# 360proto: Making Interactive Virtual Reality & Augmented Reality Prototypes from Paper

**Michael Nebeling, Katy Madier**
University of Michigan School of Information
{nebeling,kmadier}@umich.edu

## ABSTRACT

We explore *360 paper prototyping* to rapidly create AR/VR prototypes from paper and bring them to life on AR/VR devices. Our approach is based on a set of emerging paper prototyping templates specifically for AR/VR. These templates resemble the key components of many AR/VR interfaces, including 2D representations of immersive environments, AR marker overlays and face masks, VR controller models and menus, and 2D screens and HUDs. To make prototyping with these templates effective, we developed *360proto*, a suite of three novel physical–digital prototyping tools: *(1)* the *360proto Camera* for capturing paper mockups of all components simply by taking a photo with a smartphone and seeing 360-degree panoramic previews on the phone or stereoscopic previews in Google Cardboard; *(2)* the *360proto Studio* for organizing and editing captures, for composing AR/VR interfaces by layering the captures, and for making them interactive with Wizard of Oz via live video streaming; *(3)* the *360proto App* for running and testing the interactive prototypes on AR/VR capable mobile devices and headsets. Through five student design jams with a total of 86 participants and our own design space explorations, we demonstrate that our approach with 360proto is useful to create relatively complex AR/VR applications.

## CCS CONCEPTS

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

## KEYWORDS

AR/VR; physical–digital prototyping; Wizard of Oz.

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**Figure 1: Inspired by Rettig [32], 360-degree paper prototyping involves participants in different roles: *User* tests an AR/VR paper mockup of an animated butterfly scene; *Facilitator* streams the butterfly cut-out arranged on a 360° paper template, while *"Computer"* moves the butterfly along the 360° grid; *Observer* records User's behavior and feedback.**

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## 1 INTRODUCTION

Paper prototyping provides a simple, cheap, and flexible method to create interactive prototypes that can be tested with users [4, 36]. In his seminal work, "Prototyping for tiny fingers," Rettig [32] describes the advantages of low-fidelity prototyping with paper and a systematic approach to user testing. While a vital step in early-stage interaction design [7, 28, 33], several recent studies found traditional paper prototyping to be limited for AR/VR [16, 22, 29]. For example, Nebeling *et al.* [29] found it hard to distinguish real and virtual objects in paper mockups and added Play-Doh props to represent virtual 3D objects; Kelly *et al.* [22] found paper mockups too static and developed visual programming tools based on AR markers to specify interactive behavior; and Hunsucker *et al.* [16] prototyped an AR museum experience based on 3D-printed artifacts, employing human actors to simulate AR interactions in the real world. Each of these studies highlight a key shortcoming of paper prototypes; they are far away from an immersive AR/VR experience.

360-degree photos and videos provide an increasingly popular way to create immersive experiences. Such 360 content is represented in 2D, but equirectangular projection is used to map it as a texture to the inside of a sphere in 3D. Based on these representations, a new set of paper prototyping templates is emerging in the AR/VR design practitioner community [5, 20, 25]. In this paper, we study the use of these templates and develop *360proto*, a suite of tools designed to support what we call *360 paper prototyping* of interactive AR/VR interfaces. Figure 1 illustrates our method analogous to Rettig [32]. Our paper makes three contributions:

(1) We study the use of emerging paper prototyping templates for AR/VR in a series of student design jams and elicit requirements for new AR/VR prototyping tools;
(2) We develop three novel tools in *360proto* for paper prototyping of AR/VR environmental designs, AR marker overlays and face masks, custom VR controller models and menus, and 2D screens/HUDs;
(3) We demonstrate support for interactive AR/VR prototypes created from paper by extending digital capture tools with live video streaming and Wizard of Oz capabilities, to simulate many common AR/VR interactions.

## 2 RELATED WORK

The vast majority of existing AR/VR tools are purely digital. A recent survey [30] distinguished five classes: *(1)* basic interaction design tools (e.g., InVision, Sketch, Adobe XD), *(2)* AR/VR variants with 3D support (e.g., DART [27], ProtoAR [29], HoloBuilder, wiARframe, Torch, Ottifox, Vizor, ViroReact, ZapWorks), *(3)* AR/VR development tools (e.g., ARToolKit [21], Tiles [31], Studierstube [34], ComposAR [35], Facebook's AR Studio, Snapchat's Lens Studio), *(4)* 3D content creation and animation tools (e.g., Teddy [18], Lift-Off [19], Google's SketchUp, Autodesk's 3ds Max and Maya), and *(5)* full-fledged 3D application development platforms and game engines (e.g., A-Frame, Amazon's Sumerian, Unity, Unreal). Partially overlapping with the third and fourth classes are tools focused on "immersive authoring," allowing designers to create AR/VR content directly in AR/VR (e.g., [12, 26, 37], Google's TiltBrush and Blocks). Tools in higher classes, such as Unity, facilitate more complex AR/VR interfaces, but also require significantly more technical skill and experience in 3D modeling and programming, which constitute major barriers for less technical designers [6, 11].

While purely digital tools can be very powerful, there is a significant gap to early-stage, physical design artifacts like sketches and paper prototypes, which are diverse and highly dynamic, thus hard to capture digitally. With 360proto, we aim to fill this gap by providing a suite of novel physical–digital prototyping tools, enabling novice AR/VR designers to make interactive AR/VR interfaces without programming. Several key techniques in 360proto are inspired from prior research and make up our systems contribution.

One important feature of 360proto is the ability to experience paper sketches in AR/VR. Prior work also raised the dimensionality of 2D sketches, e.g., Teddy [18], which automatically constructs 3D shapes from 2D freeform silhouettes; Lift-Off [19], which allows users to trace 2D paper sketches and create 3D curves in VR; and digital "sketch-to-VR" tools like Henrikson *et al.*'s [14, 15], which augment sketches with stereoscopic 3D planes or map 2D sketches to a set of concentric cylinders that represent layers of the VR environment. In 360proto, the sketches themselves are 360-degree representations of the AR/VR environment that are mapped onto concentric video spheres in 3D scenes and can be experienced in AR/VR. The sketches are based on templates with equirectangular perspective that are finding adoption in the AR/VR design practitioner community [5, 20, 25].

360proto is also a powerful tool for storyboarding and bringing paper sketches to life in AR/VR. We found inspiration in tools like SketchStudio [23], which animates storyboards in 2.5D based on a spatiotemporal, interactive canvas; Microsoft's Sketch 360 [17], which links equirectangular sketches to 360 views; and DART [11, 27], which introduced 3D animatic actors and scripted interactive behaviors to take storyboards into AR. DART is also inspirational in that it incorporated support for Wizard of Oz to simulate interactive behavior of a system with the help of a human [9, 10]. 360proto supports live video streaming of 360 paper prototypes to AR/VR devices, which enables simulation of many AR/VR interactions in real-time. We adapt techniques known from video and 3D puppetry [2, 13], where paper cut-outs and physical objects moved by a wizard are captured and tracked by camera systems to animate 3D scenes.

Another key aspect to 360proto is that it extends other physical–digital prototyping tools previously limited to *either* AR *or* VR to supporting *both* AR *and* VR. Two recent examples are ARcadia [22] and ProtoAR [29]. Both use AR markers—ARcadia to create mappings between physical objects and digital interface components in a tangible AR programming environment; ProtoAR to create mobile AR apps with 2D overlays generated from paper sketches and quasi-3D models from Play-Doh captured with a smartphone—360proto adapts these AR prototyping techniques for AR/VR.

## 3 INITIAL DESIGN JAMS

To inform the design of 360proto, we conducted a series of student design jams with a total of 86 participants. The goal of our initial design jams was to better understand how users prototyped for AR/VR. Based on our findings, we formulated requirements, developed new tools in 360proto, and conducted three final design jams to explore the use of the created tools. This section presents our initial design jams.

### Method & Participants

We conducted two initial design jams. The first posed two specific design challenges, asking participants to recreate three interactions from two existing AR/VR applications each using paper prototyping. The second used an open design challenge in which participants had to come up with their own AR/VR application and create at least three interactions using paper prototyping.

For the specific design challenges in the first design jam, we chose Google Daydream's tutorial for VR, where the user can explore a forest with a flashlight (the controller) and observe forest animals. As the AR challenge, we chose Pokémon GO, where the user must catch a Pokémon by throwing a ball at it. We chose both for their relative popularity and complexity. Each challenge required participants to prototype three interactions. For VR, we chose *(1)* a *gaze-based* interaction, *(2)* a *controller-based* point interaction, and *(3)* a *compound* interaction, where the user first looks around, then points at a character. For AR, we chose *(1)* a *camera-based* interaction that anchors the Pokémon on the floor, *(2)* a *screen-based* swipe interaction to "throw" the ball at the Pokémon, and *(3)* an *environment-based* interaction, where the ball bounces off the Pokémon and rolls on the floor. We believe these to be examples of common AR/VR interactions.

For the open design challenges, we helped ideation by giving participants a list of nine application domains with examples from recent surveys [3, 8]. In total, participants created two VR and two AR applications. Both VR applications were in the domains of tourism and exploration: a campus tour and a museum tour. The first AR application consisted of a set of three mobile games: a bird shooting game, a bubble popping game, and a basketball game. The second was a training simulation for job interviews.

Each design jam involved two rounds of paper prototyping of at least three AR/VR interactions. In the first round, we supplied common materials including paper, pens, scissors, tape, transparencies, and cardboard, as well as print-outs of the main objects involved in the specific design challenges, but no templates yet (Figure 2). In the second round, we introduced participants to a preliminary 360 paper template and asked them to use the template to create a second paper prototype. For the specific design challenges, we also supplied 360 photos of a forest and the campus courtyard, both in equirectangular format to match the template. Finally, we introduced a preliminary mobile app for participants to take a picture of the paper prototype created using the template and obtain VR previews in Google Cardboard (Figure 3).

The first design jam involved 24 and the second 12 participants, all HCI master's students recruited via a mailing list for students interested in design jams. Each design jam

**Figure 2: Initial Daydream, Pokémon GO paper prototypes**

**Figure 3: 360 paper prototype versions viewed in Cardboard**

took three hours with two hours focused on paper prototyping in groups. At the end of each round, groups were asked to demonstrate the three required interactions with their prototypes, which we recorded from the perspective of the user. We concluded with a focus group discussion to have participants reflect on the experience as well as exit questionnaires to gather feedback in terms of two pros and two cons comparing plain and 360 paper prototyping.

### Results

There were *minor* differences between the design challenges in terms of process and prototyped interactions.

Participants commonly started by sketching storyboards, wireframes of screens, and environmental features. To demonstrate their prototypes, they composed the AR/VR interfaces from these sketches, showing changes in the interface by adding or moving sheets of paper, sticky notes, and transparencies. The open design challenges required additional discussion initially to pick an application domain and example that resonated well with everyone in the group.

The prototyped interactions were mostly gaze and camera-based interactions or screen-based interactions, such as tapping and swiping. Pointing with the controller or the hand was also common, but less prominent compared to our Daydream and Pokémon GO examples. Rather, voice and speech formed a major part in all but the mobile AR games.

There were *major* differences between the design challenges in terms of perceived complexity of AR *vs.* VR paper prototypes and in the granularity of the paper prototypes created with *vs.* without the 360 paper template.

*AR paper prototypes seemed easier despite being more complex.* We balanced the complexity of the chosen interactions for the Daydream and Pokémon GO design challenges, and participants did not mention major differences. In the open design challenges, however, we found the AR prototypes to be more complex than the VR prototypes in terms of the interactions. The VR teams mostly designed interactions involving content directly in front of the user, such as menus and HUDs. While they mentioned things that would happen around the user during demonstrations, they did relatively little to prototype it. In the feedback sessions, we asked the groups to rank their prototypes from easiest to hardest. Interestingly, despite the AR prototypes being more complex, they were considered simpler and easier to create than the VR prototypes. The AR teams only felt constrained on paper because they "[c]ouldn't show the reality part."

*Plain paper prototyping is quick, but lacks 3D context.* In the specific design challenges, participants felt efficient prototyping either application (17× participants said "quick" or "fast"). However, plain paper made it difficult to provide 3D context to their AR/VR mockups (20× "hard to imagine in 3D", "missing context", "hard to use 3D"). In the plain paper prototypes, the different aspects of AR overlays, 2D screens/HUDs, and 3D environment were commonly combined in a single sketch. In contrast, the 360 paper template made participants think more in terms of layers and separate out on-screen interactions from camera and environment-based interactions.

*360 paper template helps, but there is a learning curve.* Using the template provided more visual cues during design and allowed participants to imagine in 3D space ("[The template] helped me think about the environment"). In particular, the VR previews in Google Cardboard were appreciated (9×, e.g., "objects look more real. It allows the player to have a more interactive experience."). However, the template had a learning curve (7×). Several participants found the 360 grid too abstract to imagine what the final product would look like. Often when taking a photo of the template and viewing it in Cardboard, the result did not look as intended.

*Interactions are difficult to facilitate with physical prototypes.* A first difficulty was simulating interactions involving motion (16×). Movement along the z-axis was a major challenge as it required objects at multiple scales to support the simulation of depth. Also imagining the final interaction with a VR controller was hard. One participant explicitly asked for a better digital tool providing instant, realistic previews: "360 paper would be better if you could view it in Daydream [with a controller] to tighten the design loop."

## 4 REQUIREMENTS FOR AR/VR PROTOTYPING

Based on the above observations from the design jams, we extracted the following requirements for AR/VR prototyping:

**(R1) Support for layered prototypes.** AR/VR experiences consist of a variety of components. Designers must be empowered to prototype all parts of an AR/VR app, from the AR/VR environment in which the experience will take place, to AR marker overlays, to VR controller menus, all the way to 2D screens and HUDs. Our design jams showed that the 360 paper template helps separate the concerns and provides more structure to paper prototypes: "It's easy for the designer to imagine the specific context after a designer is familiar with [the template]. It's easy to show the VR interaction."

**(R2) Integration with digital tools.** It is a major jump from traditional paper prototyping, which is "flat" and in 2D, to AR/VR, which happens in 3D. While the 360 paper template helps, it is still difficult to imagine how things look in AR/VR. Our design jams showed that quick transition from physical prototypes to digital tools with realistic previews on AR/VR devices is necessary: "I don't have a sense of scale without using a VR device. It's hard for me to understand how the design will actually look in three dimensions."

**(R3) Wizard of Oz capabilities.** Previews need to be dynamic and updated in real-time. Wizard of Oz can be used to manipulate objects in AR/VR [9, 10]. Our design jams showed that, while "It was nice to see the 360 paper prototypes actually working," they can be difficult to facilitate for the wizard: "The interaction wasn't as clear [with 360 paper]; it was difficult to move the object in terms of the 360 view."

## 5 360PROTO TEMPLATES & TOOLS

In this section, we introduce the three digital tools we developed to address the requirements: *(1)* the *360proto Camera* for capturing paper mockups simply by taking a photo with a smartphone and previewing AR/VR content in Google Cardboard; *(2)* the *360proto Studio* for live editing of captures, composing AR/VR interfaces by layering the captures, and making them interactive with Wizard of Oz via live streaming; *(3)* the *360proto App* for testing the interactive prototypes on AR/VR devices. To illustrate the tools, we make the animated butterfly scene from Figure 1 the running example in this section. The designer's goal is to create a paper mockup of an AR scene with a butterfly moving around a user.

### 360 Paper Template: Sketch & compose 360 scenes

First, the final version of the 360 paper template is shown in Figure 4. We based it on the VR grid created by Kurbatov [24], and added layers to mark the field of view and range of motion based on work by Alger [1]. These additions were made to make designers aware of the scale and guide object movement based on the initial design jam feedback.

### 360proto Camera: Capture & preview paper mockups

To create a first mockup of the butterfly scene, our designer makes use of our first tool, the *360proto Camera*. She takes a picture of the paper mockup with her smartphone and views it as a 360 photo in Google Cardboard. To guide her when creating the digital capture, the Camera overlays the 360 paper template on the camera stream. This aids viewfinding and getting a good distance and angle to the mockup for the capture. To support prototyping of both AR and VR applications, we developed a number of camera modes (Figure 5).

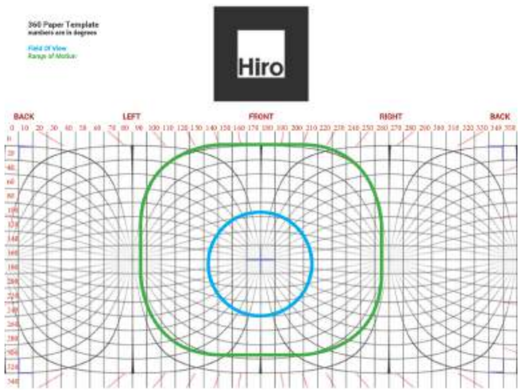


**Figure 4: 360 grid (red), range of motion (green), FOV (blue)**

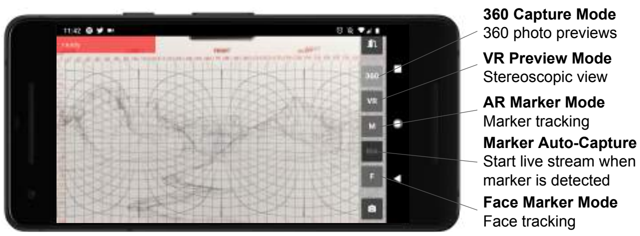


**Figure 5: Camera tool creates static captures and live streams**

*Manual Capture and Live Streaming Modes.* For the initial prototype, our designer manually takes pictures with the Camera. These captures become immediately available in the Studio. There is also support for live video streaming to the Studio. In later prototypes, she will use live streaming to animate the butterfly.

*360 Capture Mode.* To take captures of her paper mockups using the 360 paper template, our designer uses the 360 capture mode. In this mode, the Camera interprets the capture as a 360 photo and maps it onto a sphere. When deactivated, the Camera takes normal photos. This is used to capture mockups of 2D screens, HUDs, AR overlays, and VR controllers and menus.

*VR Preview Mode.* Per default, the Camera shows fullscreen 360 views without stereoscopic rendering. This is useful to prototype smartphone-based, hand-held AR interfaces. To get a sense of how her mockups would look in VR, our designer switches to the VR preview mode. She puts her phone in a Google Cardboard to see stereoscopic 360 views of her paper mockups.

*AR Marker Mode.* The modes described thus far are sufficient for our designer's initial prototypes. In later versions, she will make use of the AR marker mode. This mode enables marker tracking in the video feed and superimposes a selected capture in the Studio. The marker can be moved in 6DoF in front of the camera. The overlay will be transformed to match the tracked marker's position and orientation. Our designer will use this later to move a capture of the butterfly in live video streamed to the Studio.

*Marker Auto-Capture.* To make it easier to operate our Camera tool while animating objects in front of the phone's camera, we developed a marker auto-capture feature. This starts live streaming as soon as an ARToolKit marker comes into the view of the camera. Note that users can interrupt live streaming by pressing the phone's screen or obscuring the physical marker. This is useful to pause streaming while making bigger changes to the scene such as bringing up a new screen or menu.

*Face Marker Mode.* Finally, for prototyping AR applications that use face masks similar to Snapchat's Lens Studio and Facebook's AR Studio, we developed a special marker mode using face tracking. In this mode, the Camera overlays a selected capture in the Studio over a detected face. The overlay will now be transformed to match the position and orientation of the tracked face.

### 360proto Studio: Author interactive AR/VR interfaces

To help with the organization of Camera captures and support the creation of interactive prototypes, we developed 360proto Studio. In the Studio, designers can compose AR/VR interfaces from layers of paper mockups, see previews, and stream the prototypes to the 360proto App we describe later.

*Main Components.* The Studio is composed of four main components (Figure 6): *(1)* the *View* pane shows a simulated or live preview of the AR/VR prototype running on a smartphone (live if used in combination with the 360proto App); *(2)* the *Collect* pane shows thumbnails of the live video feed of the Camera tool, previous captures of paper mockups, and PNG images imported from the file system; the *Layers* pane shows thumbnails of the 2D, 360, and AR/VR specific layers described below; the *Capture* pane shows a larger preview of content selected in the *Collect* pane and provides tools for chroma keying to make pixels of a selected color with a specified tolerance level made transparent in layers.

The Studio is operated using drag and drop: content from the *Collect* or *Capture* panes can be dragged onto the *View* or *Layers*. Drag and drop from the file system is also supported.

*2D and 360 Layers.* The Studio supports creation of interactive AR/VR prototypes by composing interfaces from multiple layers. We distinguish three types of layers: 2D, 360, and AR/VR specific layers. 2D and 360 layers are further distinguished into background, midground, and foreground, and will be rendered on top of each other. 2D layers can be used to compose 2D screen overlays for hand-held AR applications and HUDs for head-mounted AR/VR displays. 360 layers can be used to compose 360 photos captured with

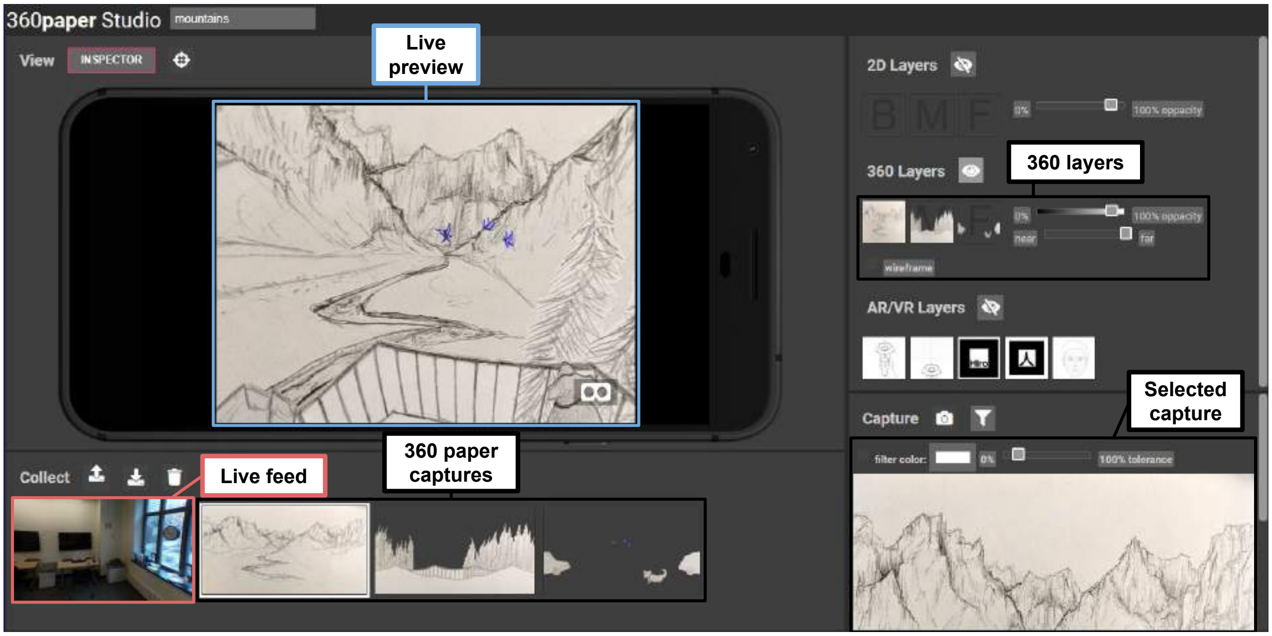


**Figure 6: 360proto Studio's *View* pane (top left) shows a simulated or live preview of the 360 paper prototype; *Collect* pane (bottom left) shows the live feed from the connected Camera tool and contains previous captures (here, three captures of mountains, trees, and butterflies, a dog and a car drawn using the 360 paper template); *Capture* pane (bottom right) shows a selected capture and provides color filters for chroma keying; *Layers* pane (top right) shows 2D, 360, and AR/VR specific layers (here, only 360 layers are used to compose a basic butterfly scene from the running example).**

the Camera or imported from the file system. 360 layers are rendered on spheres of increasing radius (per default, foreground is 1, midground 3, background 5 meters).

Coming back to our example, Figure 7 (left) shows how our designer is now starting to add content and compose the butterfly scene from layers of paper mockups. The foreground layer shows three butterflies in front of the user, a dog to the right of the user, and a car in the back of the user. She uses a midground layer to show trees a little further away from the user and a background layer to show mountains in the distance. Figure 7 (right) shows a 360 preview of the scene using spheres to render the 360 layers. We added a Studio option to render 360 layers as wireframes, which can be used to reduce the level of detail of content and better see the layer composition (see bottom right image inlay).

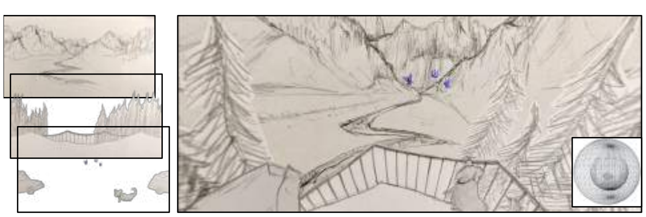

**Figure 7: Butterfly scene composed from three 360 layers**

*Transparency and Distance Sliders.* There are sliders to control the opacity of 2D and 360 layers, which makes the layers more or less transparent as they are rendered over the live camera feed in AR applications.

Additionally, there is a slider to control the distance between 360 layers. Our implementation uses a 1–5 meter range slider with 0.5 meters step granularity. As 360 layers are rendered on spheres of increasing distance, modifying the distance between layers allows for control of depth, a major requirement established in our design jams. In the example, our designer increases the distance between layers to make the mountains in the background appear at a much further distance. This gives a parallax effect making the midground and foreground layers appear relatively closer to the user.

*AR/VR specific Layers.* AR/VR layers include VR controller models and menus, AR marker overlays, and AR face masks. The VR controller layers can be used to replace the default controller model with a sketch or photo of a custom controller, such as the racket in our Racquetball example later. The menu layer can be used to show a menu relative to the controller. The position and orientation of both these layers will be updated in live previews when a Google Daydream controller is connected to the 360proto App and moved by the user. The last two layers work just like in the 360proto Camera tool. We will illustrate the use of these layers in later examples in the paper.

*Live Layer.* To support animation and simulation of complex AR/VR interactions with Wizard of Oz, we developed a live layer feature. Any of the 2D, 360, or AR/VR specific layers can be marked as live. The live layer will render whatever content is loaded in the *Capture* pane, which supports real-time manipulations and updates of the content rendered on the selected layer. This can be used for swapping layer content by loading different assets from the *Collect* pane, e.g., captures of different states of a VR menu. Because the live video feed can also be loaded into the *Capture* pane, this can even be used for rendering a live video feed from the Camera onto the selected layer. For example, this enables the creation of an animated menu rendered as 2D screen overlay for AR and as HUD or controller menu for VR. If the live layer is a 360 layer, the content will be rendered onto the corresponding sphere. This facilitates animation in 360 degrees around the user.

Our implementation supports one live layer. As demonstrated in later examples, this already provides a high degree of flexibility and power sufficient to satisfy complex AR/VR prototyping requirements. We plan to extend the support to multiple live layers as we also add support for multiple instances of the Camera tool to be connected to the Studio.

### 360proto App: Run & test AR/VR prototypes

With the 360proto App, designers can test prototypes created in the Studio on a smartphone. The App requires ARCore capable phones for AR or Google Daydream for VR, which also comes with a bluetooth VR controller.

*VR and AR Modes.* The App supports both AR and VR modes. In the VR mode, the App renders the 360 layers on spheres around the user, the 2D layers on a plane in front of the user following their gaze, and the VR controller model and menu at the controller's tracked position and orientation.

In the AR mode, the App renders the rear camera's video stream and then superimposes the 360 layers on spheres anchored at the user's physical starting location, and finally adds the 2D layers on top of the video.

*Support for Live Layers.* The 360proto App can render a live video feed coming from the Camera or Studio tools on any of the layers. This supports animations and updates of the selected layer in real-time. Figure 8 shows our designer using the AR marker mode in the Camera tool to superimpose an image of a butterfly over a kanji marker attached to a stick made from paper. In the Studio, we marked the 360 foreground layer as live and filtered white at high tolerance to remove the paper completely from the video feed. In the App, this renders the butterfly in 360 degrees around the user according to the 360 paper template's grid. Moving the marker closer/farther to the phone's camera makes the butterfly appear closer/farther to the user.

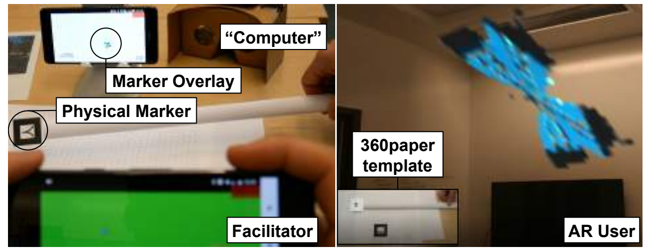


**Figure 8: AR marker to move virtual butterfly in AR view**

*Six Degrees-of-Freedom Movement.* The 360proto App supports six degrees-of-freedom (6DoF) movement so that the orientation as well as the position inside the AR/VR scene changes with device movement. We achieve this using ARCore for marker-less motion tracking.

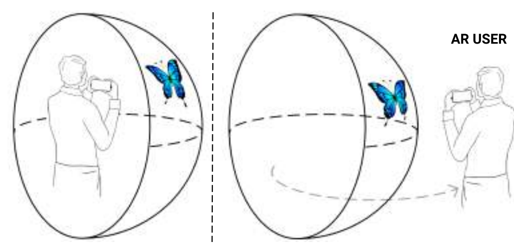


**Figure 9: AR mode with the user looking at a virtual butterfly from inside (left) and outside (right) the 360 video sphere that is anchored at the starting physical location**

To support 6DoF, the App anchors the concentric 360 layer spheres at the user's initial physical location as illustrated in Figure 9. The live video feed of the phone's rear camera is rendered and the 2D and 360 layers are superimposed to create a see-through AR display. As the user moves the phone while standing within the sphere, they can view the respective portion of the 360 layer content rendered in physical space before them. It is also possible for the user to move outside the sphere and see the content from the other side. However, the closer the user moves to the wall of the sphere, the more they experience spherical distortion of the content.

### Implementation

The 360proto tools are implemented using web technologies (Figure 10). In all three tools, we use A-Frame to specify the 3D scene and enable access to AR/VR specific features in supported browsers. In the Camera tool, we additionally use AR.js for the Marker and Auto-Capture modes and the JavaScript-based BRFv4 face tracking library for the Face Mask mode. In the App, we use a special version of A-Frame with support for WebXR for the AR mode. Live video streaming and synchronization of all three tools is done via WebRTC media capture, streaming, and data channel APIs. We tested all features successfully in Google Chrome on ARCore capable Pixel smartphones for AR and Daydream for VR. HoloLens and VR headsets like Oculus Rift and Windows

Mixed Reality all support A-Frame scenes in Mozilla Firefox and Microsoft Edge, but live streaming was not possible due to insufficient support for WebRTC.

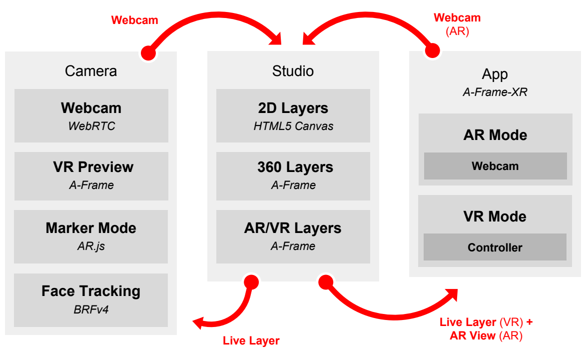


**Figure 10: Architecture of our suite of 360proto tools**

## 6 EXAMPLE APPLICATIONS OF 360PROTO

In this section, we report three prototypes created using 360proto as part of our design space explorations. The first is based on the butterfly scene we used as the running example; the second a 360 paper prototype of Star Trek; and the third a live streamed 360proto version of Google's ARCore HelloAR little Androids example. The goal of our demonstrations is to show the full spectrum of use and capabilities of our tools, while our final design jams reported in the next section aimed to evaluate 360proto's usability and practicality.

Since advanced 360proto prototypes require Wizard of Oz to simulate functionality, enacting prototypes can involve up to three participants in different roles similar to Rettig [32]:

- *Facilitator:* uses the Camera to capture the 360 paper prototype and the Studio for the digital prototype;
- *AR/VR user:* uses the App in AR or VR mode and sees a working, interactive prototype on an AR or VR device;
- *"Computer" (can be same as facilitator):* manipulates the physical prototype or uses the Studio to manipulate the digital prototype based on AR/VR user's behavior.

### Butterflies: Creating parallax 360 paper prototypes

An initial version of the butterfly running example required only one person and took the second author 2.5 hours to create. The main challenge is to compose the scene from layers so that the butterflies appear closer and the mountains farther away from the user. The second author drew the scenery on three separate sheets of paper following the 360 grid, captured the drawings with the Camera, and assigned them to fore, mid, and background 360 layers in the Studio. She—as VR user—could then see the scenery with parallax effect of the butterflies, dog, and car in the foreground, trees in the midground, and mountains in the background. Running the prototype with the App's AR mode allowed her—as AR user—to walk up to the butterflies and walk around them to see them from the other side. We consider this version of low complexity. The majority of the time was spent on the drawings. Putting the scene together and testing it in VR and AR required less than 10 minutes. As we will show in our third example, implementing the live animated butterfly requires a second person in the Facilitator/"Computer" role.

### Star Trek: Walking inside 360 paper prototypes

Our Star Trek prototype allows an AR user to walk on the bridge, see into the observation room through an open door, and walk into the room by passing through the door (Figure 11). In addition to composing the scene from layers with the commanders' chairs in the middle of the bridge, a second challenge was to arrange the spheres to create the room effect. This prototype required two people and a total of 12 hours to create. The second author created detailed 360 drawings of the commanders' chairs, the bridge, and the observation room in 8 hours. She attached the captures to foreground, midground, and background 360 layers in the Studio. The first author required an additional 4 hours to experiment with the configuration of the spheres to achieve the room effect. Using A-Frame's visual inspector tool, he—as facilitator—moved the background sphere (the observation room) away from the center, rotated it to have it intersect with the open door on the midground sphere (the bridge), and set the material from front to back. This gave the initial effect of looking into the other room. The final effect required switching the sides of the two room spheres' materials from front to back upon the user entering the room. While the second author in the role of user walked between rooms, the first author—as "Computer"—switched the material sides.

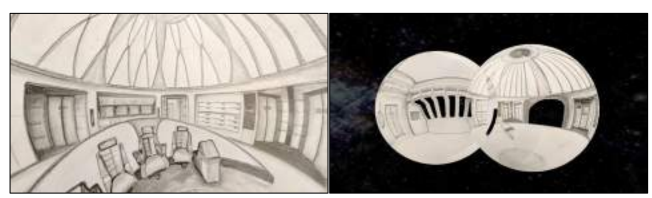

**Figure 11: Star Trek: two connected rooms made from paper**

### Androids: Bringing 360 paper prototypes to life

Our Androids prototype recreates Google's ARCore demo that places little Android figures on detected planes (Figure 12). The original demo is fairly complex, consisting of 745 LOC for the Unity scene and about 260 LOC for the full AR controller implemented in C#. This is also a challenging 360proto example as it requires mapping the 360 paper template to a live feed of the room as well as simulation of depth. Still, it required only two people and less than 20 minutes to create. The second author produced paper cut-outs of the Android figure. The first author—as facilitator—marked the foreground 360 layer as live, started live streaming in the Camera, and placed the Androids on the template to appear where the second author—as AR user—was looking. We experimented with two ways to simulate depth: using paper cut-outs of different sizes or using the distance slider marking different 360 layers as live. Both created a similar depth effect when placing Androids on the template. The first author—as "Computer"—found the first way to be easier.

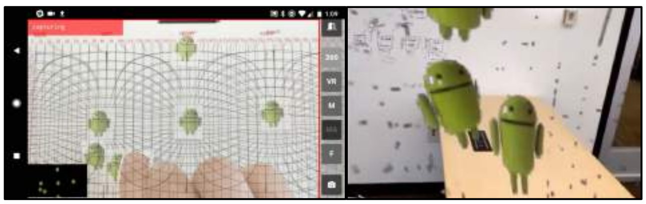

**Figure 12: Androids on paper appear in the environment**

## 7 FINAL DESIGN JAMS

This section presents the remaining three design jams we conducted to explore the use of the created tools with users. The common goal was to evaluate 360proto by asking students with varying technical skill and different backgrounds to recreate relatively complex AR/VR prototypes. The third design jam evaluated the Camera and App tools. It involved four students with technical backgrounds at the end of their 3-month long AR/VR research projects. The fourth design jam focused on the bridge from Camera to Studio. It was conducted in an introductory AR/VR course with 37 HCI master's students using different templates to create multi-layered 360 paper prototypes. The fifth design jam focused on the bridge from Studio to the App. It involved nine non-technical students with a variety of backgrounds recreating two existing AR/VR applications using Wizard of Oz. Thus, the three design jams involved students with different technical skills and backgrounds. The decision to focus on different combinations of tools, rather than study the full use of all three tools at once, allowed us to study key stages and transitions in the prototyping workflow in detail, which was more important to us than trying to demonstrate overall usability.

### Design Jam #3: Complex AR/VR scenes with 360proto

In the third design jam, we investigated how more technical AR/VR designers might use 360proto. It involved the 360 paper template for a sketching activity, the Camera tool for VR previews, and the App to test the AR/VR prototypes.

*Method & Participants.* We recruited four independent study master's students close to completion of semester-long AR/VR projects (in week 12 of 14), all experienced with common physical and digital tools. We balanced the number of projects focused on AR vs. VR. One of the students was working on a VR project, two of them on AR projects, and the fourth on a project that considered designing for both AR and VR.

We developed interviews structured into five blocks: *(1)* project requirements; *(2)* prototyping challenges; *(3)* introduction to 360proto; *(4)* hands-on 360 paper prototyping session; *(5)* final feedback. We asked questions to uncover challenges participants faced with existing tools, introduced them to our 360 paper template and tools, and explored where and how they would use them in their projects by asking them to create a 360 paper mockup. Each interview took one hour involving 20–30 minutes of prototyping. We took notes of participants' concerns and feedback regarding existing tools and the experience using the template and 360proto.

*Results.* We found that the students were working on quite complex AR/VR applications using a variety of tools, most of which require programming. Students reported that 360proto could help mitigate limitations of existing tools. They found it promising to bring AR/VR paper prototypes to life.

*Complex AR/VR applications.* Application requirements were fairly high in terms of both content and interaction. The first project *(VR)* concerned with VR traffic simulation required to have realistic city traffic and enable users to manipulate traffic conditions from a birds-eye perspective using gaze and controllers. The second project *(AR1)* concerned with virtual workspaces on AR headsets like HoloLens required users to be able to insert and manage virtual screens in a physical room using hand gestures. The third project *(AR2)* concerned with AR extensions to car windshields required visualization of speed limits, blind spots, and crossing pedestrians on a custom projection-based display mimicking the windshield. The fourth project *(AR/VR)* concerned with news in both AR and VR required switching between AR/VR modes depending on environment and task, and additionally used voice for navigating articles.

*Using a wide variety of AR/VR tools.* The tools used by students across all projects were Keynote, Sketch, InVision, Proto.io, Framer, Halo, HoloBuilder, A-Frame, and Unity. One of the main challenges was indeed finding the right tool [30]. All participants noted that they had tried several different combinations of these tools, but that, without programming using A-Frame or Unity, they would not have been able to create a prototype that correctly views in AR/VR. All also said Unity was the hardest ("I can hardly use Unity. It takes way too much time."). It was ruled out by the *(VR)* and *(AR2)* students due to the steep learning curve.

*Existing tools' VR support is basic, largely missing for AR.* While several prototyping tools recently added support for 360 photos, VR support was still lacking. Proto.io and Halo enabled preliminary prototypes in *(VR)* and *(AR/VR)*, including previews with Cardboard. But the ceiling of both was reached quickly, which required an early switch to A-Frame and Unity, respectively. Unity was also quickly chosen in *(AR1)* after paper mocks and a rudimentary prototype with Framer. The custom AR display setting in *(AR2)* was not a good fit for any tool. It mostly required 2D content though, for which Keynote and A-Frame were deemed sufficient.

*360proto promising to bring AR/VR paper mockups to life.* Students commonly saw 360proto as a useful extension to paper prototyping, e.g., "fast and easy to test," and with significant value-add. Compared to traditional paper, 360 paper was considered "more thorough" and "more about AR environment design," and praised for its "rapid previews"—"the AR view is really valuable to me." However, they also all commented on the size of objects on the 360 grid, which often initially appeared larger than expected ("pretty zoomed in"). In *(VR)*, the birds-eye view was tricky to sketch and, in *(AR1)*, bigger screens did not appear to be closer, just bigger at the same distance. The consensus was that it is "very easy to transfer to digital," but requires "a lot of trial & error."

## Design Jam #4: Multi-layered 360 paper prototypes

In the fourth design jam, we used a combination of AR/VR prototyping templates with the Camera tool, and tested them in an introductory AR/VR course with HCI master's students with backgrounds in design, CS, architecture, and business.

*Methods & Participants.* 37 students participated. They were provided the following materials: Google Cardboard VR headsets, 360 paper templates with field of view and range of motion, AR/VR specific templates for VR controller menus and AR face masks, as well as paper, pens, pencils, and sharpies. We formed groups of 4–5 students so that they could share equipment, but each student solved each design challenge.

The design jam lasted 3 hours. We started with a 1-hour introduction to 360 photos, the templates and tools, and Google Cardboard, showing some of our own 360proto examples. The remaining two hours were structured into four design challenges—two for VR and two for AR. The first and second challenges were to *(1)* create a 360 paper mockup of a YouTube VR app with two different screens, and *(2)* create a paper mockup of a VR controller menu with three different states for the YouTube VR app. The third and fourth challenges were to *(3)* create a 360 paper mockup of an AR newspaper interface, and *(4)* create a face mask mockup for a head-worn AR interface that provides information about people they meet at a job fair or conference. Participants were asked to fill out a feedback form to reflect on the design activity as homework, asking for two things they found easy and two things they found hard for each design challenge.

*Results.* From analyzing the submitted 360 paper mockups, we found that students explored a broad range of interactions. The quality of submissions varied from almost perfect perspective rendering to incorrect sketches that did not view well in 360. Several students had difficulty sketching and making correct use of the template and provided tools. Despite the field of view and range of motion guides, they struggled with understanding how to draw in scale and depth on the 360 paper template. While the students found the tools useful for design space explorations, paper prototyping with the templates alone, i.e., without Wizard of Oz which was out of scope, seemed insufficient to understand whether interactions would work well in AR/VR.

*Tools useful for design space exploration.* Figure 13 shows 29 students' ratings for three questions. The majority of students agreed that the tools helped them understand AR/VR design requirements (Q1) and design for a 360-degree environment (Q2). The ratings were lower when we asked if the tools helped them understand what interactions could be used in the given AR/VR applications (Q3). To us, this confirmed the need for prototyping with Wizard of Oz via live streaming, which was the focus of the final design jam.

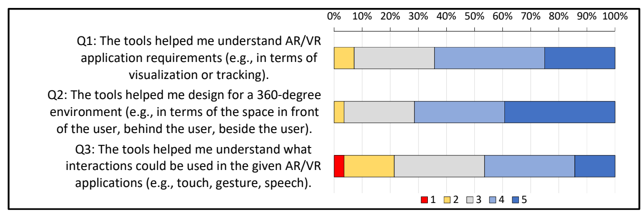


**Figure 13: Distribution of 29 responses for Q1–Q3**

Participants were also asked to mention two things they found easy and two things they found hard for each of the four design challenges. A total of 28 participants submitted 416 comments (194 about easy and 195 about hard things). 27 comments were blank or not related to the design challenges.

*Templates guide design, but sketching still difficult.* The majority of comments about easy tasks submitted by participants related to the process of designing interactions and feature components *(113×)*: brainstorming, designing, sketching. Participants mainly mentioned the templates as being helpful *(36×)* as guides for drawing accurately in perspective and to save time. One said: "Sketching with a 360 paper template makes the design of AR/VR less overwhelming."

Comments that expressed difficulty with using the 360 paper templates *(43×)* can be attributed to insufficient practice with sketching objects realistically, in scale, and with believable depth. Participants also mentioned feeling limited by the small amount of drawing space on the templates. For the AR News challenge, participants noted difficulty curating content on the 360 paper template in a way that corresponds to the real environment.

*Still difficult to imagine final user experience in AR/VR.* Many comments involved concern over creating design elements without having knowledge on how users would interact with AR/VR devices *(17×)*. Additionally, several comments from participants expressed difficulty with completing the design challenges because of lack of technical or domain knowledge of AR/VR interfaces and applications *(14×)*, e.g., "It was actually quite hard for me, as I barely have any experience with a controller and I don't play games."

### Design Jam #5: Live prototypes with Wizard of Oz

In the fifth and final design jam, we evaluated the use of the 360proto tools for real-time interactions using Wizard of Oz to simulate two complex AR/VR applications. The first application we chose was a fully interactive VR racquetball game we had implemented, using the Daydream controller as a racket and physics for the ball (Figure 14). The second application was based on Amazon Shopping's AR view, allowing users to preview products in their homes (Figure 15).

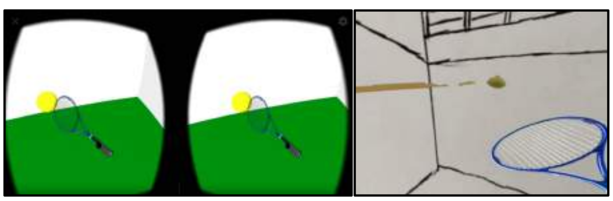

**Figure 14: Racquetball game (left), WOz version (right)**

**Figure 15: WOz version of Amazon Shopping's AR view**

*Methods & Participants.* We recruited nine first-year HCI master's students with backgrounds in business, architecture, psychology, and health informatics via our student design jam mailing list. We began the three-hour design jam with a 30-minute introduction to AR/VR devices and 360proto. Participants were shown examples of 360 paper mockups and designs made with our tools. Participants spent the first hour creating paper mockups of the VR racquetball game using the 360 paper template to sketch a gym and the VR controller template to sketch a menu to control game settings. Participants then captured their mockups to create and prototyped the ball interactions with Wizard of Oz via live streaming to Google Daydream. Afterwards, participants created paper mockups of the Amazon Shopping AR View interface and prototyped the shopping item interactions with Wizard of Oz via live streaming to an ARCore capable phone. As in previous design jams, we concluded with a 30-minute focus group discussion and the same exit questionnaires.

*Results.* Five of the nine students filled in the questionnaires commenting on easy *(16)* and hard *(14)* tasks. We compiled the feedback into spreadsheets and used thematic coding to identify themes, then pulled out representational quotes for each theme. Despite some difficulties, the two main themes were that the resulting AR/VR prototypes seemed realistic and that using Wizard of Oz raised the level of fidelity.

*Tools facilitated creation of realistic AR/VR interfaces.* Participants produced a wide range of artifacts from each challenge, with some participants creating additional sketches and artifacts within the allocated time frame. During this design jam, all drawings created on the 360 paper template were previewed using 360proto Camera. We noticed students were able to correct inaccurately mapped images by previewing drawing with the 360proto Camera tool. Students did find sketching realistically and in scale to be difficult, which was mentioned in participant feedback *(6×)*. Overall, materials produced were well crafted and many students showed a firm grasp of drawing on the 360 paper template. One put it as: "The tools we used were very intuitive."

*Wizard of Oz enabled medium-fidelity AR/VR prototypes.* We assisted the students with capturing the paper mockups and creating the prototypes in 360proto Studio. One participant—as "Computer"—was moving the ball and shopping items, while we performed the facilitator role using the 360proto Camera and Studio. Participants—as AR/VR users—were able to test the prototypes using a Daydream with controller to hit the ball and using an ARCore smartphone to place shopping items. Users felt that the simulation via Wizard of Oz gave them a good sense of the final user experience, seeing it as a medium-fidelity AR/VR prototype.

## 8 DISCUSSION

Where significant time, technical skill, and programming experience would be required with most existing tools, we showed that 360proto can enable novice AR/VR designers to create fairly complex prototypes. While we acted as facilitator and/or "Computer" in many of the prototypes, they still demonstrate that our tools can be viable in design space explorations and broaden the way in which paper can be used for AR/VR prototyping. Our tools give flexibility and, with the use of Wizard of Oz, can support a wide range of interactions, including implicit gaze, camera, and environment-based interactions as well as touch, gesture, and speech. There are three main takeaways from this work.

First, we identified a minimal set of features to support a wide range of prototypes. The fore, mid and background 2D and 360 layers give structure to prototyping [1]. Applying the layered approach to supporting AR/VR specific interface components, such as VR controller models and menus, AR overlays and face masks, keeps it simple. Our live layer enables Wizard of Oz to simulate complex functionality. The sliders are simple instruments to further adjust key AR/VR parameters like opacity and depth. The AR/VR modes and 6DoF are key to experiencing AR/VR prototypes.

Second, the majority of our participants who were novice AR/VR designers were able to learn and use our tools to create complex AR/VR prototypes in less than an hour. The learning curve is low, as expressed by four participants with 3-months A-Frame or Unity development experience.

Third, our design space explorations and student design jams showed that 360proto can be used to enact complex prototypes with Wizard of Oz without programming. Advanced prototypes may require two or more people, but the number of people is an indicator of interface complexity, not usability or practicality of our tools.

## 9 CONCLUSION

This paper explored physical and digital prototyping of AR/VR experiences using a range of 360 paper prototyping templates and our new 360proto tools. Through a series of design jams, we developed and evaluated our tools. Our overall take-away from the design jams was that students found our approach more powerful than traditional paper prototyping, making it easier for them to think in 3D, and giving them a better sense of the final AR/VR experience. While traditional paper prototypes are lacking in many regards [16, 22, 29], prototypes created with 360proto received encouraging feedback: "Very close to [the original] AR/VR experience" and "It looks way closer to the real scene." Compared to fully implemented AR/VR applications, they were considered medium fidelity.

## 10 ACCESS TO 360PROTO TOOLS & MATERIALS

Our 360proto tools, AR/VR design jam materials, and templates are available at https://360proto.com.

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