

References of the Literature Review

Below, we list the work used to elicit design recommendations from scientific papers contained in SDRs:

[1, 4, 5, 6, 7, 9, 14, 16, 27, 28, 29, 30, 33, 39, 57, 58, 66, 71, 74, 75, 76, 77, 81, 82, 89, 96, 97, 98, 116, 118, 119, 120, 122, 124, 129, 139, 143, 149, 152, 158, 168, 171, 172, 173, 174, 175, 179, 181, 184, 188, 191, 192, 204, 206, 212, 213, 216, 226, 237, 243, 261, 258, 266, 269, 270, 272, 281, 288, 295, 296, 303, 315, 321, 322, 324, 341, 347, 348, 349, 350, 355, 358, 359, 367, 369, 373, 375, 376, 377]

Part III

Research Outcome and Discussion

9 Summary of XR Interaction Design Practices and Challenges – RQ1

Part II presented the conducted empirical work and reported manifold insights into interaction design practices. It further revealed the complexity of issues faced by XR interaction designers as they form practices in an emerging field. The following sections summarize and condense the insights to answer the research question:

RQ1 What are interaction design practices and challenges in professional XR application development?

The following sections utilize the practice theory lens according to Shove [314] to structure the main findings. Shove's main concepts are briefly recapped as follows (see Section 2.4): According to Shove, practices consist of the three elements material, competence, and meaning. Material comprises all objects that are required to perform a practice, competence addresses respective explicit and implicit knowledge, and meaning is collective or individual motivational and emotional knowledge associated with the respective practice or its materials. All three elements are closely intertwined and observed through the activity of prototyping for XR interaction design.

As a final remark before diving into the main findings, it is important to emphasize that XR is a dynamic field regarding hardware and algorithmic innovation. While this aspect is not explicitly mentioned and analyzed in the presented empirical data, the theme of constant change is interwoven in several observations also presented in the following sections. Therefore, the themes of change surface from time to time when structuring the findings regarding materials (Section 9.1), competences (Section 9.2), and meanings (Section 9.3).

9.1 Materials in XR Prototyping

Materials incorporate all artifacts available to perform a practice, including "objects, infrastructures, tools, hardware, and the body itself"

[314]. In the context of XR prototyping and based on the empirical data, materials, of course, include XR specifics, such as XR display and tracking devices and controllers as well as respective software like game engines and software-based XR prototyping tools. As XR is a spatial technology, physical space itself becomes a material involved in XR interaction design practices. However, also *old* materials can be found which were adapted from related fields involving (aspects of) interaction design, such as architecture, game design, and classical interface design disciplines that follow the windows-icons-menus-pointer paradigm. Such materials include prototyping techniques and tools, manifestation types of prototypes, design processes, design conventions, and standards.

The following sections further summarize the applied materials based on the empirical data presented in the Sections 5 to 8. For the sake of reporting, materials are grouped in the following five categories: hardware, process models, prototyping tools and techniques, prototyping material in the sense of material used to construct a prototype/design artifact, and manifestations of prototypes. Further, the following sections observe material regarding new materials, old materials, and core concepts of XR prototyping.

9.1.1 Adapting New Materials

Adapting new materials is intertwined with developing new competences and meanings. This subsection focuses on new materials in the sense that they are likely unique to XR compared to other screen-based media and respective interaction design practices. Those new materials include hardware, mainly software-based prototyping tools, and the two spaces *prototyping space* (i.e., the space in which the application is prototyped) and *target space* (i.e., the space in which the finished product is executed). However, materials that are not novel because they have been used in other related fields of interaction design but *are new to XR interaction design* are listed separately in Section 9.1.2. First and foremost, the introduction of new hardware has to be listed as one of the fundamental new materials for XR interaction design. Usually, new hardware is equivalent to new XR headsets and/or controllers for interacting with virtual content. However, new hardware could also include hardware for creating 3D models, which was not in scope of the empirical studies presented in Part II. Participants frequently reported the continuous change of and incompatibility between new and old XR devices. This also means that each device brings its own limitations, such as the field of view, screen resolution, tracking capacity, weight, and supported interaction modalities that a potential designer has to take into account.

Furthermore, XR devices are frequently incompatible with prototyping tools specifically created to support XR interaction design. Such tools are, for example, Doodle Lens or the nowadays discontinued Microsoft Maquette which enables designers to prototype the spatial layout of their application. Also, the spatial sketching tool Gravity Sketch has to be listed here as well as plug-ins or extensions for integration in existing software-based tools. Such plugins specifically support XR interaction design, for example, through integration in existing software tools. Such an example is the development and application of the Microsoft Reality Toolkit that can be integrated in the game development platform Unity, one of the dominant programming platforms for XR development.

Further, the differentiation between target space and prototyping space is new in the sense that physical and spatial properties of both have to be taken into account when creating XR applications. Such properties are, for example, scaling, distances, lighting conditions, and bystanders.

Finally, it is worth mentioning that XR interaction designers reported to use new sources of knowledge, such as XR applications they downloaded in app stores or saw on social media or in movies as a supportive tool for getting inspiration, and platforms for exchanging information and good practices, such as Discord groups, Slack channels, and device manufacturers' websites. While making use of such sources is not new or unique to XR interaction design, the respective platforms, information, and content have been created for XR communities and are therefore listed as new materials. However, interesting in this regard is a reported lack of design guidelines and good practices [11] (Section 6, Section 7), and the fact that XR interaction design research has frequently published respective material over the past decades (see Section 8). This observation will further be discussed in Section 10.

When addressing new materials, XR interaction designers mentioned the frequent changes of available XR specific hardware and incompatibility of devices regarding their technical specifications and consistency of concepts and features like gestures, voice commands, or tracking ability. Further, new prototyping tools were manifold, but either too simple for designers to be used beneficially and produce sufficient outcome, or too complex regarding the required technical and programming skills.

9.1.2 Reusing Old Materials

Old materials have been used in the past but originate from a different medium or field of application. Such materials include hardware, process models, prototyping tools and techniques as well as prototyping material and the respective manifestations of prototypes. However, at the time of the presented studies, XR interaction designer was not a homogeneous profession (see Section 6) with dedicated educational programs [110]. Based on the empirical studies reported in this work, XR interaction designer is an umbrella term for professionals originating from different, more or less related domains who all bring with them their own set of materials, competences, and meanings. Therefore, materials that are known for some of the professional XR interaction designers are likely to be unknown and new to others.

In addition to new hardware like XR headsets and respective controllers, existing hardware like personal computers or smartphones are part of the material of XR interaction design practice. Furthermore, participants reported to rely on known process models like Scrum, Design Thinking or other user-centered workflows – however, analyzing process models was not the main focus of the empirical studies.

Well-known prototyping methods and techniques were often reapplied over the course of creating XR applications. Participants frequently addressed such methods and techniques as fall-back or robust but limited approaches to breaking down the complexity of XR interaction design and applications. Such techniques and tools were both software-based (e.g., Figma, Adobe XD, balsamiq), or classic tools like sketching with paper and pencil, physical prototyping using card boards, or acting-out more complex elements of interactivity. Also, techniques from domains like game development or architecture/3D modelling have been integrated as existing materials, for example, gray-boxing or sculpting. In this line, prototyping material – i.e., the material used to construct prototypes in contrast to material as it is defined by the social practice theory – does not differ from the classic materials used in, e.g., 2D interface design. Consequently, manifestations of prototypes in XR interaction design are similar or the same compared to more or less related disciplines. However, participants reported to frequently using ephemeral prototypes, prototyping by demonstration, or narration and acting-out as lightweight fall-back methods if their competences or available material was not sufficient (see Section 9.2).

Finally, XR interaction designers reported that old materials are oftentimes not sufficient to prototype complex applications, specifically animated, interactive, or spatial aspects of the target application. In fact, participants mentioned that more complex and unique interactions require them to learn and adapt to more technical tools and respective competences like programming in the game engine Unity to achieve their design goal (see Section 9.2).

9.1.3 XR Prototypes as Material

In addition to regular materials for XR prototyping (see Section 9.1.2), Section 7 investigated elements of XR prototypes describing manifested concepts and properties of XR applications. Prototypes usually addressed ten different core concepts: spatiality, physicality, world-building, flow – story, flow – hierarchy, control, locomotion, interactivity, cinematography, and content. Those concepts were present in applications across various domains and target devices, which allows the conclusion of them being robust elements of prototyping activities for XR applications. However, when observing those core concepts individually, they are not XR specific as, for example, spatiality is also present in regular 3D computer games running on a 2D screen. Nevertheless, the fact that the user itself is becoming a part of the application environment or the application becomes a part of the user's physical surroundings rather than observing the virtual elements through a separating screen, makes the composition of those elements unique to XR.

To prototype those aspects and their composition, designers applied both new and old as well as software-based and physical tools and prototyping materials. However, they reported that identified tool chains are sometimes incompatible if they have to design for a new device. This forces them to rebuild their tool chain and potentially identify and learn new tools.

9.2 Competences for XR Prototyping

Competences, according to Shove, combine "multiple forms of understanding and practical knowledgability" [314]. In the context of XR, those competences do not only address the theoretical knowledge and practical skill to operate, use, and shape material. It also addresses the knowledge about how to inform themselves about newly released hardware and applications, which step to take when in the overall design process, how to involve end-users and stakeholders, how to find and chain tools to achieve design goals, how to streamline designs for specific devices and their properties, and how to manifest ideas in ways that it serves the current task. The following sections provide insights into competences acquired by and required from professional XR interaction designers based on the empirical data reported in this thesis.

9.2.1 Developing New Competences

As XR is an emerging technology, professional designers encountering XR as a medium to design for likely might not have first-hand experience. As reported in Section 6, it is difficult for them to identify the potential and limitations of this technology as they built their understanding on marketing material and renderings rather than on using hardware and respective software applications. Further, specific hardware comes with specific limitations, for example, a reduced field of view that disqualifies design cues like peripheral vision. Also, devices have diverging limits regarding interaction modalities as well as tracking or rendering capability. Despite hardware specific limitations, spatial interfaces also require to think in three dimensions and be aware of the different behavior and placing of virtual content anchored in physical space. While some designers reported to learn such aspects by prototyping and failing, others mentioned that their interdisciplinary teams involve more experienced creators or developers early on in the design process to evaluate ideas and teach about concepts and tools – they rather build awareness about potential technical limitations than hardware specific knowledge. To gain new knowledge, participants reported to use XR applications they downloaded from app stores, reference screen recordings from social media or movie clips, read design books, or participate in respective XR design communities (e.g., Discord, Slack). Further, the empirical studies revealed that due to the current lack of specialization in XR interaction design, a broad skill set is required not only with respect to technical and programming skills, but also 3D modeling. This leads to outsourcing competences where possible (see Section 9.2.3).

9.2.2 Reapplying Old Competences

Participants frequently relied on competences they had acquired in the past, e.g., when designing for 2D interfaces or games. However, they also reported to be limited in this regard due to required programming or technical skills to build or alter interactive prototypes with a certain complexity to try out their ideas. The limiting aspects they raised frequently were prototyping interactivity and spatiality due to a lack of tool support and the increased complexity through the third dimension. However, they also mentioned competences related to identifying tools that matched their tasks and skill level as well as understanding the limitations and potential of used technology. Competences they reapplied frequently and successfully were related to the overall design process (e.g., applying the user-centered design methodology or iterative prototyping) as well as the general skill of breaking down a complex design problem into smaller packages.

9.2.3 Outsourcing Competences

As materials and competences are strongly intertwined, challenges arising from the lack of tool support, the increased complexity of XR as well as the broad skill set required to combine and understand the new material become visible when both aspects are observed together.

When focusing on prototyping, three main issues arise for designers regarding their competences and materials: Firstly, known tools from 2D design are unable to fully support XR's core concepts. This implies that existing competences and materials do not fully match XR's demands. Secondly, new *designerly tools* [334] lack the breadth and complexity to support the combination and materialization of multiple XR core concepts. This means that new materials matching a designer's competences are not sufficient to support prototyping XR's core concepts. Thirdly, tools that are able to sufficiently support XR's core concepts are over-demanding regarding technical or practical skills as they were originally targeted at developers or require specific and complex skills that are difficult or time intensive to acquire, such as 3D modeling – resulting in powerful materials not matching designers' competences.

To overcome at least some of those limitations, designers outsourced such tasks whenever possible, for example, through actively involving developers to produce artifacts of a certain level of complexity based on their ideas: For idea externalization and manifestation, designers reportedly utilized materials and competences they had acquired for 2D application design to produce respective artifacts, provided limited artifacts based on limited tools for XR design, researched or referenced existing sample implementations (e.g. based on published games), or fell back to acting-out complex system behaviour. Based on their descriptions and fall-back artifacts, developers implemented the designer's concepts in XR. As those artifacts were often inaccessible for alterations through designers due to their lack of tool competence, designers provided feedback and asked developers to adapt the artifacts accordingly. However, as also reported, experienced teams developed their own tools or tool plugins to overcome the lack of programming skills. Finally, designers also mentioned platforms they access to utilize ready-made assets as an outsourcing of modelling competences, or prebuilt interface elements if accessible and applicable to their design idea (e.g., MRTK).

9.3 Meaning in XR Prototyping

Meaning, as the third element of social practice theory according to Shove et al. [314], encompasses emotion, motivation, and beliefs. In the context of XR prototyping, meaning was externalized and embodied in constructed prototypes or ready-made artifacts originating from sources outside the current project. Those were oftentimes applied to overcome communication barriers as involved parties lacked a shared language and a common ground regarding concepts. The insights in this work regarding meaning in XR prototyping are summarized in the following sections.

9.3.1 Developing New Meanings

The lack of shared language reported by participants in Section 6 and 7 caused several issues in communicating concepts and ideas about both the targeted product as well as XR itself. As compensation, experienced XR interaction designers developed a visual language they established with their team based on colors, annotations, line types, and symbols to reduce otherwise required explanatory overhead of rough design ideas. Also, participants reported to use references to existing applications and games through which they shared experiences and memories with their team members. By referencing such experiences, designers and developers constructed a shared library to which they referred when discussing prototypes, rough ideas, and their alterations.

9.3.2 Reusing Established Meanings

There are several occasions in which *old* meanings surfaced in the context of prototyping. For example, the selection and application of tools shaping a prototype was reported as a compromise of time, skill in operating a tool and shaping respective material, design intent, target group, and requirements (see Section 6 and 7). Participants also reported to use unusual tools to form artifacts as long as they served their design goal and intent (e.g., GIPHY, a collection of GIF files, see Section 7), and, if team members knew each other well, produced less sophisticated prototypes.

Several participants also related some of their doings to unwanted practices they still executed due to a lack of resources, such as the late or seldom involvement of users for tests, as the quality and usability of the developed product might suffer (see Section 7).

However, the empirical studies, especially the deep-dive into prototyping reported in Section 7, brought to light that well-known and established concepts like *fidelity* also did not have a shared meaning but different interpretations. While some participants reported it to be a binary system of low- and high-fidelity, others proposed a multi-dimensional spectrum that is bound to single features of a prototype rather than the artifact as a whole.

9.3.3 XR Prototypes as Carriers of Meanings

Prototypes play a central role to bridge the gap of concepts between different parties involved in an XR project, such as designers, developers, and customers among others. A crucial application of prototypes was to convey the *feeling of XR*. As XR applications diverge significantly from 2D interfaces due to the addition of a third dimension, they facilitate depth and spatiality, resulting in increased immersion and a lower barrier regarding feeling present. However, this sensation is difficult to convey and designers participating in this works' studies frequently voiced experiencing the characteristics of XR as a crucial part of designing for and communicating about them as the feeling of those interfaces cannot be sufficiently explained.

As described in Section 5, 6, and 7 prototypes were frequently applied as carrier of meanings to overcome such communication-related issues and the lack of a shared language. For example, lightweight and often ephemeral prototypes were used when designers reached their skill limits to operate new tools or form and combine respective material and XR core concepts.

10 Design Implications for XR Interaction Design Tools – RQ2

Having laid out the current challenges for XR interaction designers in the industry (see Section 9), this section reflects on the findings regarding the presented empirical data and related work. Based on that, design implications for potential XR interaction design tools are formulated to provide answers to:

RQ2 What are design implications for XR prototyping tools based on professionals' XR interaction design practices?

To achieve this, the insights provided in Section 9 are combined, aligned with existing work, and discussed in the following subsections. The respective insights are presented as implications for future research and design tool creation.

Revisiting the answers provided to RQ1, one of the fundamental challenges for professional XR interaction designers is the emerging characteristic of the field itself. Emerging fields are shaped by rapid innovation and only little consistency [326, 241]. As explained by Shove's [314] and Myers' [241] work, the logical consequence of this emergent characteristic is instability [314, 241] regarding materials, competences, and meaning of practices for XR interaction design – similar to the early years of web and mobile development [326].

Nevertheless, according to Myers et al., some sort of stability (i.e., surfacing standards regarding, for example, technology and interaction design techniques) is necessary to enable the construction of tools that support designing for such technology [241]. Shove explains that the stabilization and routinization of practices require sharing knowledge and experiences as well as developing standard specifications and regulations "to the point where [they] could be defined, taught and learned" [314]. Consequently, routinization "is not an inevitable result of an increasing density of interdependent arrangements, rather, practices are provisionally stabilized when constitutive elements are consistently and persistently integrated through repeatedly similar performances" [314]. It seems unlikely that this required similarity of performances will be reached through prescription – unless legislative or any other instance with appropriate levers would successfully regulate or dictate XR interaction design practice (for example, through platform and technology monopolies or legal regulations). Furthermore, successful performances of practice (or applications of design processes including used methods and tools) might not be transferable between projects due to a change in available material, competences or meaning. Therefore, practices might largely be formed and adopted by XR interaction designers themselves over the course of time. To support their development, a possible measurement is sharing, for example, design case studies, good practices, guidelines, and sample applications within the community of XR interaction designers.

However, as participants (see Section 6 and Section 7) and related work [326, 11, 248] report, guidance and good practices are difficult to find and apply [11, 248] or perceived as being irrelevant (see Section 8). This already indicates that focusing solely on guidelines as new tools is likely insufficient. As reported in this thesis' empirical work, the field of XR interaction design is complex – as are its challenges faced by XR interaction designers. This means that a combination of several aspects has to be considered when it comes to future tool design with *instability* being the most basic one. The following implications for future design tools are structured regarding their relationship to materials, competences, and meanings. Nevertheless, keeping in mind that the separation of those three elements of practice is blurry due to their mutual influence and connectedness [314] is important. Further, the focus of this thesis lies on prototyping performed and prototypes produced during XR interaction design practices.

10.1 Implications for XR Prototyping Tools as Material

Summarized from Section 9.1, old materials are oftentimes insufficient while new materials are unstable or incompatible with other materials or a designer's competences. For example, participants in Section 7 reported that tool chains have to be abandoned if the target device changes due to technical incompatibility, or that tools for creating animations require coding skills they do not possess. This means that current prototyping tools fail to support interaction designers in breaking down, exploring, and conquering the complexity of XR as a design space. Further, the current advances of XR devices paired with a lack of interoperability between devices and tool-rendered artifacts or between tools themselves [248, 326] reduce their applicability (Sections 7, 9.1) [11]. Finally, a lack of *relevant* examples, good practices, design conventions / standards, and guidelines [11] or their traceability and availability (Section 8) fails to reduce the complexity of the field and to provide guidance for (inexperienced) designers. With this as a basis, the following sections provide respective design implications for future XR interaction design tools with a focus on prototyping and the praxiological understanding of material as follows: 1) compatibility and interoperability of tools in Section 10.1.1, 2) tools reducing design and artifact production complexity in Section 10.1.2, and 3) flexibility of tools in Section 10.1.3. Table 9 provides an overview of the respective implications, that are further described in the following sections.

Table 9
Summary of the design implications for future XR interaction design tools, derived from the empirical insights of this thesis.

Section	Design Implication
10.1.1 Compatibility and Interoperability of Tools	• Create access to tool chain and domain knowledge. • Support standard or common data formats for upward and backward compatibility – also beyond XR-specific design tools. • Enable accessible artifacts and prototype manifestation transitions through technical and conceptual tool compatibility.
10.1.2 Tools for Reducing Design and Production Complexity	• Incorporate existing assets and building blocks. • Support the efficient development of interactivity and system behavior. • Support prototyping for dynamic spaces, MR, and social context.
10.1.3 Flexibility of Tools	• Align tools with designers' tasks and practices. • Enable taylorability and appropriation of tools.

10.1.1 Compatibility and Interoperability of Tools

One has to differentiate between two major aspects in the context of XR interaction design to discuss the compatibility and interoperability of tools: technical interoperability and compatibility on the one hand, and the compatibility of tools with a designer's practices and routines on the other hand. Both types of interoperability are closely related: *technical interoperability and compatibility* enables tool chains [248] that are more flexible and therefore easier to *integrate into designers' practices*. However, iterative prototyping further requires *conceptual interoperability* to enable designers to transition their ideas between various types of manifestations and respective tools.

Based on that, the following paragraphs present three respective design implications that address tool compatibility and interoperability:

- Create access to tool chain and domain knowledge.
- Support standard or common data formats for upward and backward compatibility – also beyond XR-specific design tools.
- Enable accessible artifacts and prototype manifestation transitions through technical and conceptual tool compatibility.

10.1.1.1 Create Access to Tool Chain and Domain Knowledge. The development of key tools required for prototyping is generally directed by third parties – usually hardware providers, who also determine platform regulations, ecosystem conventions, and distribution channels for applications (see Section 8). This ecosystem-centric focus on tools and devices can force interaction designers to abandon their tool chains if the target device is incompatible with previously accustomed prototyping tools (Section 6 and 7) [248]. Also, effective tool chains are frequently unknown to designers [11] which implicates that respective platforms and communities for collecting and sharing information, experiences, and good practices have the potential to become valuable design tools. However, as XR materials are rapidly evolving, such platforms are prone to becoming abandoned if they cannot provide up-to-date information and / or respective support for their members. Nevertheless, future XR interaction design tools might act as or evolve into central hubs for *communities of practice*, i.e., “individuals united in action” [214] that share common interests and build community knowledge [167]. This research area offers a vast amount of valuable perspectives and potential questions for future XR interaction design tool research that focuses on the establishment and sharing of competences (see Section 10.2). However, this direction is not further taken in this thesis due to scoping. Nevertheless, future work in this regard promises to be a valuable addition to the empirical insights described in this thesis.

10.1.1.2 Support Standard or Common Data Formats for Upward and Backward Compatibility – Also Beyond XR-Specific Design Tools. Currently, XR lacks technical standards for XR interaction design tools which negatively impacts the forward and backward compatibility of artifacts that need to be shared between prototyping tools to enable design iterations [248]. Such standards acting as a basis for common exchange formats are already under development but not yet supported by the majority of devices and tools (e.g., cross-platform [326]).

Related work sees this lack of compatibility as one cause for the fragmented and unclear tool landscape [248, 11, 326] that renders effective tool chaining difficult (Section 6 and Section 7). Furthermore, forward and backward compatibility also includes the digitization of physical prototypes (e.g., 3D scans of physical models, scanning and transforming sketches into 3D sketches) [247, 245, 327] and the physicalization of digital prototypes (e.g., printing digital 3D models). As participants reported, they frequently have to recreate prototypes from scratch when design ideas are iterated and a more sophisticated tool becomes necessary to add or refine a prototype’s properties. Due to a lack of standard exchange formats, simply exporting, re-importing in a different tool, and adapting prototypes based on designers’ insights is often impossible and creates respective overhead. This aspect violates Lim et al.’s *economic principle of prototyping* and will further be discussed in Section 10.1.2. However, as Section 7 reported, such incompatibility issues do not only address XR-specific prototyping tools as designers also integrate tools known from classical interaction design prototyping (e.g., Adobe Photoshop). Future tools should therefore also consider existing or evolving XR interaction design practices that integrate old materials (see Section 9.1).

10.1.1.3 Enable Accessible Artifacts and Prototype Manifestation Transitions Through Technical and Conceptual Tool Compatibility. The empirical insights of this thesis' work report that the technical incompatibility of prototyping tool chains leads to inaccessible prototypes that further impact both the autonomy of designers (Sections 7 and 6) as well as the quality of insights gained during prototyping activity [248]. The latter is reported as a cause of a limited idea iteration support over various fidelity stages [248], or reduced exchange and accessibility options in collaborative work settings (Sections 6 and 2.3, but similarly reported by Dow et al. [85]). While professional XR interaction designers are able to overcome those hindrances to a certain extent because their interdisciplinary teams enable skill outsourcing (see Section 9), fostering and integrating such standards is crucial for future tools.

However, it is equally important to enable the transitioning between different prototype manifestations during iterative design work. As previously explained, iterative design work requires the use of different prototyping tools to refine a target system's properties [248, 215]. Section 7 reports that therefore, designers manifest their design ideas as different prototypes and transition between manifestation types leading to abandon some aspects while keeping others unchanged (e.g., creating a spatial layout based on a story board). This requires the conceptual chaining of manifestation types when iterating design ideas (see Lim et al.'s concept of prototypes as filters [215]), and, consequently, also the conceptual interoperability of design tools. However, further empirical insights investigating how XR properties are manifested and transitioned in iterative design work are required, for example, based on the preliminary elements of XR interaction design prototypes reported in Section 7.

10.1.2 Tools for Reducing Design and Production Complexity

As highlighted in Section 2.2.3, Lim et al.'s *fundamental prototyping principle* describes prototyping itself as an activity that aims to create artifacts to filter the qualities of interest of an overall design problem or target system [215], thus, breaking down the overall design complexity into smaller, more manageable problems. Furthermore, the *economic principle of prototyping* highlights that the best prototype depicts options and limitations as simply and efficiently as possible [215]. As empirical data in this thesis describes (Part II), XR as a design space appears to be rather complex due to new materials, especially the third dimension, the immersiveness of XR as a technology, as well as the social and physical context of use. This complexity is multiplied by the emerging and consequently unstable characteristic of XR [241, 313] and the resulting lack of interaction design tool support [11, 248, 326] (Part II). The following paragraphs discuss design tools and their ability to further reduce design complexity based on those two principles and propose the following design implications:

- Incorporate existing assets and building blocks.
- Support the efficient development of interactivity and system behavior.
- Support prototyping for dynamic spaces, MR, and social context.

10.1.2.1 Incorporate Existing Assets and Building Blocks. As This thesis empirical work reported that prototyping interactivity and system behaviour was especially challenging without coding skills as the barrier enforced by the required technical proficiency of current tools is high for non-technical designers [11] (Section 6 and 7). In this context, tools featuring ready-to-use assets like 3D models, animations, hand-tracking, and activity triggers (e.g., triggers that activate interactivity based on distance, collision, or user action) can reduce the complexity of a design task. For example, the now discontinued tool *Torch* enabled designers to build code-free interactive AR prototypes. Nevertheless, due to the prebuilt assets and interactivity combined with a lack of standard exchange formats (see Section 10.1.1), Torch required designers to rebuild their prototypes from scratch when transitioning into a more sophisticated tool for refinement of the envisioned interactivity. However, as the empirical work in this thesis and related work [248, 241] reported, such prebuilt building blocks might result in tools that are too limiting when it comes to prototyping more complex applications that require non-standard interactivity. This aspect, is discussed in greater detail in Section 10.1.2.2.

10.1.2.2 Support the Efficient Development of Interactivity and System Behavior. The difficulty of prototyping (non-standard) interactions and behavior for system designs is an issue that is also reported in interaction design domains beyond XR [85, 210, 242]. Similar to the designers' approaches reported in Section 6 and Section 7, such existing works describe fall-back prototyping methods like acting-out system behaviour or prototyping by example [85, 210, 242] in situations where tools are too demanding regarding effort and skill. As reported in Section 6 and Section 7, designers used such prototyping approaches in situations where they outsourced required technical competences (see Section 9.2.3) or rapidly iterated design ideas with colleagues based on existing artifacts (i.e., games, books, movies) and shared experiences. However, instead of creating tools that reduce a designer's need to fall-back to such lightweight methods, future work should also look into tools that are able to support such widespread and design domain-arching practices. Therefore, respective prototyping tools could support such activities, for example, by providing a collection of adaptable sample animations and system behavior (see Section 10.1.2.1), by supporting reenactment and role-playing (e.g., *experience prototypes* [49], *programming by demonstration* [73]), or by offering the functionality of annotating artifacts to better describe and visualize animations [242].

As a potential basis for such work, this thesis' empirical studies reported on *ephemeral prototypes* as frequently applied and performed rather than persistent manifestations of prototypes. Designers participating in this thesis' empirical work described prototyping following such approaches as lightweight and practical regarding materializing, communicating, and iterating design ideas (Section 6 and 7). Further investigating this approach of prototyping seems promising, especially because similar practices were reported in existing works in related design domains (e.g., ubiquitous computing environments [85], or custom interactions in general software design [210, 242]). However, despite being an intuitive and natural form of expressing interactivity and behavior(Section 6), a major drawback of ephemeral prototypes is their lack of persistence, reproducability, and unambiguity or objectivity (see [242, 211] and Section 7). Consequently, future work in this regard needs to gain more insights into their construction, manifestation, and reproduction as well as means for the effective and efficient support of ephemeral prototypes and performative prototyping practices in future design tools.

10.1.2.3 Support Prototyping for Dynamic Spaces, MR, and Social Context. Finally, as described in Section 6, designing for a third dimension and, consequently, spatiality, physicality, and locomotion increases the complexity of XR applications. In addition, especially AR and MR, but also VR applications as well as MR applications (i.e., applications that could transition from AR to VR and vice-versa along the reality-virtuality continuum [235]) need to consider the variability of social and physical aspects of their surroundings. To reduce the complexity of spatial and proportional content, respective prototyping tools could provide an immersive authoring mode, for example, with what-you-experience-is-what-you-get editors [203, 202]. Due to such tools making use of spatiality and in-situ prototyping, they can be applied beneficially to some of the related challenges [205], such as placing and scaling virtual content in relation to one or multiple users. However, physical aspects like lighting, dynamic environments, and bystanders, or social aspects concerning privacy, security, equity [244], accessibility, and user skill [241] are difficult to foresee and design for. Therefore, future tools should focus on reducing the resulting complexity and support designing and evaluating such cases. Especially AR or MR applications need to be robust against external factors in uncontrolled environments (e.g. bystanders passing through, change of weather conditions, dynamic physical objects). Therefore, respective tools could provide functionality to simulate such dynamic environments (see [241, 85]) to evaluate respective prototypes in multiple scenarios. Further, tools supporting designers to relate to user groups with varying bodily and cognitive abilities could be valuable in reducing design complexity.

10.1.3 Flexibility of Tools

Section 7 reports that designers prefer simple and easy to use tools as long as they enable them to achieve their design goal, as they see "design as a pragmatic and situational process" [334]. This is in line with the aforementioned *fundamental prototyping principle* and the *economic principle of prototyping* [215], but also supports Stolterman et al.'s *Tool-in-Use* model and their differentiation between tools for thinking (i.e., tools appropriate for learning about a design) and tools for outcome (i.e., tools appropriate for producing artifacts as outcome). Myers et al. further emphasize the need to understand and experience a designer's tasks before building respective tools [241]. However, this is especially challenging in emerging technologies as the pace of innovation makes it difficult to keep up with the development of new interface techniques and design targets [241]. Based on this, this section proposes two design implications for future prototyping tools regarding their flexibility:

- Align tools with designers' tasks and practices.
- Enable taylorability and appropriation of tools.

10.1.3.1 Align Tools with Designers' Tasks and Practices. To overcome this challenge, Section 7 applied Lim et al.'s interpretation of *prototypes as filters* that traverse a design space and observe aspects of interest through manifesting respective design ideas. The highlighted elements of XR prototyping as robust aspects of XR interaction design can guide the development of tools that are both practical and more robust to change. Further, such work can support developing the understanding of XR interaction design challenges and XR as a design space. However, Section 7 can only be seen as initial work because it lacks aspects of, for example, MR and social context prototyping. Future work in this regard needs to further incorporate current advances of XR technology and prototyping practices to further explore XR's design space.

10.1.3.2 Enable Taylorability and Appropriation of Tools. Finally, the empirical insights in Part II describe that designers or their teams repurposed, appropriated, adapted, and personalized tools to integrate them in their design practices. While this observation is well presented and discussed in CSCW (computer-supported cooperative work) discourses and known as *taylorability* and *appropriation* [86, 332], it was not further researched and considered in this work due to this thesis' scope. Taking the instability of emerging XR interaction design practices into account, however, further work is required to relate respective insights to existing frameworks and models of the large field of CSCW. Nevertheless, the appropriation and tayloring activities described by participants emphasize the need of interaction design tools to be flexible up to a certain extent. Such flexibility enables designers to adapt tools they are experienced with to changing design targets and fosters the creation of stable tool chains (see Section 10.1.1).

10.2 Focusing on XR Interaction Design Competences

Based on Section 9.2, required competences do not fully match designers' previous experiences and already acquired competences. This means that XR as an emerging field currently requires either design and developer generalists who are able to compensate challenging and lacking material through their broad knowledge about and experiences in XR application design and development (Sections 6, 9.1, 9.2, [11, 248]) or an interdisciplinary team and materials that can provide this knowledge and compensate the lack of respective designerly tools [334] and technical expertise. As empirical studies revealed, designers outsource competences that do not match their skills or whose acquisition would exceed their limit of resources. However, this outsourcing also comes with the drawback of inaccessible artifacts and a respective dependency on developers to operate tools for design changes and adaptations (Sections 6, 9.1, 9.2), finally resulting in a reduced autonomy of designers in the design process.

While related work addressing XR interaction design competences oftentimes highlights the need to incorporate learning resources and features into future interaction design tools (e.g., [11, 10, 244]), the following sections take two alternative perspectives on XR competences: 1) outsourcing of competences, and 2) carriers of competences.

10.2.1 Outsourcing of Competences

The outsourcing of competences as reported in this thesis' empirical work is a direct consequence of tools being too demanding regarding coding skills. This skill barrier was also reported in related work [11, 248] and frequently results in calling for tools requiring less technical skill. In this regard, Myers et al. coined the concept of *threshold* and *ceiling* [241], namely the difficulty to learn a tool and the bandwidth of what a user could achieve with it. Both, Myers et al. [241] and Nebeling et al. [248] emphasize the need for tools that have a low threshold and a high ceiling. This is often attempted to achieve with simplifying the required programming task for interactive and software-based tools through, e.g., incorporating ready-made assets and building blocks or visual programming. However, as reported by the empirical data in Part II, this reduction in threshold also lowered the ceiling of respective tools and lead participants of this thesis' studies to outsource the required coding skills to their more technically skilled colleagues. This outsourcing then reduced designers' autonomy and resulted in both inaccessible artifacts and an increased workload for technical developers.

An interesting direction to tackle the threshold and ceiling of XR prototyping tools has been taken in the latest advancements of large language models (LLM), such as OpenAI's GPT-4 [260]. Current showcases demonstrate LLMs' abilities to generate working code samples [289] and assets like virtual environments [275] and avatars [329] based on text prompts. Similar to XR, however, this field is just emerging and needs to be treated as a *disruptive event* [314] that might have a lasting impact on the role of designers and their practices. As of today, the potential and limitations of current and future LLMs still need to be explored regarding their social and praxiological impact. However, a potential area of application of such models is the co-performance [189] of designers and LLM-based tools who jointly explore and refine design targets (see Section 10.1.2). Co-performance is a concept that "considers artifacts as capable of learning and performing next to people" [189]. Consequently, LLMs might bear the ability to substitute a designer's practice of outsourcing coding skills to technically skilled developers and jointly create, evaluate, and iteratively refine their prototypes. However, achieving such working modes requires a deeper understanding of both LLMs' limitations and potential as well as designers' practices in XR interaction design. This opens up an interesting direction for future interaction design tool research.

10.2.2 Design Guidelines and Good Practices as Carriers of Competences

As highlighted in Section 2.1.4 and Section 9, design guidelines and good practices can be seen as both design tools as well as carriers of design knowledge because they additionally bear the praxiological properties for material and competence [314]. Guidelines and good practices can ease the design process [256, 114] by sharing *formal* or *explicit* knowledge [314], for example, about approaches and tools that worked well in past projects and products, or aspects that should be prototyped based on experiences gained through creating previous products or artifacts [170]. Consequently, design guidelines and good practices can streamline prototyping [256, 114] through sharing previous experiences and insights (e.g., effective tool chains as described in Section 10.1.1, animations, or interaction techniques).

In the context of XR interaction design practices, however, an issue frequently raised in the qualitative studies presented in Section 6 and 7 as well as related work [328, 248, 11] is a general lack of design guidelines and good practices. Further, Section 8 highlights that there are guidelines existing, and the perceived lack is likely due to them being perceived as irrelevant for XR interaction design practices (see Section 8). Predominantly design guidelines and good practices addressing XR interaction design conventions (e.g., gestures and interface behavior, [11]), technical aspects like the compatibility of tools for tool chaining and respective data formats (see Section 10.1.1), and the accessibility of artifacts (see Section 10.1.2) are required to effectively support XR interaction designers. Future work should therefore focus on building the required knowledge as well as sharing it with respective communities (see Section 10.1.1).

However, *tacit* or *implicit* knowledge [309, 67] (i.e., how to apply a design guideline) has to be acquired through integrating, applying, and performing design guidelines and good practices [314]. To ease this integration as well as the process of identifying relevant design guidelines and good practices, it is important to emphasize a designing guideline's or good practice's purpose and context, as well as to clearly state their intended application (see Section 8). Finally, when further exploring the role and use of design guidelines and good practices in XR interaction design practice, future work should also embrace the heterogeneity of XR interaction design as an emerging field (see Section 7 and Section 9.1.2) and lean on concepts and practices originating from related domains, such as architecture, 3D modelling, and general interaction design.

Finally, to elicit implications for such design aides, future work could benefit from incorporating concepts of related fields, such as CSCW and the prominent notion of *situated knowledge* as well as *maps and scripts* [302]. However, those activities are out of scope for this thesis as they require the collection of dedicated empirical data and a respective and detailed critical reflection. Therefore, those efforts remain future work.

10.3 Carriers of Meaning

As a final perspective on the presented empirical work in this thesis, the praxiological lens of meaning is applied to discuss respective insights in the light of RQ2:

As reported in Part II, existing and emergent meanings lack a common ground. Not only does this apply to meanings that were integrated from other practices, such as the concept of fidelity, it also addresses the lack of language and shared concepts of XR-unique aspects (see sections 6, 7, 9.3.3). If possible, lightweight prototypes as carriers of meaning (see Section 9.3.3) in combination with explanations or past events as a reference point for experiences are used to convey both ideas and the feeling of XR. Prototypes for demonstration (see Section 6) were also applied to overcome the asymmetry of knowledge [107, 285], often resulting in performative *ephemeral* artifacts (see Section 7 and Section 10.1.2.2).

Future work needs to critically assess the theoretical concepts present in interaction design literature and their meaning in the context of interaction design practice. This might potentially lead to updated basic concepts of interaction design theory. For example, empirical insights in this thesis described that *fidelity* lacks a common meaning among the participants of this thesis' studies (see Section 9.3.2) and their mental models span from fidelity as a binary system to a multi-dimensional spectrum based on a products' properties. Respective insights in this thesis provide a starting point for future research interest.

When further discussing meanings in XR interaction design practice, prototypes appeared to have three interdependent roles: Firstly, prototyping is a practice that both produces and reuses prototypes. This means that prototypes are, in fact, objects and therefore *material* (see Section 9.1.3) integrated into (XR) interaction design practices. While some of them are created during the activity of prototyping, others stem from external sources (e.g., previous projects, published XR applications) and are integrated and adapted to reach a design or communication goal (see Section 6 and Section 7).

Secondly, as prototypes are a product of using and forming material, they show *traces of the designer's competences* – or, as Cross articulates it, embody design knowledge [70]. For example, prototypes show designers' skill in using tools, their design rationale, and their understanding of the design problem (see Section 9.2). Thirdly, however, prototypes were also reported as *carriers of meaning* (see Section 9.3.3) to aide in communicating concepts, ideas, and experiences (see Section 7). Other work also reported on prototypes being used as artifacts for communication, for example by Bäumer et al. who described prototypes in the context of software development processes [21]. Houde and Hill further added that prototypes do not need to be self-explanatory as their meaning depends on their context of use [156]. Lastly, especially ephemeral prototypes (see sections 6, 7, 10.1.2.2) demonstrate that meaning is also influenced by the stakeholders' knowledge and past experiences during performative practices in prototyping – which renders prototypes themselves as well as their meaning as being ambiguous, subjective, and non-persistent (see Section 10.1.2.2).

Finally, due to their characteristics of bearing meaning, *filtering a design space* and being bound to the *economic principle of prototyping* [215] (see Section 7), it seems valuable to further analyse prototypes in their creational context when investigating how future tools could and should support XR interaction designers. As prototypes are the results of several aspects of prototyping, for example, design rationale, available tools, available materials, applied technique, skill, and resources (see Section 7), they allow to understand the rationale behind why characteristics of the target application are of interest, as well as why applied prototyping materials were selected. In this regard, it is important to further deepen the understanding of a designer-tool relationship, as proposed by Stolterman et al. [334].

11 Conclusion

In this work, the emerging practice of XR interaction design was investigated through two distinct but complementary lenses: the scientific design and the social practice theory lens.

Therefore, **Part I** forms the motivational and theoretical foundation of this work and introduces the two research questions. By painting an overview of the past and current situation of XR design practices and practitioners as well as interaction design research in Section 1, the thesis provides an explanation of the fundamental concepts of XR, such as a differentiation between AR, VR, MR, and XR. Section 2 summarizes relevant related work regarding scientific design, the theory-practice gap, and the social practice theory to lay the theoretical foundation. Furthermore, the current state of the art regarding prototyping theory and practice is introduced as prototyping is handled as one of the core activities in interaction design. This section provides the scope of this thesis. As a the final section of related work, a summary of recent studies investigating design practitioners' challenges in both XR and general interaction design industry forms the focus of the presented empirical work in Part II. The final Section 3 provides a summary of applied methods for the empirical studies and a general overview of how the studies supported answering the research questions guiding the work of this thesis.

Part II explores the current challenges and practices of XR interaction design from the two perspectives *design practice* in Section 5 and *design studies* in Section 6, 7, and 8. Section 5 presents a sample workflow over the course of a three year project. Section 6 takes a broader perspective on general challenges and practices in XR interaction design industry and an initial description of workarounds for collaborative and interdisciplinary work. This perspective is further focused on prototyping practices as well as how theory applies to the work of XR interaction designers from industry in Section 7. As a final zoom-in, Section 8 focuses on design guidelines from both academia and industry. The closing Section 9 of Part II provides a summary of the main findings with a focus on material, competences, and meaning.

The concluding **Part III** summarizes and discusses the main findings through the lens of the social practice theory based on Shove et al.'s concept of dynamics of practice [314]. Section 9 highlights the dynamic characteristics of XR as an emerging field and discusses XR interaction design practices and challenges using material (Section 9.1), competence (Section 9.2), and meaning (Section 9.3) as a guiding structure. Section 10 further engages with those findings and discusses them in relation to related and potential future work. Section 10.1 proposes nine design implications (see Table 9) for future XR interaction design prototyping tools observed through the lens of material. The main focus lies on *compatibility and interoperability of tools*, *tools for reducing design and production complexity*, and *flexibility of tools*. Section 10.2 reflects on XR interaction design competences with a detailed discussion of their *outsourcing* and *design guidelines and good practices as their carriers*. Finally, Section 10.3 turns towards meaning in the context of XR interaction design practices and underlines the lack of common ground for shared meanings and theoretical concepts. Moreover, this conclusion is the final section of Part III.

11.1 Limitations

Over the course of this work, several parallels to technological innovations from the past, such as the mass adoption of the personal computer or the integration of the internet into today's society, surfaced without being explicitly considered. While this thesis has the potential to answer questions regarding general support for designers and developers during the early stages of mass media evolution and adoption, as well as the respective challenges and levers academia and industry could apply, a rigorous scientific analysis and generalization process was not within the scope of this work. However, approaching the questions raised in this thesis from a more holistic perspective based on current and past observations as well as aiming at good practices in general for future technological innovation sparks new, interesting potential for further research.

A major limitation of the presented work is the lack of observational studies regarding professionals and their prototyping practices. While this was a direct result of the Covid-19 pandemic related lock-downs, it limited the possibility to understand prototyping practices and their context during their actual performance as the empirical data mostly relies on interviews. As also described in Section 3.2, this might be problematic since recorded data is based on a participant's recall and interpretation of actions rather than contextual observation of performed actions [293]. This lack of context and unbiased observations limits the findings of this thesis to a certain extend and leaves room for future work. For example, complementing the interview insights in this thesis with a dedicated observational study over a longer period supports identifying further issues and the development of workarounds in collaborative and individual work practices.

Another limitation is the focus of the thesis, as it only observes *design as practice* [178, 177]. However, a holistic view requires to include the investigation of *designs in practice*, as issued by Kimbell [178, 177], to understand how XR interaction design practices affect the appropriation of such XR artifacts as well as their impact on the individual and society. As briefly addressed in Section 5, XR has the potential to estrange users from social bounds and provoke the feeling being remote-controlled. Also, related work hints towards more complex and grave issues regarding XR's potential that still need to be explored [320]. However, as XR as a mass-adapted technology matures, regulations, standards, and legislative also will have their impact on *design as practice*. However, actively participating in and contributing to this field as it matures as well as understanding the implications of current and future developments remains a challenging task worth taking on.

Finally, this thesis was primarily motivated by the potentially existing gap between theory and practice in XR interaction design research. As highlighted in Section 2.1.5, this refers to "an undesirable gap between HCI research aimed at influencing interaction design practice and the practitioners in question" [132]. However, just like the limitations of interaction design, which only allows for designing for a specific use case without the means of influencing if a respective artifact is used according to the designer's intention [178], only time will reveal if this work has an impact on both scientific and industrial practices.

11.2 Contributions

This thesis contributes to ongoing discourses and research in the field of XR interaction design by taking two different analytical perspectives: the scientific design lens and the practice theory lens (see Section 1.2). As such, the presented work offers two major scientific contributions that are interrelated:

From a *social practice theory* perspective, this thesis provides a reflection of current XR interaction design practices in the industry through the praxiological lens of material, competences, and meaning (Section 9). By detailing their instability based on empirical data, the presented work offers a novel way of approaching tool research for XR interaction design practices. Furthermore, nine design implications for future XR interaction design tools through the lens of material are provided (Section 10). Finally, a holistic perspective describes prototypes as material, carriers of competences, as well as carriers of meaning. This perspective offers an integral approach to further understanding the challenges and interdependencies of inaccessible tools and inaccessible artifacts in emerging fields and interaction design practices.

From a *scientific design* perspective, this thesis highlights several areas of potential future work focusing on contributions to ongoing discourses in scientific design research (see Section 10). Firstly, insights into prototyping practices, sample design processes, and the respective use of prototypes in XR interaction design as an emerging field are provided (sections 5, 6, 7). Those insights do not only follow a call to action of related work proclaiming the necessity to ground research aiming at supporting interaction design practice *in* interaction design practices [132, 286, 136], but also follow Yvonne Roger's suggestion that researchers need to adopt a mindset that views design practitioners as partners instead of the learners in a respective educator-learner relationship [287]. Secondly, theoretical contributions describe and align the manifestations and elements of XR prototyping with existing work. A resulting initial taxonomy of robust design space filters (i.e., the ten elements of XR prototyping in Section 7) are provided as a basis for future design tool research and theory development. Thirdly, *ephemeral prototypes* and their important role as efficient fall-back methods for creating and iterating complex interaction design properties (e.g., interactivity and animations) are described for the first time. Finally, design guidelines as tools for XR interaction designers are analyzed based on a perceived lack of XR interaction design practitioners [248, 11] (see Section 6) and the respective implications for formulating design guidelines are presented (see Section 8).

Lastly, this thesis provides two minor contributions for readers interested in supporting their own design practices:

- From an *XR interaction designer* perspective, this thesis offers a collection of good practices and workarounds for some pitfalls of XR interaction design, especially in the context of prototyping and prototypes.
- For readers interested in *creating or investigating supportive tools* or *sharing and establishing competences* for XR interaction designers, this thesis provides a list of design implications and perspectives as a starting point for their own work.

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