

Creating Augmented and Virtual Reality Applications: Current Practices, Challenges, and Opportunities

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ABSTRACT

Augmented Reality (AR) and Virtual Reality (VR) devices are becoming easier to access and use, but the barrier to entry for *creating* AR/VR applications remains high. Although the recent spike in HCI research on novel AR/VR tools is promising, we lack insights into how AR/VR creators use today's state-of-the-art authoring tools as well as the types of challenges that they face. We interviewed 21 AR/VR creators, which we grouped into hobbyists, domain experts, and professional designers. Despite having a variety of motivations and skillsets, they described similar challenges in designing and building AR/VR applications. We synthesize 8 key barriers that AR/VR creators face nowadays, starting from prototyping the initial experiences to dealing with “the many unknowns” during implementation, to facing difficulties in testing applications. Based on our analysis, we discuss the importance of considering end-user developers as a growing population of AR/VR creators, how we can build learning opportunities into AR/VR tools, and the need for building AR/VR toolchains that integrate debugging and testing.

Author Keywords

AR/VR authoring; augmented reality; virtual reality; end-user development; AR/VR development; AR/VR design;

CCS Concepts

• Human-centered computing~Human computer interaction (HCI);

INTRODUCTION

The increased availability of AR/VR-equipped devices is opening the door to exploring a wide range of consumer-oriented applications and opportunities beyond gaming and entertainment [53,54]. Although interest in creating AR/VR applications is rapidly growing, creators are often dealing with a number of technical hurdles with AR/VR authoring environments [55] and struggle in designing compelling user experiences [1,53].

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While research on novel AR/VR tools is growing within the human-computer interaction (HCI) community, we lack insights into how AR/VR creators use today's state-of-the-art authoring tools and the types of challenges that they face. Findings from preliminary surveys, interviews, and workshops with AR/VR creators mostly shed light on isolated aspects of the proposed AR/VR authoring tools [1,15]. We especially lack an understanding of motivations, needs, and barriers of the growing population of AR/VR creators who have little to no technical training in the relevant technologies and programming frameworks.

In this paper, we describe a semi-structured interview study with 21 AR/VR creators that investigates how they approach design and implementation in AR/VR. To better understand the diversity in AR/VR creation practices, we recruited participants with a wide range of motivations, backgrounds, skill levels, and experiences. For example, we included hobbyists creating their own games, researchers trying to apply AR/VR for domain-specific problems, and professional designers working on enterprise-level AR/VR products. These creators worked on a variety of applications, such as in-home design, sports and rehabilitation, medicine, cultural studies, and games, among many others.

Our overall findings indicate that, although AR/VR creators vastly differ in their motivations and skillsets, they experience similar challenges in designing and building AR/VR applications. We synthesized 8 key barriers described by AR/VR creators: from understanding the initial landscape of authoring tools, to designing and prototyping AR/VR experiences, to implementation, debugging, and testing.

While almost everyone mentioned the importance of creating a good user experience, most of our participants who were not in professional design teams were not aware of any formal UX design approaches and proceeded to development environments. In contrast, most participants who were designers tried using UX principles to prototype and test AR/VR user experiences, but constantly struggled with available design methods and tools, and felt that most required “too much coding.” Compared to web and mobile application development, we found that the barriers that AR/VR creators faced during implementation, debugging, and testing were more acute as creators had to deal with “too

many unknowns” and keep up with the rapidly evolving AR/VR hardware and software.

Our paper makes the following contributions:

- 1) Producing empirical insights that portray the unique motivations and backgrounds of AR/VR creators using today’s authoring environments.
- 2) Providing a synthesis of 8 key barriers that were common across all AR/VR creators: from understanding the landscape of AR/VR development, to exploring designs and prototypes, to implementation and testing challenges.
- 3) Identifying opportunities for future HCI research to support end-user developers as a growing population of AR/VR creators, to build learning opportunities into AR/VR tools, and to design AR/VR authoring toolchains that integrate debugging and testing.

RELATED WORK

To situate our study findings in the broader HCI literature, we draw upon insights from existing research on developing AR/VR authoring tools, observations of AR/VR creators in different contexts, and how we can look at emerging AR/VR creators as end-user developers.

AR/VR Authoring Tools in Research and Practice

Previous research on AR/VR authoring has addressed the specific development needs of creators across a wide spectrum. For example, early tools such as *ARToolKit* [21] and *Studierstube* [45] provide a low-level framework requiring the creator to have a strong programming background. Commercial AR/VR creation tools, such as *Unity*, *Unreal*, *Visor*, and *A-Frame*, are starting to provide new capabilities that make high-fidelity prototyping easier but still require some coding. Overall, the landscape of AR/VR authoring tools appears to be fragmented [39] and creators are required to learn multiple different tools.

Some research tools have explored how early stages of AR/VR prototyping can be facilitated without the need for programming (e.g., *DART* [31], *ProtoAR* [38], *360proto* [37], *ARtalet* [20], *iaTAR* [26,27], and *Amire* [51]). Although these approaches have been instrumental in opening a new space of AR/VR authoring, they are designed to work on specific predefined tasks and are usually not compatible with multiple platforms, frameworks, and hardware. Furthermore, these tools do not cover the full design cycle from prototyping to development and testing on AR/VR devices.

Despite the recent research progress in authoring support for AR/VR, we know little about how AR/VR creators (particularly those who are not professional developers) are using the tools available today. Our study provides such empirical insights, detailing how AR/VR creators approach the learning process, and where they face barriers during design and development activities.

Observations of AR/VR Creators

A number of AR/VR authoring tools that have been developed in HCI research have often included formative

studies or evaluations with AR/VR creators. However, as is common with system evaluations [25], most have a limited scope to demonstrate the benefits of the tool.

The closest work that aligns with our project is “*DART, ten years later*” [15], a study on AR prototyping that investigated the work of 8 AR creators with design backgrounds using the DART timeline-based visual AR authoring tool that reduces the need for programming [31]. Similar to results reported in that study, we found that even creators with technical backgrounds had difficulty in debugging and wanted to minimize the extra effort required to integrate more tools into their existing workflows.

Another relevant study focused on extending AR applications for cross-device collaboration [46]. The authors reported findings from a survey with 30 designers, developers, and end-users. This study asked participants to consider two scenarios of an available AR application and to discuss challenges they would expect to face when implementing them. Findings of this study provided insights on technical challenges of AR development, such as cross-device communication, calibration, environmental mapping, obtrusiveness of authoring platforms, gesture definition, and tracking in collaborative settings.

Our findings complement these prior works by adding insights from a more diverse pool of both AR and VR creators: hobbyists, domain experts, and professional designers. We also provide new empirical insights into the AR/VR authoring process by considering the full spectrum of user research, prototyping, development, and testing, as part of AR/VR creation. In addition, we illustrate differences between AR vs. VR during different stages of authoring.

AR/VR Creators as End-User Developers

Since our study includes participants with a wide range of technical expertise and motivations, we look toward the literature on end-user development to situate our findings.

End-user development has been a core topic in HCI for decades [5,24]. End-user programmers are non-professional developers with a variety of backgrounds (often other than computer science) who learn to write code as complementary to a task they are assigned in their educational or work settings or for leisure [30]. These types of programmers are opportunistic in terms of coding and do not always have a clear plan for their development needs. A dramatic rise in the number of such end-user programmers has been reported in several studies [2,44], shedding light upon the learning areas in which these programmers show more interest, the bottlenecks they face while working with existing programming environments [8,12,50], and the use of their peripheral learning resources [28,32,41]. Various studies have demonstrated that many end-user programmers are reluctant to learn high-level concepts, showing more interest in informal learning and trial and error [10,42,43].

Our work adopts a similar perspective and focuses on the emerging community of AR/VR creators, such as hobbyists

ID	Tools	Occupation	Example Projects
Professional Designers (PD)			
P4	Unity	AR/VR design consultant	AR work safety training app
P10	Unity, Unreal	Design instructor/ UX researcher	VR-based vection research
P14	Unity	Test engineer	AR Work training app
P16	Unity	UX designer	AR medical education app
P17	Unity	UX designer	VR social platform
P18	A-Frame	UX designer	AR doodling app
P19	Unity	AR/VR entrepreneur	VR Wilderness training app
P21	Unity	UX designer	AR storytelling app
Domain Experts (Dx)			
P1	Unity	Biomedical engineer	Research in stereo deficiencies in AR/VR,
P2	Unity	Biomedical engineer	VR-based sports & rehabilitation training
P8	Unity	Cognitive scientist	Research in human lucid dreaming in VR
P12	Unity	Linguist	Research in culture revitalization (AR)
P15	Unity	Psychologist	Research in attention(VR)
P20	Unity	Audio designer	Research in sound design (AR & VR)
Hobbyists (H)			
P3	Unity	CS student	Temple run game in VR
P5	Unity	Tangibles researcher	AR Christmas card/ games
P6	A-Frame, Unity	Web developer	AR 360° city showing app/ VR flight game
P7	Argon.js, A-Frame	French language student	AR home design app/ games
P9	Unity	Info Viz researcher	VR Maze game
P11	Unity	Software developer	VR game
P13	Unity	Gaming instructor	Various AR/VR projects

Table 1: Summary of study participants

and experts in domains other than AR/VR, who informally learn development in a contextualized manner. While prior work on end-user programmers' learning process shows that novice end-user programmers' strategies differ from the ones who learn programming in a formal learning setting [6,19,52], we have limited insights into how end-user programmers participate in multidimensional AR/VR environments. Our study reveals that beyond challenges of prototyping and selecting the most suitable development framework, AR/VR creators also have to deal with a wide range of hardware challenges, such as selecting proper headsets targeted to their project and dealing with lengthy installation procedures specific to headsets and other peripherals.

STUDY DESIGN

To investigate current AR/VR design and development practices, we used a qualitative approach, conducting semi-structured interviews with 21 creators who had recently worked on an AR/VR project for work or for leisure. The goal of our interviews was to better understand AR/VR creators' design, implementation, and testing approaches and to learn about any challenges that they faced along the way.

Participants and Recruitment

To obtain a broad overview of AR/VR creation practices, we focused on recruiting participants who were new to AR/VR and excluded experienced AR/VR developers. We recruited AR/VR creators by connecting with local AR/VR meet-up

groups in person and through their mailing lists. We also recruited creators by advertising posters at local educational organizations, and through personal connections and snowball sampling. We aimed for a diverse participant pool in terms of the backgrounds of the participants and the types of projects they worked on.

We ended up with 21 participants (10F/11M) who had diverse backgrounds and roles, including user experience designers, gaming enthusiasts, instructors, and academic researchers (summarized in Table 1). They ranged from having several years of programming experience to having no technical training, working on AR/VR projects ranging from enterprise products, to games, to biomedical studies. Our participant pool covered a range of age groups: 18-24 (23%), 25-34 (52%), 35-44 (5%) and 45-54 (20%). Although most of the participants were recruited from the greater Vancouver area, we also conducted phone interviews with creators from 6 different cities in Canada and USA.

The Interview Protocol

Before conducting the interviews, we collected demographic information from the participants via a questionnaire (e.g., age, gender, occupation, previous experience in programming, education, and AR/VR creation tools they use). We started the interview by asking participants to describe their current or recent AR/VR project and to describe if there was a team involved. Next, we asked about factors that influenced their initial encounter with AR/VR, their learning process, and the resources they used for getting started. Next, we asked participants to describe their creation and tool selection process, and methods used from the design step to the final product (prototyping, to coding, to evaluation). Throughout the interviews, participants with programming and design backgrounds were asked to describe differences in their AR/VR practices from their other types of development (e.g., mobile/ web).

Data Analysis

To investigate the workflows, tool preferences, and challenges of AR/VR creators, we coded all of the transcripts and analyzed them using the *Atlas.ti* software. We used an inductive analysis approach [9] and created affinity diagrams using the gathered data to explore the themes around our main research questions. Two members of the research team first began with an open coding pass to create a list of potential codes. Through discussion and use of affinity diagrams, we arrived at a single coding scheme. During the coding process, we focused on the motivations of different groups towards AR/VR creation, and the steps involved in the AR/VR authoring process, including prototyping, development, and testing.

Organization and Presentation of Result

We present our main findings by first describing the motivations of AR/VR creators in our study and how we categorized interviewees based on differences in their backgrounds, motivations, and the types of projects they pursued. This gives context to our findings and demonstrates

8 Key Barriers in Authoring AR/VR Applications
1. Difficult to know where to start: problems related to understanding the AR/VR landscape and selecting tools.
2. Difficult to make use of online learning resources: problems related to understanding the nomenclature, formulating search queries, and finding relevant and up-to-date information.
3. Lack of concrete design guidelines and examples: problems related to knowing what is good design in AR/VR relative to good design in other types of development and lack of example projects.
4. Difficult to design for the physical aspect of immersive experiences: problems related to design of natural VR experiences and understanding of human motion, gesture, and audio design.
5. Difficult to plan and simulate motion in AR: Problems with planning targeted experiences in AR and forecasting users' actions/movements.
6. Difficult to design story-driven immersive experiences: problems related to providing a compelling, distraction free AR experience.
7. Too many unknowns in development, testing, and debugging: problems related to constant changes in AR/VR technology and viable debugging strategies.
8. User testing and evaluation challenges: problems related to understanding of viable testing methods, users' knowledge of tool usage and accessibility to AR/VR devices.

Table 2: Summary and description of eight key barriers described by participants

the variety of AR/VR projects created by our participants. Despite many differences between groups, we found that most of our participants expressed similar challenges when pursuing AR/VR projects. We synthesized these challenges as 8 key barriers in AR/VR creation (Table 2) and explain how each manifested in the experiences shared by our participants.

AR/VR CREATORS AND THEIR MOTIVATIONS

Our 21 participants had a variety of different motivations for getting involved in AR/VR creation. The participants also varied in their technical skills and formal training in user research and design (UX design). Based on these differences, we saw three groups of participants emerge from our data: 1) *professional designers* who worked on creating consumer-facing commercial AR/VR products; 2) *hobbyists* who tried out AR/VR projects as a hobby or out of curiosity; and, 3) *domain experts* who used AR/VR as a new approach to tackle a domain-specific problem.

Professional Designers: Many of our participants (8/21) were professional designers, including user experience/interface designers and design consultants. These participants were typically asked to work on a range of commercial AR/VR products as part of their job and were motivated to keep up with the evolving landscape of AR/VR technologies and evolving design practice. For example, one designer explained what motivated him to learn AR/VR design guidelines:

When you put on [a] VR headset, you immediately understand that

this is going to be a part of the future...from a design perspective, I realized that there's a lot of new principles and guidelines I have to learn and follow if I want to get ahead of the market. (P18-PD)

All of the professional designers in our study had formal training in UX design and half of them (4/8) also had training in CS. However, only 3 of them had worked on AR/VR design projects during their training—the rest were all learning about design methods in AR/VR on the job:

I already had experience designing mobile apps and desktop...but I didn't know anything about [design in] VR or AR.... I was really interested in getting involved and exploring those fields just to see how it works. (P16-PD)

Although all designers believed that UX design techniques were critical to designing compelling AR/VR products, compared to other types of design, these participants felt that the UX learning curve in AR/VR was steeper and they thought it was particularly important to understand the engineering effort required in AR/VR creation:

Compared to the traditional apps and games that I've worked with...you just have to be really involved [with VR]...you actually have to try to understand how your developer works, how your software engineer works, and what it actually takes to implement a certain design...or a certain behavior. (P14-PD)

Hobbyists: Another group of our participants was comprised of hobbyists (7/21) who were not working on commercial products and mostly described gaming-related personal projects. They often stumbled upon AR/VR creation out of curiosity or simply to try out something “new and trendy”:

...we started googling app ideas and things like that. And, we came up with a few things that used AR and we thought that would be cool, especially after Pokémon GO was so successful... (P7-H)

Most of the hobbyists (6/7) had formal training in CS or engineering and felt confident in tinkering with new technologies. However, none of them had any formal training in UX design and felt that they lacked the knowledge to create intuitive interfaces:

I played a lot of games before and I was pretty confident that I knew how a game should look like. But, it turned out that I had limited knowledge. So, there was this one point where I was personally satisfied, but when I showed my project to [others], everybody commented on the experience being unintuitive. (P9-H)

Domain Experts: As shown in Table 1, participants categorized as domain experts (6/21) were mostly researchers and subject matter experts in areas such as sports and rehabilitation, cognitive science, biomedical engineering, and cultural heritage preservation. These domain experts commonly saw a new approach in using AR/VR to tackle a domain-specific research problem. For example, a cognitive scientist explained how she used VR to better understand human behavior around lucid dreaming:

...lucid dreaming is something you can't experience in normal life. It's really hard to train for it, and learn it...you can't watch somebody have a dream. So, this [VR] is one way to experience that

same thing. I don't see really any other medium that could really give you that same experience. (P8-Dx)

Most of the domain experts (5/6) in our study did not have any formal training in CS and did not feel confident in starting AR/VR projects from scratch. They looked for existing examples of projects online and sought methods for showing a “proof of concept.” Some domain experts informally talked to end-users during their research process, but similar to the hobbyists, none of the domain experts found it easy to translate their knowledge to AR/VR:

My degree was in anthropology. I worked in a community where there's no electricity and no technology. I do interviews. I know how to hold focus groups and all those things. Which is a lot of what HCI does, but I was like, "I don't know what I'm doing." (P12-Dx)

Overall, our participants got involved in AR/VR creation for a variety of reasons and came with a range of backgrounds and skillsets. However, when they started designing and building AR/VR applications, they expressed common difficulties (Table 2), as we discuss below.

BARRIERS IN UNDERSTANDING THE AR/VR LANDSCAPE

Our participants reported a variety of formal and informal strategies that they used to understand the AR/VR authoring landscape, highlighting three major challenges that they faced along the way: difficulty in knowing where to start, making use of online learning resources, and dealing with the lack of design guidelines and examples.

1. Difficult to know where to start

Given the pace at which the landscape of AR/VR hardware and software is evolving, a major difficulty our participants experienced was in knowing how to even get started and understanding what is “state of the art.”

Some barrier-to-entry issues were related to knowing about and having access to the current AR/VR hardware and software versions. For hobbyists and domain experts, not understanding the hardware was particularly problematic. For example, one hobbyist participant who was keen on AR development shared his frustration:

I think we should have played around a little more with it [AR.js] and seeing if it really met our needs. We got somewhere really fast and then we found out it doesn't support what we wanted in the middle of the implementation. (P7-H)

Another issue that participants explained was that there were few relevant experiences available in AR/VR to draw upon, unlike web and mobile application development which are well established today:

It was hard to get started in terms of choosing what we were going to do. No one knew what was possible. We didn't have a model list. There's no AR app for language revitalization out there...It was like, "I don't even know what I'm doing." (P12-Dx)

Our participants also indicated that they usually failed on their own to find an AR/VR authoring tool that would meet their exact needs. We learned that AR/VR creators relied on

their own personal and professional contacts to get recommendations and begin the creation process:

I needed to develop something that can run on different platforms and there [are] a lot of graphical things going on there... I was talking to my buddy and then he said, you can use Unity...And, then since he was using Unity, he knows all the stuff. I said why don't you just walk me through it? And that's why I chose Unity. (P5-H)

Most participants (19/21) reported using Unity as the first and main platform they used for AR/VR creation. For example, another participant explained why his team often chose Unity even at the prototyping stage:

Usually, not everyone on the team knows how to use them [other prototyping apps]. Teams are fairly large and most people already know how to use Unity...they just don't want to add that extra effort to learn something if they already know something else. Unity might not be perfect, but it's enough for them. (P10-PD)

Although Unity is widely used among professional developers [48], our participants reported a number of issues in getting started with it. For example, participants reported difficulty wrapping their heads around the new programming structure in Unity:

...problem with Unity is that you have to fight to get it to work...you kind of have to learn how to make it work instead of the opposite way around...if you're creating your own system, you need to work with their rules. (P10-PD)

While there are many other authoring tools available that are easier to access and use, including many of those created in research, most participants said that they were not aware of other options.

2. Difficult to make use of online learning resources

Our participants reported using many different learning resources in their AR/VR creation process. The main resources used for learning included online search, video channels (e.g., *YouTube*), Unity forums, *Stack Overflow*, and Online MOOCs (e.g., *Coursera* or *EDX*).

Despite the growing availability of online learning resources on AR/VR creation, several participants said that these were either difficult to locate, not comprehensive enough, or became easily outdated:

...if I look at some higher-level tutorials [on YouTube], I don't really understand it as I don't know what I should've learned before I learn this one... YouTube sometimes has some short videos that are for some specific small projects. (P2-Dx)

AR/VR creators also shared examples of their struggles in locating relevant tutorials, dealing with different platforms, and new versions of previously familiar technologies:

A-Frame itself keeps updating. It keeps updating or upgrading its versions but the documentation is not there, and not enough for us for more advanced usage. (P18-PD)

I used to develop for Oculus and Vive...but for the Windows Mixed Reality [framework], I had a lot of difficulty since the documentation is either not updated or without many examples. (P1-PD)

Even when a relevant resource was located, several

participants (7/21) struggled with technical jargon and unfamiliar AR/VR terms. For example, if one creator wanted to know the position of a specific item [in Unity], the keyword *transform* would be needed to get relevant results. As an extreme case, one participant reported that he struggled with search keywords for two months due to his lack of knowledge in platform nomenclature:

I always start by Google, hopefully there's some tutorial... My first big issue took me like a month or two and the problem was that I didn't understand Unity enough and the nomenclature of it to actually figure out what was going wrong [with my search]. (P4-PD)

As a result, given the difficulties in finding useful learning resources, many of our participants relied on more informal trial-and-error methods for learning AR/VR development.

3. Lack of concrete design guidelines and examples

A key deficiency noted by participants was that compared to other mediums like mobile or web development, AR/VR development lacked concrete design guidelines and examples. This problem was particularly acute for hobbyists and domain experts with no background and little experience in UX design. For example, a hobbyist explained:

We didn't have any guidelines...I mean, they say [in documentation] ...you have some assets in this Unity package, like standard buttons or standard windows. You can use them. But, they didn't say how to use them. (P11-H)

Although professional designers' backgrounds in designing user interfaces gave them some intuition about good design, they reported that the available AR/VR guidelines were not only scattered all over the Web but also not suitable for supporting many complex scenarios:

We were trying to apply some scattered guidelines from Medium, Apple or Coursera, but they were superficial...for example, when Google is designing for the Google Map, they pay attention to reminding users of "you don't want to stare at your phone all of the time." This is not something that's implemented in VR applications I've interacted with nor the design guidelines. (P17-PD)

There [has] been tons of research on how to approach designing for 2D experiences...But, for VR I think we're so early that we really require everyone's input into what makes a design good...So, depending on what your experience is in VR, you should know what makes it comfortable...what makes it not comfortable? What is good design to [users]? What is bad design to them? (P19-PD)

In fact, participants noted that the available guidelines (mostly through *Apple* and *Google*) still fell short when confronting the complexity and ambition expressed by many designers. At this stage, Apple and Google limit their focus to simple, single scene applications and make little allowance for complex mechanics or anything beyond simple object placement and sticker-like functionality. In particular, we found that guidelines were lacking for participants designing applications with interactive features such as object selection, conditional actions, scene flows or storyboards driven off of user behaviour, and movement between scenes using teleportation.

BARRIERS IN DESIGNING AND PROTOTYPING AR/VR EXPERIENCES

The next set of barriers described by participants related to their struggles in trying to design interactive AR/VR experiences. Although some of these challenges manifested both in AR and VR, participants differentiated some struggles that were unique to either AR or VR.

4. Difficult to design for the physical aspect of immersive experiences

Some participants explained that while VR might look easier than AR in terms of maintaining the users' attention, VR experiences mostly fell short of providing natural and realistic experiences. This problem was reported due to two underlying reasons. First, as has been reported previously [47], designers described the difficulty they faced in simulating models and in providing realistic gestures:

I was not satisfied with having the same idle movement for all bipedals...it wasn't realistic at all. I was like, I have to figure out a way to randomize idle states, while they're just standing around doing nothing. So, I built a randomizer [such] that it chose different actions. (P10-PD)

According to the professional designers, while the initial user research step of design in AR/VR shared many similarities with designing 2D desktop/mobile applications, the physical aspects of designing immersive experiences were particularly difficult to address. For example, participants described how user research for AR/VR involved designing the posture of users, reducing fatigue, and eradicating simulators' sickness. In addition, our participants pointed out the importance of the cognitive aspect of how users navigate and how to maintain their attention via audio design.

There's the challenge of landmarks [in VR]...for example, some experiments can't have any landmarks, so [we are] really stripping away anything that would help them [users] figure out where they're oriented. (P8-Dx)

Some designers explained after extracting user journeys and different use case scenarios, they would follow up with a couple of brainstorming sessions to generate design ideas. As the first step of converting ideas to semi-tangible products, some designers (3/21) exploited methods such as 360° storyboarding, while others used role-playing (6/21) to illustrate immersive experiences.

One of the important differences between 360° storyboarding and flat storyboarding was having no control over the users' actions. In VR and AR experiences, users are not primed to perform specific interactions designed by the experience creator. This unlimited nature of the immersive experience is a significant departure from the 2D mobile/desktop experiences. While storyboarding was reported to be an effective method for conveying ideas, participants reported role-playing as a more effective, faster, and easier way to portray their thoughts. For example, one participant who had experience teaching VR prototyping to high school students reported the effectiveness of this method in easing the learning process for newcomers to VR:

We do some storyboarding and sketching. Then we do some 'acting it out' because, paper prototyping kind of works, but it doesn't really get the feeling of what you want to do. So often we do kind of role-play of like, if you were in VR, what would you do? (P10-PD)

Our overall results revealed that prototyping for AR/VR was open-ended and non-representative of the real VR experience. Methods like role-playing or physical prototyping can simulate the real experience to some extent but were still not considered to be accurate in visual aspects (as has been shown in prior work [37]) and many other variables such as lighting and audio. For example, one UX designer reported the ineffectiveness of available methods in the representation of the real experience:

In either AR or VR settings, the world is all around you. So the tilt, frame, or angles to show actually matter compared to 2D [prototyping]...it's going to involve multiple people...it's inevitable if we're making [mock up] videos from the objects that we create with paper, those objects are relatively small compared to our body [when showing the interactions], so the whole scene will look a little bit messy. (P17-PD)

5. Difficult to plan and simulate motion

Another aspect of having limited control over users' actions was the difficulty designers faced when providing users with a targeted experience. Designing AR experiences can involve multiple users with different physical characteristics, different usage trends, and a variety of environments where the application may be used. Our participants reported having difficulty anticipating users' behavior and the way users hold their phones based on their different preferences in designing marker-based AR experiences:

We have very practical usability issues...It's really awkward to hold a phone above a page...I actually programmed it to hold it perpendicular. But a lot of people go directly above. (P12-Dx)

Another participant shared difficulties in simulating multiple use case scenarios as a limitation of existing AR prototyping tools. This participant described a potential workaround, but felt that it involved a lot more coding effort than she was willing to expend during prototyping:

... to demonstrate that kind of process [different user scenarios] we have to use a lot of animation tools to simulate that...I can make 2 to 3 simple codes to access turnarounds or the phone's orientations because I know how to code. But, that kind of thing would be more challenging for designers because if they don't know how to code, they have to simulate everything in animation tools. (P18-PD)

6. Difficult to design story-driven immersive experiences

Storytelling is a crucial aspect of creating immersive experiences [3]. In immersive experiences, end users are not just watching a story, but are actually a part of the story. While storytelling matters both in AR and VR, our participants explained some differences that they had experienced. In particular, participants who had worked on both AR and VR reported that they had an easier time authoring a compelling experience for VR applications.

Compared to AR, VR lent itself more to storytelling due to the encompassing and limited nature of the experience:

I see VR more as a storytelling medium than AR...That's not always true, but AR tends to lend itself towards shorter experiences. A lot of AR experiences are collection-based experiences. So, they're short. They don't involve much story unless there's a background story to why you should be collecting an object. (P20-Dx)

Since the story in VR is driven by the context and the environment around the user, a key challenge in VR is creating a virtual environment that tries to provide the sensations and engagement of the real world.

On the other hand, the restricted environment of VR actually reduces the distractions of the real world. In contrast, AR relies on an uncontrolled physical environment to drive the story. In fact, AR creators gave several examples of problems that they had in understanding where augmentation would affect the user experience and how to maintain users' attention while experiencing the real world around them:

We have a lot of questions within AR; like, how do we want the user to look around and what do we want them to see while they're already experiencing the real world? How we are going to maintain their attention, and for how long before they're distracted by the real world. (P18-PD)

BARRIERS IN IMPLEMENTING AND TESTING AR/VR APPLICATIONS

Another set of barriers that emerged in our interviews was the nuances of implementing AR/VR experiences. In doing so, participants described various challenges in debugging and testing their applications.

7. Too many unknowns in development, testing, and debugging

Since the hardware and software needed for AR and VR development are constantly evolving, participants felt that they were always dealing with "too many unknowns" and had to plan ahead to anticipate and deal with problems:

I think it really is the unknown unknowns...you just don't know until you start to program...when you start to create, these problems surface...[we have to] anticipate and plan for problems. (P20-Dx)

Compared to hardware available for 2D applications, rapid changes in hardware made things become obsolete more quickly in AR/VR industries. Persistent changes in AR/VR industries made it hard for creators to keep up-to-date and survive when the application might not be supported by the next generation of hardware to come:

You're working in an environment where not everyone has figured out what's possible on that particular HMD. Or, you try your best to create an AR experience for the Samsung...and it doesn't work on any other Android phone. And, the client wants it on multiple phones. So, suddenly the team faces persistent changes. (P20-Dx)

Another aspect of having persistent changes in hardware was that AR/VR creators found it difficult to locate relevant technical support. In cases where most of the contributors to AR/VR technologies are start-up companies, tools can have a short lifespan and creators end up losing support:

I own headsets that you can't get [an] SDK for any more...you spend \$2,500, get on the early adopter program of something that seems to be viable and you use it for a year and then next thing you know they go bankrupt because their venture capital funding is pulled out...If they get bought up, their IP may go away and you don't have access to it anymore. (P13-H)

Participants noted several times how current development tools were not flexible in supporting diverse interactions. This sometimes forced creators to switch platforms in the middle of development as new requirements came up, which introduced even more unknowns in the creation process:

When programming all these different interfaces...maybe I want to use an Apple watch that can change the visuals instead...I would have to go in and reprogram everything to include that. It would be great if there was something that's more flexible [such that] it recognizes the device and then you can just map it to whatever... (P8-Dx)

One of the main problems is that AR change is very fast...the technology, the SDKs, the platform, the library that you use to create changes very often...I had to work with 3 different libraries, just because every time I worked in a library, it got canceled and I had to switch to a different one. (P10-PD)

The issue of dealing with unknowns made it especially difficult to debug AR/VR applications. Participants identified many variables, including the dimension of motion and the complex structure of programming with Unity, as posing many difficulties in the debugging process. For example, one domain expert explained the difficulties she faced in systematically finding the location of errors:

I don't like the debugging experience in Unity...sometimes the bug comes from Unity...like if I didn't attach some piece of code to objects in Unity. Sometimes the bug actually is in the code itself. So, the debugging becomes confusing. (P2-Dx)

In another example, one professional AR/VR creator described the physical aspects of the debugging process that remain neglected in online tutorials:

It's good to see the person doing what they say they're doing physically. Maybe all the code is correct but what you're doing with your body in VR is incorrect. And usually people don't write about that aspect. (P10-PD)

An important part of debugging AR/VR experiences involves checking the application behaviour by testing and inspecting the interactions visually. Our participants reported problems in referencing bugs that manifested visually but were hard to pinpoint in code, expressing a lack of efficient ways to control multiple, often concurrent, events without losing track:

How am I going to make 400X number of targets? Also, every single target corresponds to a different audio clip: how am I going to keep a visual reference to what that audio clip is? What happens if my files get mixed up? Essentially, I had to create a way of keeping track of what was going on and then figure out a way that I could debug these targets. (P12-Dx)

In both AR and VR implementations, participants explained how locating the originating bug can be a difficult task. For example, the environment the application is being tested and the lighting can affect the object tracking process. Moreover,

in marker-less AR with new tools like *ARCore* or *ARKit* decent knowledge in programming is usually required:

It's just like it either works for me or it doesn't work and then there's no way to fix it my background does not involve any sort of computer vision (CV) and stuff. I believe there's this part in AR [that] is CV and tracking or recognition... I have no idea how those work. So those are like a black box [for me]. (P5-H)

8. User testing and evaluation challenges

As described in the barriers above, AR/VR technologies are “bleeding edge” at this stage and most of the effort is expended on getting things to work. The sheer number of barriers we identified implies that creators are busy dealing with many other issues, leaving little time for formal user testing or evaluation.

When there was interest in doing user testing, most AR/VR creators did not know how to do it properly. In particular, hobbyists and domain experts explained that they were not familiar with any usability evaluation methods, even if they wanted to improve the user experience of their applications:

I pulled up old Xerox documents on user testing and pulled up their articles, and read about what they do. I picked up some books in the library and was like, "I need to learn how to do user testing. Let's read up on user testing, and how to do this." (P12-Dx)

Even for the professional designers who were invested in user-centered design and evaluation, there were major challenges in translating the UCD guidelines to AR/VR. They often attempted to test their applications with UX methods they had learned, but ultimately most participants in this group felt that their approaches fell short. Since most end users are still unfamiliar with AR/VR technologies, participants explained how there can be a long onboarding process for them. In addition, for many types of users, their lack of familiarity with the AR/VR technologies introduced unanticipated variables that affect the output of the experience:

The moment it [VR headset] is placed on a user's head, it's one of the biggest challenges...especially if it's a new user, you're suddenly asking them to be blind and reach out and find their controllers...they see a virtual representation of it, so they have problems to grasp that connection in their minds that what they touch is the equivalent of what they're seeing virtually. (P20-Dx)

As mentioned in the prototyping section, a key challenge for authoring AR applications was designing a compelling experience with minimum distractions. While the points of distraction are expected to be gleaned from user testing, a challenge resulting from low control over experiment variables was the lack of ability to pinpoint the specific sources of distraction.

Another point of difficulty in conducting user testing was the hardware used by both test participants and developers. The constant transition between the virtual world and the debugging console caused nausea and fatigue among AR/VR creators, often leading to either prematurely releasing an application or engaging in a long iterative testing process:

	Understanding the landscape	Designing and prototyping	Implementing and testing
Professional Designers (PD)	attended local meetups (5/8), asked technical colleagues (3/8), asked questions in internal Slack (2/8)	used their prior experience/resources in 2D design (6/8)	used their prior experience in testing 2D apps (8/8), took formal courses in testing and implementation online and in person (4/8)
Domain Experts (Dx)	sought inspiration via online search (5/6), asked social contacts (4/6)	skipped this phase (3/6), mimicked similar online projects (3/6)	followed implementation-focused online tutorials and patched together code examples, but had trouble with debugging (6/6), skipped usability testing (5/6), failed to implement the project (1/6)
Hobbyists (H)	inspired by seeing interesting online videos/posts (6/7), heard from or asked social contacts (3/7)	skipped this phase (4/7), some ideation by sketching code on paper (3/7)	followed implementation-focused online tutorials and had functional apps (7/7), skipped any form of usability testing (5/7), performed QA testing (2/7)

Table 3: Summary of different AR/VR creation approaches and key activities among different groups of creators

... in almost every way it's more difficult [in VR]...you can't look at what you're experiencing in VR, and then also look at what's happening on the screen on the Unity window. And also, you have controllers, it's a two-handed experience and so you can't use your keyboard and mouse at the same time as well. (P18-PD)

From the perspective of users testing a VR application, the heaviness and warmth inside the HMDs posed additional difficulties. In some cases, VR controllers were not deemed to be representative of interactions in the real world and were confusing for users, as shown in other research [34]. With a longer onboarding process to help users pick up the new methods of interaction, the actual testing sessions tended to be time-consuming not always insightful for creators.

DISCUSSION

Our findings overall illustrate the current state of practice of AR/VR creation in our relatively diverse group of participants in terms of how they design, implement, and test AR/VR applications (summarized in Table 3). In particular, we have highlighted 8 design and implementation barriers (Table 2) that were common between our participant groups. We now reflect on the implications of our findings for future research in HCI. In particular, we discuss the importance of considering end-user developers as a growing population of AR/VR creators, how we can build learning opportunities into AR/VR tools, and the need for building AR/VR toolchains that integrate debugging and testing.

Important to consider needs of AR/VR end-user developers

A lot of the current hype for AR/VR is among professional developers who can usually access cutting-edge tools on-the-job. But, as illustrated in our findings, hobbyists, domain experts, and designers can have different needs for prototyping, programming, debugging, and testing AR/VR applications. Given that there is already a lot of momentum in HCI to better understand and support end-user developers [5,24], we consider our study to be a starting point for looking at modern AR/VR development through this lens.

Most notably, we found that domain experts and hobbyists may not even know where to start and rely on ad-hoc social recommendations to select their authoring environments. This can result in choosing a tool that, while fitting their project need, may not fit their level of experience, and even if there are no major issues in the design phase, the issues

tend to be aggravated during implementation and testing.

The frequent AR/VR hardware and software updates can make end-user developers feel especially left behind and struggle to keep up. One of our participants put it as:

The industry [is] trying to solve the problem to get as many headsets in consumer's hands as possible...but at the same time, they're leaving the developers behind. (P13-H).

Several of our participants expressed a similar level of frustration and considered giving up because of the dramatic hardware or software changes they experienced and the lack of relevant expertise that they had in getting back on track. This is an important finding for future tool developers, where it would be worthwhile to consider techniques such as progressive enhancement from web development (also suggested in [46]), to help users manage these transitions.

Building learning opportunities into AR/VR tools

Our results show that AR/VR creators used two main classes of authoring tools. The most prominent category consisted of professional, feature-rich frameworks, such as Unity, which was originally designed as a game engine and only recently grew into a popular platform for AR/VR. Since these tools are more established, there is often a larger community of AR/VR creators to provide support and examples for learning [29,36]. However, the large feature set poses issues with tool explorability and has a steep learning curve. The second class of tools was more targeted at AR/VR development, but consisted of tools created in start-ups (e.g., *Torch*), or tools developed in research (e.g., *Argon.js*). Our participants found these tools were often less refined and had a relatively smaller user community, with fewer accompanying examples and more limited support.

In light of the authoring-related issues described by AR/VR creators, we discuss potential avenues for HCI research.

Supporting early-to-middle-stage AR/VR prototyping

Some current work is already exploring methods for lowering the barrier to entry in AR/VR development. For example, *Torch* tries to provide a code-free experience for designers such that they can quickly prototype their ideas. However, such tools may, in fact, be too high-level and abstract away all the design and development challenges. This can lock creators into the tool and make it hard to

transition to more powerful platforms such as Unity, which they will ultimately need when going beyond the prototyping stage. One approach could be to adapt the principles from emerging prototyping tools, such as ProtoAR [38] that use Play-Doh props as 3D model stand-ins or 360proto [37] for new paper prototyping templates, and integrate them with advanced tools like Unity as a way of supporting early-to-middle-stage prototyping even in developer tools.

Personalizing AR/VR authoring tools based on expertise

Our hope for future authoring tools is that they can find a better match between expressivity and learnability—end user developers in AR/VR can benefit from starting with a simple development environment but with the opportunity to learn the more advanced concepts directly inside the tool. One way to do this could be to draw upon the adaptive interfaces literature to tailor feature-rich interfaces of complex authoring environments according to users' expertise level [4,14]. Another direction could be to explore ways of making AR/VR authoring tools more collaborative such that novice creators could express ideas and explore interactions while more experienced developers could take the ideas through to implementation [17,33]. This could also be extended to use online and on-demand developer communities [7,16].

Integrating access to learning resources within implementation workflows

We identified several learning barriers experienced by AR/VR creators: lack of understanding and background knowledge in nomenclature, problems finding relevant tutorials, and figuring out what basic knowledge is important before jumpstarting an AR/VR creation task. Just like with the problem of constantly evolving tools, the updating rate for the tutorials and contents does not map with the update rate of the technology. This means that tutorials quickly become outdated and put the creation process at stake. Future work can draw upon learnability research for feature-rich software [18,22] to better understand and support the learnability of AR/VR authoring tools. An interesting challenge here would be the interplay between hardware and software and design of help for immersive experiences.

Building AR/VR toolchains with integrated debugging and testing facilities

A recent review of the AR/VR tool landscape [39] shows that there is a rapidly growing number of authoring tools, but only a few transition points between them. Our interviews confirmed this, highlighting many difficulties when designing for the physical aspect of immersive experiences and the need to plan for and react to users' motions. The need to constantly transition between a VR headset and the console made it especially difficult to debug and properly test applications.

This opens up the design space for new AR/VR tools where debugging and testing facilities could be an integral part of the authoring experience. Although it would be difficult and not even desirable to build a tool that fits all needs, it is worth exploring how to design transition points into authoring

tools. For example, this could mean that AR/VR creators could move from a transition point focused on prototyping, to different ones focused on implementation and debugging, to again different ones focused on testing. Future work could also explore more interactive debugging tools like the *WhyLine* [23] and investigate how they can be extended in these virtual environments to help people locate bugs and discern why their applications are not behaving as intended.

A lot of promising work in HCI is already considering testing and evaluation issues for AR/VR. For example, Dey et. al's comprehensive review of ten years of AR usability [11] reported 369 AR user studies. However, we found that most AR/VR creators, even in professional design teams, are not using these "more research-style" approaches. It may be worth thinking about what could be the parallel "discount usability" [40] methods for testing AR/VR applications that can help practitioners. A starting point would be to revisit and reconcile heuristics [13,35,49] proposed in prior research for evaluating specific AR and VR applications.

Lastly, even when creators had user tests set up, they often struggled to get experienced AR/VR test participants. Although some participants had experience with a certain AR/VR headset, that experience did not always transfer to a different device. It would be worth exploring emulator designs that can help with parallel testing and level the playing field in AR/VR creation.

Limitations

One limitation of our study is that it presents perspectives of AR/VR creators from North America only. Given the qualitative characteristic of our study, there should be some caution used in generalizing the findings. Future research can complement the insights from this study with large-scale surveys or other approaches that include more geographically diverse groups of AR/VR creators.

CONCLUSIONS

We have presented insights from a study of 21 AR/VR creators of different backgrounds using today's authoring environments. The 8 barriers we identified present a number of opportunities for the HCI community to make AR/VR authoring more user-centered and to support emerging groups of end-user developers. Our long-term vision is to broaden participation in AR/VR authoring so that end-user developers can solve domain-specific problems and create more compelling and meaningful user experiences. Overall, there needs to be more research into understanding the needs of different types of consumers trying to get started with AR/VR development and better support their authoring experiences.

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