VRCreatIn: Taking In-Situ Pen and Tablet Interaction Beyond Ideation to 3D Modeling, Lighting, and Texturing

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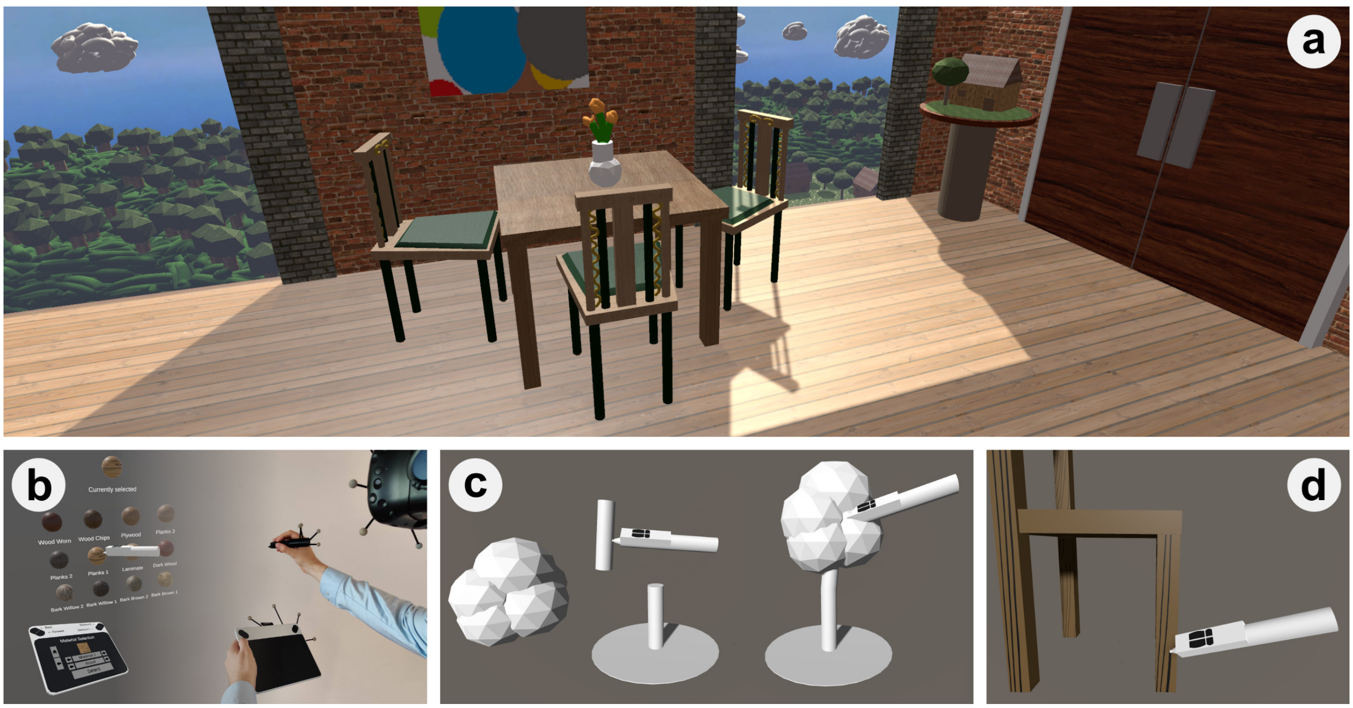

Figure 1: *VRCreatIn* is a virtual reality (VR) 3D content creation solution that supports the process of 3D scene creation (a) starting from ideation and going beyond to modeling (c), lighting, and texturing (a, d). It is based on a design space focusing on in-situ interaction for unconstrained 3D mid-air and constrained 2D surface-based interaction using pen and tablet (b).

Abstract

Mixed reality (MR) in-situ authoring has demonstrated advantages for 3D content design regarding perception, understanding, and accessibility, satisfying the growing demand for MR content in industry, education, and entertainment. However, existing MR tools mostly focus on ideation and sketching, making further steps such as 3D modeling, lighting, and texturing not sufficiently researched yet. This research gap raises the need to explore end-to-end 3D content creation workflows in MR environments. We introduce *VRCreatIn*, an all-in-one virtual reality (VR) solution for 3D content creation informed by expert interviews (N=6) and a design space analysis. It pioneers an integrated multimodal workflow through all stages of 3D modeling, lighting, and texturing based on pen and tablet interaction. Our usability walkthrough (N=10) confirms that *VRCreatIn* transfers the benefits of pen and tablet to the whole content creation workflow, broadening the scope of 3D content creation in VR. These contributions pave the way for future research, establishing *VRCreatIn* as a cornerstone for comprehensive

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3D design in VR environments that can be transferred to the whole MR continuum.

CCS Concepts

• **Human-centered computing** → *Walkthrough evaluations*; *Mixed / augmented reality*; **Virtual reality**; **Interaction techniques**; **User interface design**; *User centered design*; • **Computing methodologies** → *Shape modeling*.

Keywords

virtual reality, mixed reality, visualization, interaction, 3D modeling, content creation, authoring

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1 Introduction

The growing popularity of mixed reality (MR) in diverse sectors such as industry, education, and entertainment has intensified the demand for sophisticated 3D content creation solutions [70]. Traditional desktop-based tools like *Blender* [14] and *Unity* [83] offer comprehensive features, yet MR-based in-situ authoring has shown unique advantages in the perception and understanding of 3D design [72]. It further improves upon the trade-off between complexity and functionality found in traditional tools and expands the user base by increasing the available content by allowing those without expert knowledge to author content [9, 30, 70]. This will be important in the future so that 3D content can be generated for MR-based social media or so that teachers and lecturers can create their MR teaching materials.

However, existing MR tools for 3D content creation often specialize in narrow tasks like sketching (e.g., *VRSketchIn* [30] or *SymbiosisSketch* [9]), contrasting with the broader capabilities of traditional desktop applications. A professional workflow supports the whole process, starting with sketching/ideation and continuing with modeling, lighting, texturing, and animation [14, 83], while only the latter create actual high-fidelity 3D assets. Therefore, it is currently not investigated how to create high fidelity 3D assets for MR in-situ in MR, wasting to transfer the mentioned benefits (e.g., perception and understanding of 3D assets [72]) to this.

We introduce *VRCreatIn* to investigate 3D content creation beyond sketching/ideation in virtual reality (VR). Our system design builds upon previously validated designs that leverage pen and tablet interactions for MR in-situ sketching (e.g., *VRSketchIn* [30] and *SymbiosisSketch* [9]; see Figure 6). Both Drey et al. [30] and Arora et al. [9] have demonstrated that this design approach effectively combines the freedom of 3D mid-air drawing with the precision of 2D surface-supported drawing and that it works interchangeably in VR and augmented reality (AR), meaning the whole MR continuum [28, 68]. *VRCreatIn's* focus on modeling, lighting, and texturing is based on expert interviews conducted with 3D content creators (N=6; evaluated using thematic analysis [15, 16]). We define a content creation process based on their feedback (see Figure 2) and create a design space (see Figure 3) to ground the system design of *VRCreatIn*. With this work, we are the first to investigate additional content creation phases of 3D assets using pen- and tablet-based interaction.

To validate our approach, we implemented a feature set, selected for its representativeness, into a prototype. We explain the prototype through a use-case demonstration (see Figure 7). It was tested during a usability walkthrough by N=10 participants conducting two content creation tasks (see Figure 8) and evaluated using thematic analysis [15, 16]. Individuals of varying skill levels welcomed the tool's adaptable and modular features. It was deemed beneficial to have pen- and tablet-interaction also in advanced process steps, including the seamless switching of all process steps as they are all provided in one tool. Our research shows that *VRCreatIn* enhances in-situ 3D design to process steps beyond ideation and enables iterative improvements across multiple process steps, thereby expanding the possibilities for 3D content creation in VR (results are transferable to the whole MR continuum [28, 68]).

VRCreatIn provides the following three main contributions, categorized according to the contribution types of Wobbrock and Kientz [86]:

(1) The definition of a design space derived from a 3D content creation process based on expert interviews (N=6) as well as previously validated system designs that leverage pen and tablet interactions for MR [9, 30]. It represents and categorizes interaction metaphors for an MR in-situ 3D content creation workflow. *(theoretical and empirical contributions)*
(2) The concept and implementation of the *VRCreatIn* system applying unconstrained 3D mid-air pen and 2D surface-based pen and tablet interaction to content creation steps beyond sketching/ideation, namely *modeling*, *lighting*, and *texturing*. This is exhibited by a use case demonstration. *(artifact contribution)*
(3) Initial insights on usage patterns of *VRCreatIn*, based on a usability walkthrough (N=10) encompassing two 3D content creation tasks. *(empirical contribution)*

2 Related Work

Previous works in the areas of traditional 3D content creation, as well as works using MR, set the base for *VRCreatIn*.

2.1 Definition and History of 3D Content Creation

First, we want to define what we consider as 3D content creation in this work. 3D content creation refers to any software-aided process involved in generating computer imagery or virtual 3D objects in a virtual 3D space [13, 22, 25]. The field became accessible with Ivan Sutherland's 1963 software, *Sketchpad* [22, 81]. Industry adoption of computer-aided design (CAD) software like *AutoCAD* in the 1980s led to standardization and affordability [35]. Nowadays, the availability of free tools such as *Blender* has expanded the field to freelancers and hobbyists that create video games or animated movies [14, 73].

3D content creation involves several phases, also tailored to different stakeholders and use cases (e.g., CAD engineer vs. game designer) [30]. Major phases that *VRCreatIn* focuses on are ideation/

sketching, modeling, and texturing [14, 22, 49]. We will describe related works for them here briefly before conducting expert interviews in the following to define the phases for a content creation process used for *VRCreatIn* (see Figure 2).

As the first phase, ideation and sketching are often interlinked, as ideas can be fast and efficiently expressed using sketches. Sketching apps use 3D lines/strokes, as seen in *Surface Drawing* [78] and *Thor* [7], rather than volume-based representations. These lines usually lack additional features like anchor points.

For modeling 3D objects, primitives (e.g., cubes or spheres) are used as a base. Primitives can often be selected from a list and placed in the 3D scene to build complex objects, as seen in *Blocks* [42], *Mix&Match* [80], *3DBrushVR* [88], *HoloSketch* [26], and *CaveCAD* [79]. 3D shapes can also be generated from 2D contours by drawing on a 2D plane and extruding it [30, 75] or by drawing contours from multiple perspectives for more complex shapes [61, 62, 76]. Constructive Solid Geometry (CSG) allows the creation of complex shapes based on primitives by combining and modifying them using operations such as union, difference, and intersection on them [38, 67]. Various manipulation techniques focus on vertices, affecting the object's edges and faces. Operations include extrusion, smoothing, and warping. More complex methods like sculpting also manipulate vertices [22].

To enhance the realism, 3D objects use textures to have a surface showing colors. Texturing can be performed through various methods, e.g., by drawing them [36, 52, 64] including artificial intelligence (AI) support [87] or choosing predefined ones from a database [21]. Results can range from simple coloration to complex textures that simulate effects like roughness or opacity (e.g., mosaics [1] or simulated oil paint [23]).

2.2 3D Content Creation in MR

Early milestones in 3D content creation in VR were *3DM* [17], *HoloSketch* [26], *CavePainting* [55], and *FreeDrawer* [85], which allowed 3D volumetric objects and sketches. With the availability of consumer head-mounted displays (HMDs), applications such as *TiltBrush* [6] and *Gravity Sketch* [40] were created, focusing on artistic sketching-based content creation. Lately, commercial tools have implemented some further content creation steps in MR, e.g., *Adobe Substance 3D* [2], which supports modeling and sculpting or *Shapelab VR* which also supports texturing [60].

To support users in mastering the degrees of freedom (DOF) of 3D mid-air interaction, previous works have investigated how physical and virtual surfaces can be supportive constraints to increase precision and usability [10, 34, 56]. The works *VRSketchIn* [30] and *SymbiosisSketch* [9] have built on this and investigated system designs on how to combine 3D unconstrained mid-air and 2D constrained surface-supported input. They used interaction techniques based on a 3D pen and a 2D pen on a tablet, which could seamlessly be switched. Their results show that bringing together 3D and 2D interaction can improve system usability and creative possibilities by combining the freedom of 3D with the precision of 2D. Further works exist that emphasize the positive influence of the haptic feedback of a pen or haptic objects in general on a physical surface on the user experience and creativity (see *SpARklingPaper* [31] and Fujinami et al. [39]). Besides pure sketching, Jetter et al. [52], Auda et al. [12], and Fender et al. [36] investigated how painting on 2D planes or 3D objects itself could be implemented using gestures, transparency effects, or physical brushes. However, they did not focus on process steps such as object modeling or 3D in-situ sketching.

This work will build on these system designs and use unconstrained 3D mid-air and constrained 2D surface-supported interaction based on a pen and tablet interface. It is the first to apply these interaction methods to further content creation steps, as discussed below.

3 Content Creation Process

Expert interviews were conducted to consider the complexity of 3D content creation and provide a profound basis for the content creation process used in this work and the creation of a design space.

3.1 Expert Interviews

The previous VR in-situ authoring work *VRSketchIn* [30] described a content creation process with the steps (1) *ideation*, (2) *modeling*, (3) *texturing*, (4) *animation*, and (5) *verification*. These are typical steps described in the literature, often extended by dedicated *sketching* and *lighting* steps [14, 22, 49]. To get practitioner insights into the steps of content creation, we conducted interviews ($M = 68$ *min*, $SD = 15$ *min*) with six experts ($M = 32$ *years*, $SD = 11$ *years*, female=1, male=5) with two in the fields of CAD, three in object creation via Blender and one is a lecturer on 3D content creation and supervisor of projects in the area of games/serious games. Participants were asked open questions regarding 3D content creation, and the previously shown content creation process and steps were discussed and iteratively advanced. One author analyzed the results of the interviews by conducting a reflexive inductive thematic analysis similar to Brown and Clarke [15, 16].[1]

3.1.1 Theme 1: Content Creation Process Steps. The different technical backgrounds of the participants influence their focus areas and preferences within the broader field of 3D content creation. This variance in expertise and interest sets the stage for unique challenges in the 3D content creation process (e.g., creativity for game assets vs. precision for CAD). Typical steps our experts named for content creation are *ideation*, *sketching*, *measuring*, *modeling*, *texturing*, *lighting*, *animation*, *rendering*, *verification*, and *export*.

3.1.2 Theme 2: Workflow. While a general order of the process steps exists from ideation to graphical fidelity, it is an iterative and dynamic workflow. It is further tailored to the goal, as lighting and rendering were not deemed necessary for CAD, and accurate measuring was only directly mentioned by the participants with a CAD background [P1, P5]. Therefore, participants favored a modular and individual workflow, signifying a need for flexibility in the tools process steps order used for 3D content creation [P1, P2, P4, P5, P6]. Such flexibility would favor different technical backgrounds and use cases.

[1] Interviews were recorded and automatically transcribed. The coded text passages were sorted, refined, and arranged to overarching themes. Before finalizing, the themes were cross-validated with another author.

3.2 *VRCreatIn* Content Creation Process

The interviews show that 3D content creation is a modular process that involves multiple steps, traditionally requiring multiple programs and interaction patterns. For example, ideation is performed by sketching concept art (e.g., with pen and paper) [4] while modeling is done using Blender [14], texturing using Adobe CC [3], and lighting during scene creating in Unity [83]. This has the restriction that switching between creation phases (modeling, texturing, lighting, etc.) also enforces a switch of tools and their interaction paradigm, making rapid iterations difficult. The goal of this work is to provide an integrated workflow for in-situ authoring in VR by enabling the benefits of pen and tablet interaction beyond ideation and allowing a seamless transition between the phases. We further emphasize that each phase (e.g., modeling, texturing) has its own ideation process that can be supported by pen- and tablet-based sketching (see *VRSketchIn* [30] or *SymbiosisSketch* [9]), making sketching an integral metaphor of *VRCreatIn* and its underlying workflow. For example, modeling is supported by sketching in defining initial outlines, rough shapes, proportions, and orientations to manifest a scene, gradually refining a concept or an idea. For texturing, sketching is helpful to ideate over different surface appearances and concrete textural features. Painters use layer-wise sketching techniques to gradually develop complex surface textures, color gradients, or detailed local features.

Investigating all use cases mentioned during the interview is not goal-oriented for a first step and, therefore, we set the focus of this work on the creation of 3D game assets, excluding CAD use cases and aid functions/steps such as *measuring* or *export*. This is in line with the scope of *VRSketchIn* [30] and features the artistic setup of this work. We further focus, as a first step, on static assets, excluding the *animation* phase.

Therefore, we apply pen and tablet as a novel contribution to the process steps *modeling*, *texturing*, and *lighting*. As they also have an initial ideation process, we see *ideation* (supported by sketching techniques) as an omnipresent phase guiding content creation using *VRCreatIn*. This results in the content creation workflow shown in Figure 2 that emphasizes the novel modular and iterative approach using one tool and interaction technique (pen and tablet) during the whole creation process.

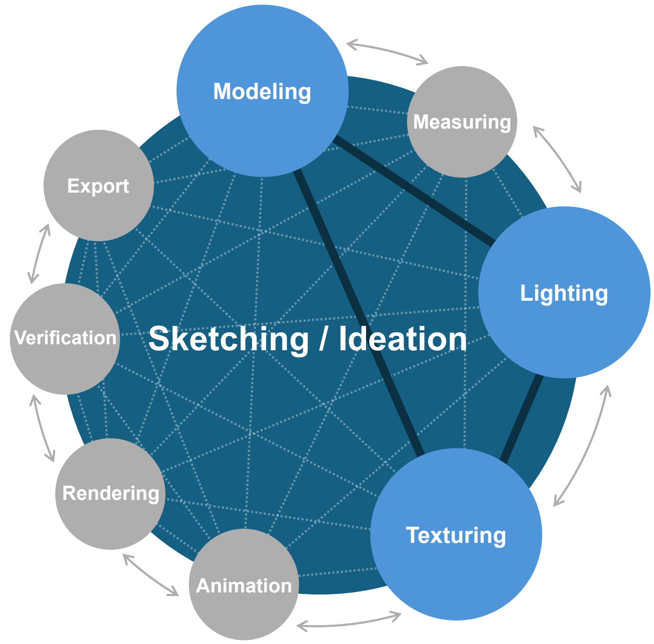

Figure 2: The *VRCreatIn* workflow: The phases and arrows on the outside represent a traditional 3D content creation process based on our expert interviews, which tends to enforce a sequential workflow and makes transitioning difficult due to necessary tool and interaction concept shifts. With *VRCreatIn*, we introduce an approach for transitioning seamlessly between phases in the creative workflow that is supported by omnipresent ideation based on an underlying shared sketching paradigm enabled through pen and tablet interaction. This work focuses on the novel investigation of the phases *modeling*, *lighting*, and *texturing*.

4 Design Space

We created a design space to encompass a broad spectrum of content creation based on the defined process (see Figure 2) and used it to brainstorm the functions of our prototype.

4.1 Dimensions and Scope

We used the previously described content creation process to define a design space that also considers the system design of *VRSketchIn* [30], which combines unconstrained 3D mid-air drawing with constrained 2D surface-based drawing. It was created through a morphological analysis with three iterations and is visualized as Zwicky box [89] (see Figure 3). The two axes are the main dimensions (D), which each have multiple parameters (P) to specify them further. D1 *Input Devices* is derived from the design space of *VRSketchIn* as this work uses the same system design. This means it focuses on the input devices, *pen* and *tablet* (P1), as well as their *2D* and *3D* interaction capabilities (P2). D2 *Interaction* is based on our expert interviews and covers the previously defined content creation process (P3) (see Figure 2). Whereas the design space of *VRSketchIn* also focuses on drawing aids, namely the specific 2D interaction based on the drawing surfaces, this work is tailored to interaction metaphors for content creation. That is why no object type parameter exists, and P4 directly addresses the input type, meaning *direct* and *indirect* input according to Hinckley and Wigdor [44]. The intersection of a row and a column defines a cell, which represents specific interaction metaphors. We brainstorm and describe several of them as a base for our prototype in the following.

According to Drey et al. [30], our design space fulfills three main use cases, namely (1) as a brainstorming guide for interaction metaphor ideation, (2) to maintain an overview of an application's feature set, and (3) to categorize prior art.

4.2 Interaction Metaphors

According to the first use case of the design space, all authors used it as guidance to brainstorm functions for *VRCreatIn*. We focused

<table>
<tr><td></td><td></td><td></td><td colspan="2">D2: Interaction</td></tr>
<tr><td></td><td></td><td>P3: Content Creation</td><td colspan="2">Sketching/Ideation | Modeling | Measuring | Lighting | Texturing | Animation | Rendering | Verification | Export</td></tr>
<tr><td></td><td></td><td>P4: Input Type</td><td>Direct</td><td>Indirect</td></tr>
<tr><td rowspan="5">D1: Input Devices</td><td>P1: Device Type</td><td>P2: Input Dimensions</td><td></td><td></td></tr>
<tr><td>Pen</td><td>3D</td><td></td><td></td></tr>
<tr><td>Tablet</td><td>3D</td><td></td><td></td></tr>
<tr><td rowspan="2">Pen+Tablet</td><td>2D</td><td></td><td></td></tr>
<tr><td>3D</td><td></td><td></td></tr>
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Figure 3: Zwicky box visualizing the design space for in-situ content creation, developed through three iterations of morphological analysis. It incorporates the system design of *VRSketchIn* [30] and expert interviews regarding a typical content creation process. The design space has two main dimensions (D): Input Devices (D1) and Interaction (D2), each elaborated by multiple parameters (P). The design space serves three main use cases: guiding brainstorming in interaction metaphor ideation, maintaining an overview of an application's feature set, and categorizing prior art.

on the previously described scope narrowed down to the content creation phases *ideation*, *modeling*, *lighting*, and *texturing*.

4.2.1 Brainstorming Ideation. Often, sketching is used for ideation (see *VRSketchIn* [30]). In MR, it benefits from enhanced spatial understanding, especially for 3D objects [45, 71]. Standard sketching tools employ lines/strokes in a 3D environment to symbolize objects and usually lack volumetric representation due to simplification [6, 9, 30]. These tools often rely on mid-air or surface-based drawing interaction metaphors, categories previously discussed in this work, and can be transferred to the pen- and tablet-based design of *VRCreatIn* (see design space). Early frameworks such as *Surface Drawing* [78] and *CavePainting* [55] exemplify this approach, where the lines generated are usually freeform, lacking additional attributes like anchor points or defined surfaces. The design space of *VRSketchIn* [30] focuses on this kind of sketching and was an inspiration for our prototype. Although lines are commonly used, alternative sketching methods are also viable, such as employing flat surfaces [77, 78] or basic geometric shapes [88].

4.2.2 Brainstorming Modeling. The main interaction metaphors for modeling can be classified as *vertex modeling (e.g., point definition)*, *contour modeling (e.g., edge/face definition)*, and *volume modeling (e.g., volume drawing)*. Interaction metaphors can be defined in multiple ways, e.g., in mid-air and also on the tablet's surface (see design space). Vertex modeling involves the creation or modification of an object through the specification or alteration of its vertices. For instance, constructing a cube by outlining its eight edges and positioning vertices at these points falls under vertex modeling [14], both possible in mid-air with the pen or in 2D on the tablet. Contour modeling focuses on object creation or alteration based on their outlines. This includes transforming a 2D sketch into a 3D object [51] (from the tablet to mid-air), using grids and curves for manipulation [22], and beveling, which involves rounding or slanting the edges or corners of an object [14]. Volume modeling pertains to operations rooted directly in an object's 3D volume. Techniques include generating an object from full-volume point clouds, not merely contours [48] and free-form sculpting [14] (e.g., both created by the pen in mid-air) or employing CSG operations (e.g., hierarchically visualized on the tablet). Objects can also be generated or altered indirectly (see design space), bypassing direct interaction with their physical properties. Recent methods include the creation [53] or alteration [18] based on parameter definition (e.g., text input) alone. The limitation has to be stated that this classification can overlap. For instance, altering connected vertices on an object's edge could be considered both vertex and contour modeling.

4.2.3 Brainstorming Lighting. For a 3D scene, it is necessary to specify its lighting so that during rendering, the objects can be illuminated as intended [49]. Typically, there are local as well as global light sources [5]. While global or ambient light sources are often edited using parameter definitions, local ones, e.g., a spotlight, are also placed in the scene to highlight and illuminate specific objects [5]. As these local light sources are virtual objects, they can be handled during in-situ authoring with the same interaction metaphors as modeled objects [14, 83]. For example, they can be placed by the pen in mid-air or using the tablet on 2D layers.

4.2.4 Brainstorming Texturing. While sketching toolkits enable the application of various colors to basic shapes, they are mostly limited in their texturing capabilities [9, 30]. However, some tools already proposed the first concepts by directly drawing on the object's surface [20, 52] (possible with the pen). Textures can be directly applied to 3D objects or, more accurately, from a technological standpoint, onto an underlying 2D texture that is mapped to the 3D object, a process often called UV mapping [22]. This could be a basic color or more complex textures that simulate additional properties like roughness or opacity [74]. Such 2D textures can be modified by drawing with the pen on the tablet. These textures can also be physical or 3D in nature, such as the use of mosaic tiles [1] or oil paint simulation [23]. Textures can also be applied through algorithm and AI support [57, 87] and template assignment using a database [21]. In the field of AR, users can scan the texture of real-world objects or 2D images and map them onto 3D models [50, 64, 65].

5 The *VRCreatIn* System

VRCreatIn focuses on interaction metaphors possible with pen and tablet input [9, 30]. This work is the first that extends this interaction technique to further content creation steps as described in Figure 2 and the design space (see section 4).

5.1 Feature Set and Design

Inspired by *VRSketchIn* [30] and *SymbiosisSketch* [9], this work has a focus on depicting interactions equally in 3D and 2D using the 3D unconstrained mid-air pen interaction and the 2D surface-supported constrained tablet interaction. The content creation steps (see Figure 2) were implemented as follows during a User-Centered Design (UCD) process with five iterations:

- ***Ideation:*** The system supports both direct line sketching in 3D mid-air via a pen and sketching on a 2D plane by using

the tablet. An annotation feature for textual input using a virtual keyboard in 3D space is also included.
- ***Modeling:*** The system supports vertex modeling through direct manipulation using the pen, allowing for the selection and displacement of individual or multiple vertices (see Figure 4 (b)). This feature is also extended to contour modeling, enabling the displacement of object lines and faces. Volume-based modeling is facilitated through CSG operations and parameter definition in 3D space (see Figure 4 (a)). Indirect modeling allows for parameter definition via a tablet user interface (UI). Additionally, primitive objects can be chosen from a 2D list or directly within 3D space and included in the scene.
- ***Lighting:*** Users have the option to choose from preset scenes, such as an office building interior, along with various lighting conditions (see Figure 1 (a)). These ambient scenes can be toggled on or off, enabling users to validate their created objects within different virtual settings.
- ***Texturing:*** Texturing of objects can be achieved either by direct coloring in 3D space using the pen on the object (see Figure 5 (a)) or with the tablet using 2D planes (see Figure 5 (b)). Additionally, materials or colors can be directly assigned to objects (see Figure 6 (a)). This facilitates a hybrid approach combining both (see Figure 5 (c)).

Furthermore, overarching aid functions are implemented to enhance usability, maturity, and comparability to commercial tools as well as previous works (e.g., *VRSketchIn* [30] and *SymbiosisSketch* [9]): *Transformation.* Transformations such as gizmo usage, direct movement, rotation, and ray cast/anchoring are implemented. For 2D interactions, movements are supported on both predefined and tablet-projected planes. *History.* Enables quick undo actions and state comparisons, addressing a functionality gap of *VRSketchIn* [30]. *Scaffolds.* Users can enable and adjust 3D scaffolds and grid overlays for each axis to improve spatial orientation. *Distance Measuring.* A feature for precise distance measurement between points along each axis is included. *Parameter Definition.* Numerical placement and transformation via tablet coordinates are available for increased precision. *Preset Camera Perspectives.* A set of predefined camera angles can be accessed. *Color Selection.* An advanced color selection system, inspired by *VR Color Picker* by Kim et al. [58], operates in both 2D and 3D spaces. *Layering.* A layering system enables object assignment to different layers, which can be toggled on or off for specific workflows.

5.2 Prototype Setup

The hardware configuration employed for *VRCreatIn* is inspiration from *VRSketchIn* [30] and *SymbiosisSketch* [9] and has been similarly previously applied in 3D content creation research [30]. As HMD, a VIVE Pro 2 [47] is used. Input is managed through a custom 46-gram 6DOF tracked pen with four buttons, which is used in conjunction with a 6DOF tracked Wacom Intuos Draw graphics tablet [69] (see Figure 6). Motion tracking is executed by an OptiTrack Flex 13 system [84], covering a 2.5 * 2.5-meters area. The computing system is equipped with a GeForce GTX 980 graphics card, and *VRCreatIn* runs on Unity 2019 LTS [83] using software assets (see supplementary material).

6 Use Case Demonstration

To demonstrate how *VRCreatIn* transfers pen- and tablet-based interaction to modeling, lighting, and texturing, we present a use case for creating a bed. The in-situ scale was 1:1 (about 2.2x1.6 meters). This use case was chosen because it effectively showcases a substantial portion of the tool's features while remaining easy to understand. *VRCreatIn*, however, is capable of handling more complex objects and scenes (see Figure 1 (a)). The object was created by one of the authors with no professional background in 3D content creation, lasting roughly 20 minutes, showing its eligibility and efficiency for non-experts (e.g., teachers or engineers). Selected steps of the creation process can be seen in Figure 7. A time-lapse is provided in the supplementary video.

As the first step for ideation (1), the rough outlines of the bed were sketched with the free-hand sketching tool. The measuring tool (red line in Figure 7 (1)) was used to validate the dimensions of the sketch. To support spatial awareness and provide a basis for comparison, the indicators of the x, y, and z-axis with a length of one meter were enabled at the pen tip. The ideation was continued in the second step (2). Here, further outlines of the bed were created using a combination of freehand and line sketching tools. To better keep track of the different dimensions of the bed when rebuilding it with volumetric elements, the measurements were annotated in the 3D scene (red numbers in Figure 7 (2)). The finished sketch is used as a basis to model the bed with volumetric objects (3). *VRCreatIn* can create volumetric objects in different ways (see feature brainstorming section 4.2.2 and implemented features section 5.1). We used a combination of creating objects with parameter definition for precision as well as free-hand interaction for fast placement and an what you see is what you get effect. Created objects were transformed via parameter inputs and a 1DOF/3DOF gizmo. To duplicate objects, the copy tool was used. After the volumetric objects were placed in the right position and size, the sketch and annotations were removed with the layering tool. For texturing, *VRCreatIn* offers a selection of different materials as well as color definitions that can be assigned in different scales to objects. A wood material was assigned to the bed corpus in step four (4). Selecting predefined textures, objects with realistic high-fidelity graphics can be easily created with little effort and without artistic skills. Further details of the bed are added in step five (5). The mattress was created by defining the object's dimensions directly in the scene. The sketching feature can be used again for a second/intermediate ideation phase to see if additional details fit the object. This highlights the iterative and flexible content creation approach as propagated in Figure 2. Here, first, the outlines of the blanket were sketched to the bed in red (5). By supporting undo and redo actions via the history feature in addition to the layering feature, *VRCreatIn* supports the rapid prototyping of different ideas. Step six (6) shows the finished bed. For creating the pillows, cylinder objects were the base and deformed into a fitting shape via the gizmo. If objects with a less regular form are needed, the vertex manipulation tool can be used. Finally, the created object can be exported and later used in other 3D scenes, including scene-specific lighting (see Figure 1 (a)).

We want to emphasize that with this use case, we were able to present an example workflow, including several of the implemented

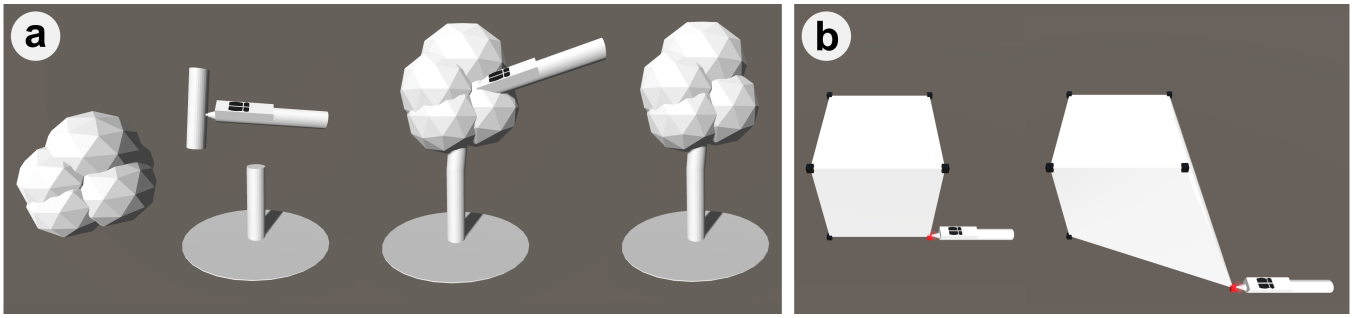

Figure 4: Modeling. a) Complex objects can be created based on primitives also supporting CSG. b) Primitives can also be edited through vertex modeling.

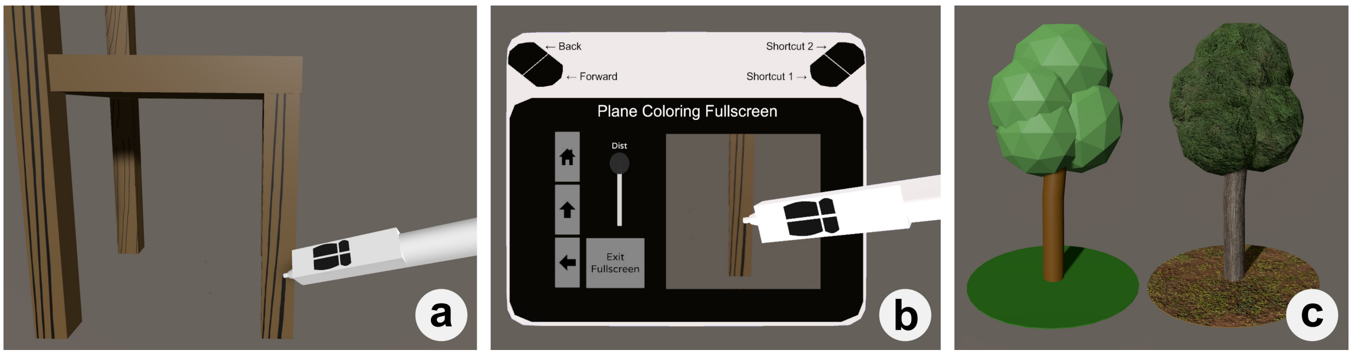

Figure 5: Texturing. a) Objects can be textured by painting on them in 3D. b) It is also possible to texture objects using predefined 2D planes with surface support on the tablet. c) Colors or textures/materials can also be assigned to objects.

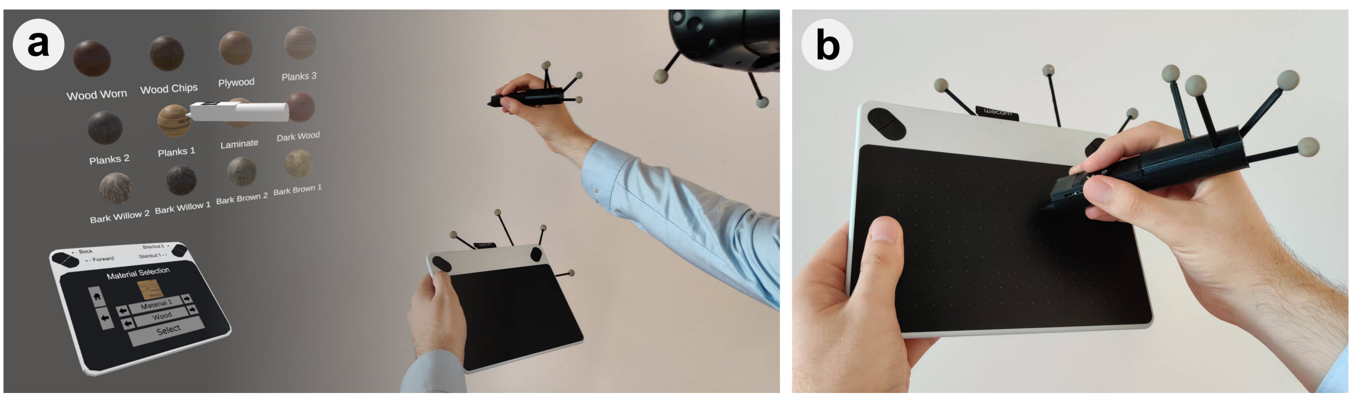

Figure 6: The hardware of *VRCreatIn* is based on a pen and a tablet, which are both tracked in 3D for immersive interaction (a). It is also possible to use the pen on the tablet for surface-supported 2D input (b).

features, on how we would advise using *VRCreatIn*. However, *VRCreatIn* can meet the needs of users from various fields, who may prefer different features and sequences of steps, as previously mentioned in our interview results with diverse experts. This was investigated further in a usability walkthrough.

7 Usability Walkthrough

This chapter describes the evaluation of *VRCreatIn* by conducting a usability walkthrough.

7.1 Procedure

Our usability walkthrough is designed as a multi-step think-aloud study, which was used in previous works to explorative evaluate systems and artifact contributions [9, 30, 86]. First, we conducted

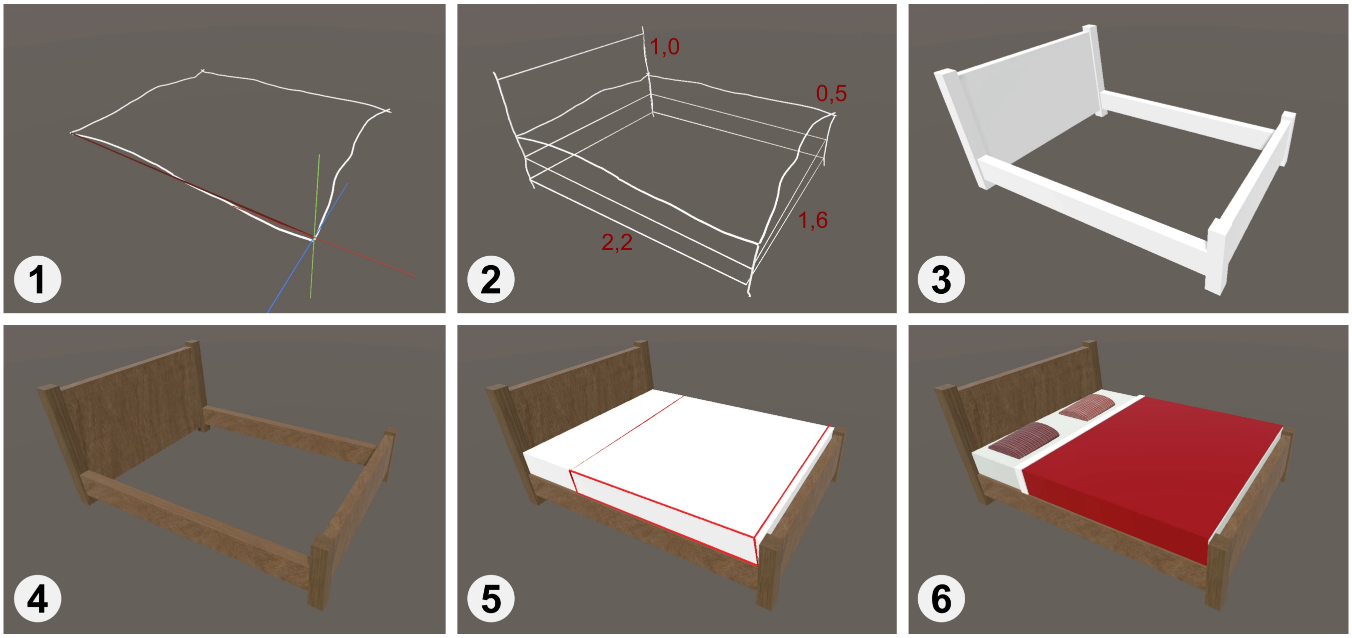

Figure 7: This use case demonstrates how *VRCreatIn* can be used to create a queen-size bed showcasing six key steps. First (1), the rough outlines are sketched and measured. Afterward (2), the sketch outlines are completed and the taken measurements are annotated. The sketches are used as scaffolds for volumetric object creation (3) and are removed afterward. Materials are then added to the bedposts (4), followed by more object details (5 and 6). The final object (6) can be exported for further use.

a *preparation* and a *tutorial* where we explained the procedure of the usability walkthrough and the features of *VRCreatIn* to the participants. For *task 1*, participants created a chair followed by a table (max. 30 min). They provided intermediate feedback in *interview 1*. In *task 2*, participants created a house with a garden (max. 30 min). During *interview 2*, questions were asked about detailed aspects of the tool. A full description of the process is provided in the appendix.

7.2 Participants

We recruited 10 participants through convenience sampling ($M = 25$ *years*, $SD = 3$ *years*, female=3, male=7) who had previous experience with 2D and 3D art creation. We asked for their previous experience regarding VR ($0h = 2; < 20h = 5; 20 - 160h = 1; > 160h = 2$) and 3D content creation ($0h = 2; < 20h = 6; 20 - 160h = 2; > 160h = 1$). Participants were compensated with 20 €.

8 Results

We will present the results of the usability walkthrough by showing selected 3D models and a thematic analysis of the participants' feedback and behavior.

8.1 3D Models Created by the Participants

During the user study, participants used all implemented 3D content creation process steps, namely *ideation*, *modeling*, *lighting*, and *texturing* (see Figure 2). Selected results are shown in Figure 8. Both tasks, chair and table, as well as house and garden, were each limited to 30 minutes. Most participants were satisfied or "very" satisfied [P1, P2, P8] with their results unless the time was too short [P6, P7]. We further composed a sample scene using our preset office scene, where we placed a table, chairs, houses, and trees created by the participants into it (see Figure 1 (a)). While this scene was created and rendered by us after the conduction of the user study, it would have been possible for our participants to create it with *VRCreatIn*.

8.2 Thematic Analysis

We conducted a reflexive inductive thematic analysis as per Brown and Clarke [15, 16] based on the data of the usability walkthrough. Post-coding, codes were refined and categorized into two distinct themes.[2]

8.2.1 Theme 1: Content Creation Workflow. *VRCreatIn* received positive feedback for being intuitive [P5, P8, P7, P9], allowing for quick 3D object creation [P7, P9]. It is offering users the freedom to "do everything you want in the way you wanted" [P1]. It was particularly convenient for sketching, ideation, and rapid content creation [P1, P2, P5, P6, P7].

Sketched lines were mainly used for detailing [P1, P7] or for "parts that would have taken too much time in other ways" [P1]. Those who did not use it still saw its potential for adding small details [P3, P9] but criticized its imprecision [P9]. One participant [P4] would use either sketching or modeling methods exclusively, naming mismatched optical styles. One participant [P2] particularly

[2] The audio recordings were auto-transcribed and initially coded using a predefined codebook, which was later expanded. The coding process was conducted by a single coder and repeated four times to minimize bias and maximize data extraction. Theme saturation was observed [41, 43]. Before finalization, themes were cross-validated with another author.

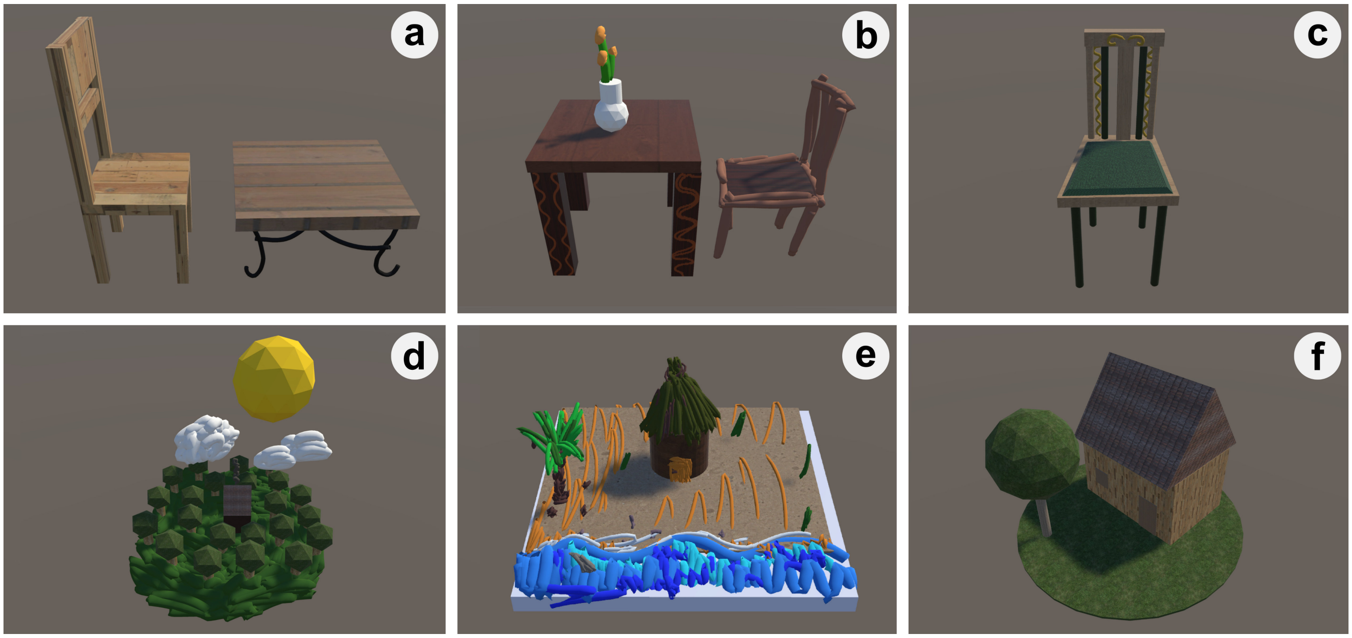

Figure 8: These are the results of selected participants during our user study. The first row shows the results of the first task, where participants had to create a table and a chair (a: P1, b: P2, c: P7). The second row shows the objects for task 2, where a house with a garden should be created (d: P1, e: P2, f: P4). Both tasks were limited to 30 minutes.

favored sketching, stating it is a key reason for using such a VR tool.

For vertex manipulation, almost all participants [except P7] briefly used it for size adjustments before switching to gizmo tool scaling or value transformation. Participant P7, with a professional *Blender* background, was used to the provided features and noted missing advanced ones like extrusion and subdivision surfaces.

The material assignment feature received the most positive feedback [P1, P3, P5, P6, P7, P9]. Participants emphasized the variety of materials [P2, P6, P9] and that they give objects a "more professional" look [P5]. The 3D preview was favored over the traditional 2D approach. It allows easy visualization of material "roughness and [...] profile" [P7] and is "pretty intuitive" [P9].

8.2.2 Theme 2: 3D Pen and 2D Pen and Tablet Interaction. Participants favored 3D interaction methods over 2D for being "more fun" [P3, P7, P8] and "more intuitive" [P3]. The 3D version was deemed "more practical" [P2, P4, P6]. However, 2D methods were considered more precise [P1, P5, P7], especially for plane movement [P2, P6] and sketching [P7, P10], but also more time-consuming [P1, P5]. Physical feedback from the pen on the tablet was a 2D advantage, but the tablet size was limiting [P1].

9 Discussion

The participants enjoyed the possibility of iteratively developing their 3D content using all content creation process steps interlinked as proposed in Figure 2. As such behavior can be achieved only using multiple expert tools such as *Blender* or *Unity* [14, 83] together, *VRCreatIn* is the first work that investigated and observed this for VR in-situ content creation in one tool and provides one interaction technique (pen and tablet) seamless for all process steps. This also allowed rapid changes between phases and the use of sketching techniques for *modeling* and *texturing*, enhancing ideation in these phases. The usability walkthrough approved that it could close this research gap to current MR research, mainly focusing on ideation supported by sketching as the initial process step (see [9, 27, 30, 54]).

Regarding pen and tablet interaction, the participants tended to use 3D interactions in all process steps. This is in line with the findings of *VRSketchIn* [30], which uses a similar hardware setup. Drey et al. [30] also stated that 2D and 3D interaction were used for distinct tasks, using their respective strengths (e.g., 2D precision vs. 3D freedom and ease of use). For instance, traditional sketching is often done in 2D with physical pen and paper, making it more intuitive, while tasks like object manipulation are more naturally performed in 3D [9, 30, 31, 33]. This behavior could also be observed with our *VRCreatIn* participants, showing that the innovative interaction metaphors of *VRSketchIn* could be, as intended, transferred to further steps of the content creation process. It was also possible to enable sketching-based ideation during the whole creation process as intended in our created process (see Figure 2). Furthermore, expert users were more open to 2D interactions, recognizing their utility in specific scenarios (e.g., plane-based transformations and vertex manipulation). This variety accommodates the diverse needs and preferences of users, supporting the previously mentioned flexible and modular approach.

10 Limitations and Future Work

During the study, one participant's logging and video data were lost due to technical issues (no impact on thematic analysis as audio is available). The study's time constraints limited participants' full understanding of the tool. While a learning effect was observed between the first and second tasks, the results likely underestimated the tool's potential. Future work could use an extended structured tutorial as support [24, 37, 66, 82], in-tool assistance [29, 32], and investigate longitudinal use [8, 46, 59, 66]. The implemented features of the prototype are designed for non-organic, low-poly object creation. This is currently unsuitable for organic shapes without future enhancements such as sculpting, including the possibility of AI supported form generation [63]. Further, the prototype currently focuses on the creation of static objects. However, a lot of objects, e.g., game characters, are also animated [11, 19], which is done in a further content creation process step (see Figure 2) not covered yet. It should be investigated how this can be achieved using pen and tablet in MR, too.

11 Conclusion

This work introduces *VRCreatIn*, a pioneering all-in-one solution for in-situ 3D content creation in VR, addressing as first work multiple content creation process steps beyond ideation/sketching. The system's design is built upon approved MR in-situ authoring tools using 2D and 3D pen and tablet interaction. We implemented a comprehensive feature set that supports a broad range of user needs based on expert interviews (N=6). With a usability walkthrough (N=10), we showed *VRCreatIn's* applicability in facilitating iterative 3D design interlinking multiple process steps with the same interaction technique (pen and tablet). The results and the system design of *VRCreatIn* can be transferred to e.g., AR including see-through devices, and it serves as a foundational step towards the future of in-situ 3D content creation. *VRCreatIn* also establishes a design space based on the input devices (pen and tablet) and content creation process steps (e.g., ideation, modeling, lighting, texturing), providing a framework to develop its approach further in the future.

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A Usability Walkthrough Procedure

The conducted usability walkthrough followed this procedure:

(1) ***Preparation:*** As the first step, we provided a brief description of the system used. We also informed participants about how a think-aloud study operates and what we expected from them.
(2) ***Tutorial:*** We offered a standardized explanation of all features to ensure that each participant could potentially use the tool in the same manner. Participants were encouraged to ask questions if any concepts were unclear to them.
(3) ***Demographics:*** After completing a brief demographic questionnaire, participants had the option to take a break up to five-minutes.
(4) ***Task 1:*** In the first content creation task, capped at 30 minutes, participants initially focused on creating a chair before moving on to a table. They had the freedom to choose the specific type of object within the given category and its scale, such as miniature or life-size. There were no restrictions on the tools used or task structure.
(5) ***Interview 1:*** Following the first creation task, a brief interview consisting of three questions was conducted to collect participants' feelings about the tool and their work. The questions addressed participants' satisfaction with their results, their perceived proficiency with the tool, and any behavioral changes they might consider for the next task. After the interview, participants had the option to rest for up to five minutes.
(6) ***Task 2:*** In the second content creation task, also limited to 30 minutes, participants were initially directed to create a house before proceeding to a garden. As with the first task, they could choose the specific type of object within the given category and its scale. There were no constraints on the choice of tools or how they structured their task.
(7) ***Interview 2:*** In the second interview, a more extensive set of 21 questions was asked, covering various aspects of the tool and user experience. These questions targeted areas of interest, such as comparing 2D and 3D features, participant behavior, and potential tool use cases. If the session warranted it or if unusual behavior, such as a strong focus on using a particular tool, was observed, customized questions were also included in the interview to gain deeper insights.