VRSketchIn: Exploring the Design Space of Pen and Tablet Interaction for 3D Sketching in Virtual Reality

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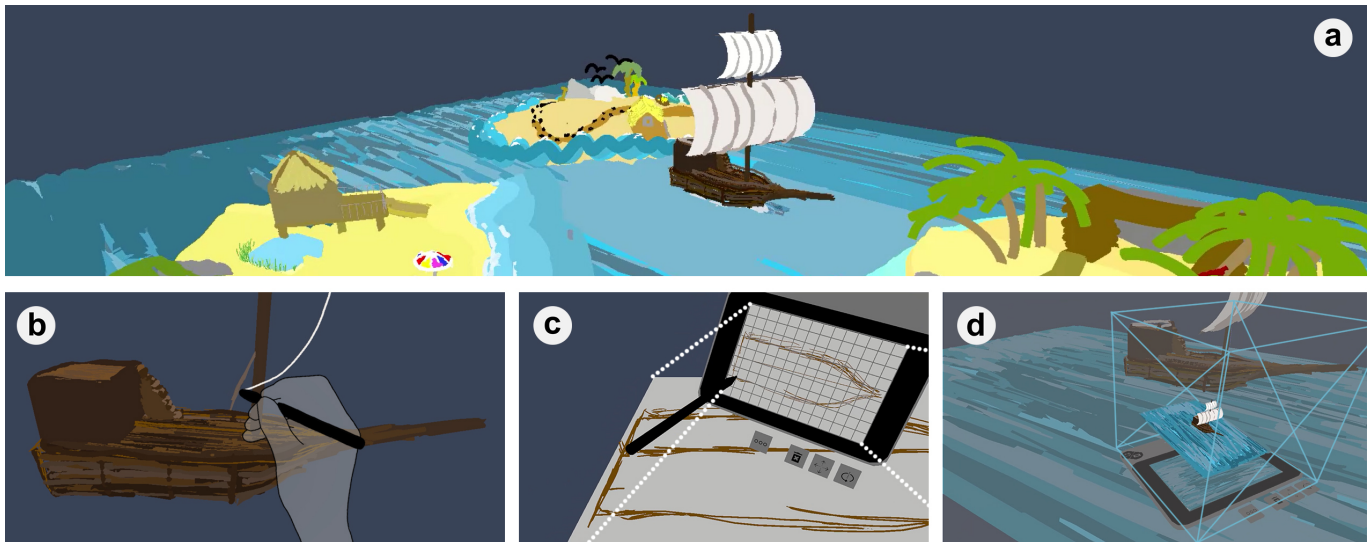<firstname>.<lastname>@uni-ulm.de

Figure 1. *VRSketchIn* **is an (a) immersive sketching application combining (b) unconstrained 3D mid-air sketching with a pen and (c) constrained surface-based sketching with pen on tablet. We created a design space and describe multiple interaction metaphors such as drawing surfaces (c) or World In Miniature (d) to enable a combination of 2D and 3D mid-air sketching.**

ABSTRACT

Sketching in virtual reality (VR) enhances perception and understanding of 3D volumes, but is currently a challenging task, as spatial input devices (e.g., tracked controllers) do not provide any scaffolding or constraints for mid-air interaction. We present *VRSketchIn*, a VR sketching application using a 6DoF-tracked pen and a 6DoF-tracked tablet as input devices, combining unconstrained 3D mid-air with constrained 2D surface-based sketching. To explore what possibilities arise from this combination of 2D (pen on tablet) and 3D input (6DoF pen), we present a set of design dimensions and define the design space for 2D and 3D sketching interaction metaphors in VR. We categorize prior art inside our design space and implemented a subset of metaphors for pen and tablet sketching in our prototype. To gain a deeper understanding which specific sketching operations users perform with 2D and which with 3D metaphors, we present findings of usability walkthroughs with six participants.

Author Keywords

sketching; pen and tablet; mid-air painting;
virtual reality; interaction metaphors; design space;

CCS Concepts

•**Human-centered computing** → **Virtual reality; Graphics input devices;** *Interaction techniques;* Walkthrough evaluations;

INTRODUCTION

Sketching is an important part of the design process, enhancing visual thinking [54], having a positive impact on the individual experience of the design process and also ultimately on the quality of the resulting solution [49]. With the growing availability of consumer-grade augmented reality (AR) and virtual reality (VR) technologies, designers and researchers started to explore the ability of sketching in mid-air [3, 14, 29].

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It has shown to benefit the design process by enhancing perception and understanding of 3D volumes [43].

However, currently available VR sketching software (e.g., Tilt-Brush [2], GravitySketch [19], or Quill [15]) is mainly focusing on unconstrained *3D mid-air* drawing, disregarding traditional 2D sketching workflows. This can partly be explained with the current lack of alternative input devices in VR besides controllers, which are highly optimized for entertainment applications (e.g., mimicking guns with triggers for shooter games).

We present *VRSketchIn*, an immersive sketching application using a 6 degrees of freedom (DoF) tracked pen and a 6DoF-tracked tablet as input devices, allowing interchangeable usage of 2D input (pen on tablet) and *3D mid-air sketching* (pen). To explore the possible design space arising from this 2D and 3D combination for VR sketching, we derived a set of design dimensions. They were based on expert interviews conducted with ten artists, illustrators, designers, and engineers about their current workflow. We used these design dimensions to define the resulting design space of interaction metaphors. It consists of two dimensions: *(1) input devices* (*2D: pen+tablet*, *3D: pen*, *tablet*, *pen+tablet*) and *(2) sketching operations* (*select*, *add*, *subtract*, *rotate*, *translate*, and *scale*). We populated the design space with metaphors presented in prior art, adapted existing metaphors, defined metaphor groups (*3D mid-air sketching*, *drawing surfaces*, *World In Miniature (WIM)*, *primitive extrusion*, *portal into space*) that fit to the dimensions of our design space and implemented a metaphor subset inside *VRSketchIn*.

One key aspect of *VRSketchIn* is the ability to place arbitrarily sized *drawing surfaces* inside the virtual environment (see Figure 7a) and sketch on them using pen on tablet (see Figure 1c/7b). The ability to scale these *drawing surfaces* allows to effortlessly create large scale objects and tiny details within a 2D constrained and physically less demanding workflow in the vicinity of the user. We additionally combined this 2D sketching ability with 3D metaphors from our design space. This includes the usage of only the pen for 6DoF-tracked 3D input (e.g., *3D mid-air sketching*; see Figure 1b) and the combination of pen and tablet as 6DoF-tracked 3D input devices (e.g., *WIM* metaphor [50]; see Figure 1d/8a). In a user evaluation, we presented *VRSketchIn* to six users and conducted usability walkthroughs that revealed usage patterns and provided insights on the usability of the individual metaphors. We discuss these findings and the implications for VR sketching applications. Our observations show that 2D and 3D sketching metaphors were each used for distinct tasks, leveraging the benefits of the individual input device. We argue that including pen and tablet in immersive environments for sketching can open a large set of new opportunities and benefits to the user.

The main contributions of our work are:

1. The definition of a design space derived from a set of design dimensions based on expert interviews (N=10) as well as the presentation of interaction metaphors arising from the combination of 2D and 3D pen and tablet input in VR.

2. The concept and implementation of *VRSketchIn*, a sketching application using a 6DoF-tracked pen and a 6DoF-tracked tablet as input devices, combining unconstrained *3D mid-air*

sketching with constrained *2D surface-based sketching* in VR.

3. First insights regarding usage patterns of *VRSketchIn*, based on a two-hour-long usability walkthrough study with six participants.

RELATED WORK
Our work is strongly influenced by previous work on pen and tablet interaction, pen and tablet in immersive environments, and sketching interaction metaphors.

Benefits of Pen on Tablet Interaction
Previous work has found benefits regarding precision when pen-based drawing is performed on a haptic surface and not in the void. Arora et al. [4] compared pen-based mid-air painting in VR with surface supported painting and found that accuracy, measured via the mean overall deviation from a target stroke, was significantly improved when a physical drawing surface was available (see [3, 46]). This can be explained with the different properties of these interaction concepts. 3D mixed reality (MR) is categorized as immersive, unconstrained, and life-sized, whereas 2D pen and tablet input is precise, constrained, and ergonomic [3]. Furthermore, gridlines can be displayed on the tablet to provide perspective cues or to support drawing straight lines as used by Xin et al. [62].

Watson et al. [59] and *Studierstube* [48, 52] used 2D user interface (UI) controls on hand-held devices (e.g., personal digital assistants (PDAs), physical pads) but without systematically evaluating the performance benefits. This was investigated by Bowman and Wingrave [11] when they compared floating menus with occlusion selection against pen- and tablet-based menus, showing that the pen- and tablet-based task completion time was significantly faster in an object manipulation task. Similar benefits were shown by Lindeman et al. [33, 34] for passive haptic feedback, such as that provided by a tablet. They compared it with touching the void in docking and selection tasks as well as widget usage and measured task completion time and accuracy. As one of the goals of our work was to combine traditional sketching tools (pen and paper) with immersive environments, we incorporated a combination of pen and tablet interaction techniques including a 2D UI.

Pen and Tablet in Immersive Environments
Immersive environments can provide a full-body painting experience, which is perceived as very pleasant by users [29]. 3D Palette by Billinghurst et al. [9] is a system combining pen and tablet with VR to create and draw primitives on a tablet interface and visualize them in 3D space, using widgets for parameter adjustment. They use pen, tablet, and VR as well, but did not focus on sketching or the definition of a design space. Deering [14] investigated pen-based free-floating mid-air VR drawing environments in 1995 but provided no true scale sketching at room size. Older work, in general, was implemented with hardware that is quite limited regarding the field of view and display quality compared to current head-mounted displays (HMDs) which can provide a better base for an evaluation.

Further work exists [28, 29, 45, 60, 63] that uses only a pen for drawing input without a supporting surface. Although our work

focuses on the combination of pen and tablet, we additionally implemented *3D mid-air sketching* using only the pen. This demand for having a mix of 2D and 3D sketching techniques was found by Gasques et al. [17, 18] with their presented *PintAR* system that provided only pen and tablet and no mid-air interaction.

TabletInVR [51] is a recent work that creates a design space for tablet-based 3D solid modeling in VR. They define a design space based on user observations whereas our design space focuses on the combination of pen and tablet and defines multiple parameter levels to categorize interaction metaphors. The authors used a tracked tablet and combined finger touches on the surface of the device with mid-air hand gestures. Their approach provides several interaction metaphors for 3D modeling that we considered when creating our design space, such as tablet-based object selection and manipulation. However, we focused on the combination of pen and tablet due to the higher precision and the similarity to a physical pen. Furthermore, objects are created in *TabletInVR* based on a set of primitives and modified afterwards, whereas we created a system with the focus set on large scale freehand sketching.

SymbiosisSketch [3] combines free form mid-air pen-based sketching in AR with pen and tablet to sketch on flat and curved *drawing surfaces*. It is closely related to our approach in combining tablet and pen for sketching in virtual environments. While *SymbiosisSketch* uses an AR implementation and explores the relationship to real-world objects, our work aims at combining pen and tablet inside of VR environments and focuses on sketching for artists and designers (e.g., 3D models, concept art). Additionally, we see our main contribution not solely in the implementation of the system, but in a holistic combination of a structured exploration of the design space and the resulting system *VRSketchIn*, highlighting possible interactions arising from the combination of pen, tablet, and VR.

Mobi3DSketch [31] is a sketching application for mobile AR and uses no HMD. Despite different hardware, the interaction metaphors for sketching with a smartphone in mid-air can be mapped to a tablet such as the used virtual *drawing surfaces* or the selection or rotation metaphors.

Sketching Interaction Metaphors
We defined a design space for pen- and tablet-based sketching in VR. This design space is strongly influenced by the fields of *drawing surfaces*, *WIM*, *portal into space*, and *primitive extrusion*.

Drawing Surfaces: Most sketching applications include *drawing surfaces*, sometimes called planes [30], canvases [3], frames [62], or proxies [31], to improve accuracy during stroke creation. We will use the term *drawing surfaces* in this work to provide a consistent description. Surface metaphors can be grouped into flat surfaces [30, 32, 35, 37, 62], curved surfaces, and work supporting both [3, 31]. Furthermore, different surface creation metaphors exist, such as sketching [3], tablet or device position and orientation [31, 32, 35], and automatic alignment [30, 37, 62]. We will use flat surfaces in this work and link them to the tablet position and orientation.

World In Miniature: Stoakley et al. [50] introduced with *Virtual Reality on a WIM* a system that attaches, as in our approach, a 3D *WIM* to a hand-held tablet, which allows quick changes

of the point of view. The true scaled objects in the space can be manipulated in the miniaturized version with interaction metaphors such as object selection and manipulation or navigation. These metaphors were considered during our design space creation, as interaction metaphors are a user requirement for *WIM* [17, 18]. Compared to our approach, Stoakley et al. [50] used a furniture planning use case to evaluate their system and did not test their approach for sketching in VR.

Portal into Space: *Portals* can, like *WIM*, provide an overview of the environment with a zoomed-out camera view. Multiple views (e.g., attached to the tablet) can be used to see the scene from different perspectives and at different points in time [10, 47, 58]. Another way is to use a tablet as a see-through device or lens [27, 56]. This provides a different rendering of the scene such as an X-ray view or a cut plane to look inside objects. Both ways of using *portals* fit in our design space.

Primitive Extrusion: *Primitive extrusion* based on AR, HMDs, smartphones, controllers, and hand gesture interaction targeting computer-aided design (CAD) was investigated in the past [5, 39]. *Extrusion* is often linked to a dedicated axis, but free-form *extrusion* at an arbitrary side of an existing 3D object is possible as well [13]. We included *extrusion* in this work as it is a basic CAD feature for the creation of solid objects out of primitives and investigated it for immersive sketching using pen and tablet.

Overall, our system was highly inspired by *SymbiosisSketch* [3], *TabletInVR* [51], and *Mobi3DSketch* [31]. It incorporates metaphors from AR as well as mobile systems, but focuses on the combination of unconstrained *3D mid-air sketching* with pen- and tabled-based constrained *2D surface-based sketching* in VR.

PRELIMINARY EXPERT INTERVIEWS
Before we started to create our design space and *VRSketchIn*, we conducted ten interviews with experts (6 male, 4 female), who are currently using some form of CAD tools. This helped us to analyze and better understand their complex workflow and to create a system tailored to their needs. We used a similar process as in [4, 22, 24, 51] and interviewed one VFX artist, one product designer, two concept artists, one graphical designer, one illustrator, one animator, one architect, one interior designer, and one mechanical engineer. We chose these participants because designing is part of their daily work. The participants were recruited through personal and professional contacts and were interviewed via telephone as most of them live further away. Conducting the interviews, we identified sketching as the most promising step in the design process that would benefit from a combination of precise 2D input and 3D large-scale spatial understanding. Therefore, this section will focus on the interview findings related to sketching.

Procedure
For the semi-structured interviews, questions were designed, which can be grouped by the description of (1) their job in general, (2) their creative design process, and (3) their usage of hard- and software as well as VR. The lead author conducted the interviews, which were between 30-60 minutes long (M=52 min, SD=11 min). A thematic analysis was conducted going systematically through the taken notes. Identical answers

were grouped and the sketching workflow they use during their creative process was described, as presented later on. We stopped after ten interviews as we gained a fundamental understanding of sketching in their daily work. A lot of repeating answers indicated some form of saturation.

Results

Sketching Preferences: The most important criterion for the importance of sketching in their daily work is the personal preference and way of working. Some people prefer to sketch on paper (n=2), some on tablets (n=4), some just use their imagination (n=2), and some start with desktop tools (n=2). The second criterion is their job. Sketches are very useful for illustrators and concept artists and sometimes not only a tool but their product. Therefore, we chose this target group and discussed their work in detail. Sketching is of minor importance for jobs where the product needs high precision as for mechanical engineers or architects.

All interviewees agreed that digital tools for sketching have many benefits compared to pen and paper like object manipulations, fill options, pencil preferences, or undo/redo functionality. In addition, data exchange and changes by multiple individuals are easier to handle and it saves time to start with the productive digital tools and skip the analog sketching step. One participant stated that sketching has not changed, but the tools have.

Sketching Workflow: We asked all participants to describe their creative process when they start a new project. For the concept artists, illustrators, and animators, we identified a workflow with multiple steps: *(1) ideation, (2) modeling, (3) texturing, (4) animation*, and *(5) verification*. Sketching is used in all five steps, but a clear focus is set on the steps *ideation (1)* and *modeling (2)*. During *ideation (1)*, sketching is part of giving your plan the first shape with a tool depending on personal preference (see above). For *modeling (2)*, sketching provides basic shapes and proportions of the planned picture or 3D model. It is important to note that they use 3D sketching with primitives, too. This means they use a software tool and create cubes, cylinders, or basic skeletons to get a low fidelity 3D model. Depending on the planned product, they refine it to create the high-fidelity 3D model or use it as a template to paint a 2D illustration. In the steps *texturing (3)*, *animation (4)*, and *verification (5)*, sketching is only an auxiliary tool (e.g., to hint the planned movement of an object or to take notes).

Sketching Tools: Our participants prefer software tools such as Adobe Creative Cloud [1], 3ds Max [6], ZBrush [44], or Cinema4D [38]. Graphical tablets with screen and without are common, and it depends on personal preference if the occlusion of the hand or ergonomic aspects regarding the offset of input and output are crucial. Therefore, *VRSketchIn* will allow both sketching on the tablet with direct output and offset output on floating mid-air *drawing surfaces*. For now, VR is not used by our participants for content creation. Some created hobby projects with apps like TiltBrush [2], but they only use VR productively for verification and reviewing content.

Discussion

The interviews show the current preferences of designers and illustrators to use 2D tools (e.g., pen and tablet) for sketching. Immersive VR environments were mainly used for reviewing the results of their work. This complements our motivation of combining traditional creation tools (pen and tablet) and immersive visualizations (VR HMDs). It solves a need explicitly stated by one participant who missed constrained *2D surface-based* input when sketching with TiltBrush [2]. We decided to set the focus of *VRSketchIn* to *ideation (1)*, as sketching is used there in its pure form and as a major tool. Therefore, our design space is based on basic sketching object manipulations used by our participants such as adding, subtracting, selecting, and modifying strokes, and on the combination of unconstrained *3D mid-air sketching* with constrained *2D surface-based sketching*.

DESIGN SPACE

To systematically explore the combination of a 6DoF-tracked pen and a 6DoF-tracked tablet as input devices for sketching in VR, we created a design space that combines pen and tablet interaction with sketching operations. It allows the grouping of interaction metaphors and the visualization of the task allocation between *3D mid-air* and *2D surface-based sketching*. We used this design space to brainstorm further metaphors and selected metaphors for implementation and evaluation with *VRSketchIn*. We further classified prior art with it.

Design Dimensions

During a morphological analysis with five iterations, we created a multidimensional matrix (see Figure 2) known as Zwicky box [64], which is a common design space tool (e.g., [25, 40, 51]). The axes that span the matrix of our design space are the two main dimensions **(D)** which are defined by our two constraints *(1) hardware* and *(2) sketching workflow*. They were derived from the expert interviews. Each dimension has multiple parameters **(P)** that define the rows and columns of the matrix with their values. The intersection of a row and a column defines a cell. Each cell represents interaction metaphors (e.g., draw mid-air strokes) in our design space (see Figure 2/3).

Dimension 1 **(D1)** is based on the physical hardware pen and tablet. It is called **(D1) input devices** and placed on the y-axis. Its parameter 1 **(P1) device type** represents the possible hardware combinations of pen and tablet with the values ***pen/tablet/pen+tablet*** (see Figure 2). Each **device type (P1)** can be used with different DoF. Parameter 2 **(P2) input dimensions** distinguishes, therefore, between *2D surface-based* and *3D mid-air* input and has the values *2D/3D*. The parameter combinations *2D* with ***pen*** as well as *2D* with ***tablet*** are not applicable for a VR sketching application and were removed during the iterations of the morphological analysis (see Figure 2).

Based on the expert interviews and the described sketching workflow, we focused on the phase *ideation (1)*. Therefore, we added sketching operations to the design space that are needed in this phase. We named dimension 2 **(D2) sketching operations** and placed it on the x-axis. Our chosen operations are derived from the interaction categories defined by Szalavári and Gervautz [53] (object manipulation, navigation, system control) and Foley et al. [16] (select, position, orient, path, quantify, text). The selected category subset for parameter 3 **(P3) object operation** is tailored to the basic sketching operations adding, subtracting, selecting, and modifying strokes stated by our experts during the interviews. We defined the values

		D2: Sketching Operations			
	P3: Object Operation	Select/Add/Subtract/Rotate/Translate/Scale			
	P4: Object Type	Primitive		Drawing Aids	
	P5: Input Type	Direct	Indirect	Direct	Indirect
P1: Device Type	P2: Input Dimensions				
Pen	3D				
Tablet	3D				
Pen+Tablet	2D				
	3D				

Figure 2. A design space for pen- and tablet-based VR sketching applications. Interaction metaphors are categorized into cells of this space by selecting the appropriate input devices (D1) and sketching operations (D2) parameters (P). This matrix was created during a morphological analysis.

select/add/subtract/rotate/translate/scale (see Figure 2). *Surface-based sketching* provides *drawing surfaces*, a conceptual difference to *3D mid-air sketching*. *Drawing surfaces* are drawing aids that support sketching and no primitives such as strokes, but the operations of **(P3)** are applicable to them as well. We created parameter 4 **(P4) object type** with the values *primitive/drawing aids* to distinguish between these two (see Figure 2). As an immersive environment can be a large space, typically there are different interaction metaphors for near and distant objects. Hinckley and Wigdor [23] differentiate between direct and indirect input. Direct input combines input and output in the same physical space, whereas indirect input does not [23]. Direct interaction metaphors are usable for near objects as they are in the vicinity of the user and directly manipulable in the near physical space, whereas indirect ones are usable for distant objects. With our last parameter 5 **(P5) input type** with the values *direct/indirect* we are able to categorize interaction metaphors accordingly (see Figure 2). We stopped at this level of parameters for **D2**, as we have narrowed down the sketching specific object operations of **P3** to basic input concepts of **P5**.

Our design space has three main use cases we used for the creation of *VRSketchIn* and it can support other researchers during the design of sketching applications in the same way. It is (1) a brainstorming guide for identification and ideation of new interaction metaphors, it helps (2) to remain aware of gaps while defining an application and to purposefully close them, and (3) it is possible to categorize prior art with the design space and keep track of underexplored parts. As we categorized prior art with our design space (see Figure 3), we will show how to place an interaction metaphor from *SymbiosisSketch* [3]. We chose *pen-based 3D mid-air drawing* as example. To place an interaction metaphor, first of all, **device type (P1)** and **input dimensions (P2)** of the used input device have to be selected. This would be *pen* **(P1)** and *3D* **(P2)**. It leads to a row in our design space, where this specific interaction metaphor will be placed later on. The second step is to evaluate **D2**. Drawing is an *add* **object operation (P3)** and creates a *primitive* **object type (P4)**. As mid-air drawing is a direct interaction in the immersive environment, it is a *direct* **input type (P5)**. This leads to a column in our design space that fits the interaction metaphor. The intersection of the previously defined row of **D1** and the column of **D2** specifies the cell where the interaction metaphor *pen-based 3D mid-air drawing* can be placed. We placed this and further interaction metaphors as well as other prior art in our design

space as shown in Figure 3. Cells without a reference show to the best of our knowledge currently underexplored parts.

Interaction Metaphors and Interaction Metaphor Groups
We examined our design space to find similarities and differences between rows and columns. Whenever we found interaction metaphors (e.g., *mid-air drawing*, *selection by intersection*) that overlap at specific parameter values and are based on a similar concept, we grouped them and defined an interaction metaphor group. We created definitions for five interaction metaphor groups (*3D mid-air sketching*, *drawing surfaces*, *WIM*, *portal into space*, and *primitive extrusion*) and describe them in this section. These groups can be used to reduce the number of cells that have to be considered when our design space is used to ideate (1), find gaps (2), or categorize metaphors (3). Interaction metaphor groups are not exclusive and other interaction metaphors can have the same parameter values but be in different groups. An example is *selection on the tablet surface* (*drawing surfaces* group) and *selection through a portal* (*portal into space* group). Furthermore, we do not claim completeness. We used the design space and the metaphor groups to ideate (1) *VRSketchIn* and selected the emphasized interaction metaphors in Figure 3 for implementation and avoided functional gaps (2).

3D Mid-Air Sketching: *3D mid-air sketching* with a controller, or, as in our work, with a 6DoF-tracked pen, is the default interaction method for MR sketching applications (e.g., Tilt Brush [2], Quill [15], *SymbiosisSketch* [3]; see Figure 5a). It is uniquely defined by **D1** because a *pen* is a **device type (P1)** with 3 **input dimensions (P2)** and all parameter values of **D2 sketching operations** are applicable. Therefore, the interaction metaphor group *3D mid-air sketching* spans a whole row in our design space that is framed by a black line in Figure 3.

Drawing Surfaces: *Drawing surfaces* define constrained 2D sketching areas where interaction (e.g., drawing) is possible in 2D inside a 3D immersive environment. Most of them use a combination of *pen+tablet* **(P1)** and provide flat [30, 32, 35, 62] or curved [3, 31] surfaces. The input is constrained to *2D* **(P2)** as the pen draws on the surface of the tablet. *Drawing surfaces* can be integrated into immersive environments by mapping the drawing surface on the tablet to a surface inside the space (see Figure 7a). All parameter values of **D2 sketching operations** are possible. The interaction metaphor group *drawing surfaces* spans a whole row in our design space which is framed by a dotted black line in Figure 3. We define a drawing surface interaction metaphor as *direct* **(P5)** when the pen tip is on the tablet surface for input as well as when output is visualized on the tablet surface (e.g., drawing; see [23]). These direct metaphors can still have an indirect part like the distant object creation on the mid-air surface.

World In Miniature: *WIM* provides a miniaturized version of the whole immersive space (see Figure 8a). It was introduced by Stoakley et al. [50]. They describe how a miniaturized version of the space can be attached to a hand-held tablet. Besides the visualization and verification of the space through *WIM*, it is also possible to manipulate objects inside the space through *WIM*. This allows manipulating distant areas of the immersive environment in the vicinity of the user. It uses the **device type pen+tablet (P1)** and allows *3D* **(P2)** input with the pen. As all

Part 1

P1: Device Type	P2: Input Dimensions	Select — Primitive Direct	Select — Primitive Indirect	Select — Drawing Aids Direct	Select — Drawing Aids Indirect	Add — Primitive Direct	Add — Primitive Indirect	Add — Drawing Aids Direct	Add — Drawing Aids Indirect	Subtract — Primitive Direct	Subtract — Primitive Indirect	Subtract — Drawing Aids Direkt	Subtract — Drawing Aids Indirect
Pen	3D	*Intersection* [53] [13] [50]	*Ray Cast* [58]	*Intersection*	*Ray Cast*	*Draw* [3] [4]	*Copy* [3] [58]	Draw [3]	Gesture [3]	Rubber	*Selection* [58]	Intersection	*Selection*
Tablet	3D	Intersection [51] [47] [39]	Ray Cast [51] [39]	Intersection [8]	Ray Cast [8]	Draw [51]	Copy [51] [39]	*Transform*	Gesture	Slicing [51]	Selection [51]	Intersection	Selection
Pen+Tablet	2D	*Intersection* [47] [58] [13]	Portal Ray Cast [51] [47]	Double Tap [21]	Swipe	*Draw* [3] [62] [58] [4] [31] [30] [21]	Portal Draw [3]	Draw Subset [62]	Gesture [30] [21]	Rubber [58]	Portal Rubber [47]	Draw Subset	Gesture
Pen+Tablet	3D	Handle Bar [50] [31]	*WIM Inters.*	Handle Bar	WIM Inters.	Draw + Ext. [47] [39] [53] [13] [31]	*WIM Draw* [31]	Trans. + Gest. [53] [31]	WIM Draw	Draw Punch	*WIM Select.*	Intersection	Selection

Part 2

P1: Device Type	P2: Input Dimensions	Rotate — Primitive Direct	Rotate — Primitive Indirect	Rotate — Drawing Aids Direct	Rotate — Drawing Aids Indirect	Translate — Primitive Direct	Translate — Primitive Indirect	Translate — Drawing Aids Direct	Translate — Drawing Aids Indirect	Scale — Primitive Direct	Scale — Primitive Indirect	Scale — Drawing Aids Direct	Scale — Drawing Aids Indirect
Pen	3D	*Gizmo* [13] [50]	Gesture	Gizmo [3]	Gesture	*Gizmo* [13] [50]	Gesture	Gizmo [3]	Gesture	*Gizmo* [13]	Gesture	Gizmo [3]	Gesture
Tablet	3D	Orientation [39]	Gesture [39]	Orientation	Gesture	Gizmo [39]	Gesture [39]	Gizmo	Gesture	Gizmo [39]	Gesture [39]	Gizmo	Gesture
Pen+Tablet	2D	Gizmo [58] [53] [13]	Gesture [51]	Gizmo [62]	Gesture	Gizmo [58] [13]	Gesture [51]	Gizmo [21]	Gesture	Gizmo [58] [53] [13]	Gesture [47] [51]	Gizmo	Gesture
Pen+Tablet	3D	Handle Bar [50] [31]	*WIM Gizmo*	Handle Bar	WIM Gizmo	Handle Bar [50] [31]	*WIM Gizmo*	Handle Bar	WIM Gizmo	Handle Bar [31]	*WIM Gizmo*	Handle Bar [31]	WIM Gizmo

Interaction Metaphor Groups: 3D Mid-Air Sketching | Drawing Surfaces/Portal into Space | *Implemented*
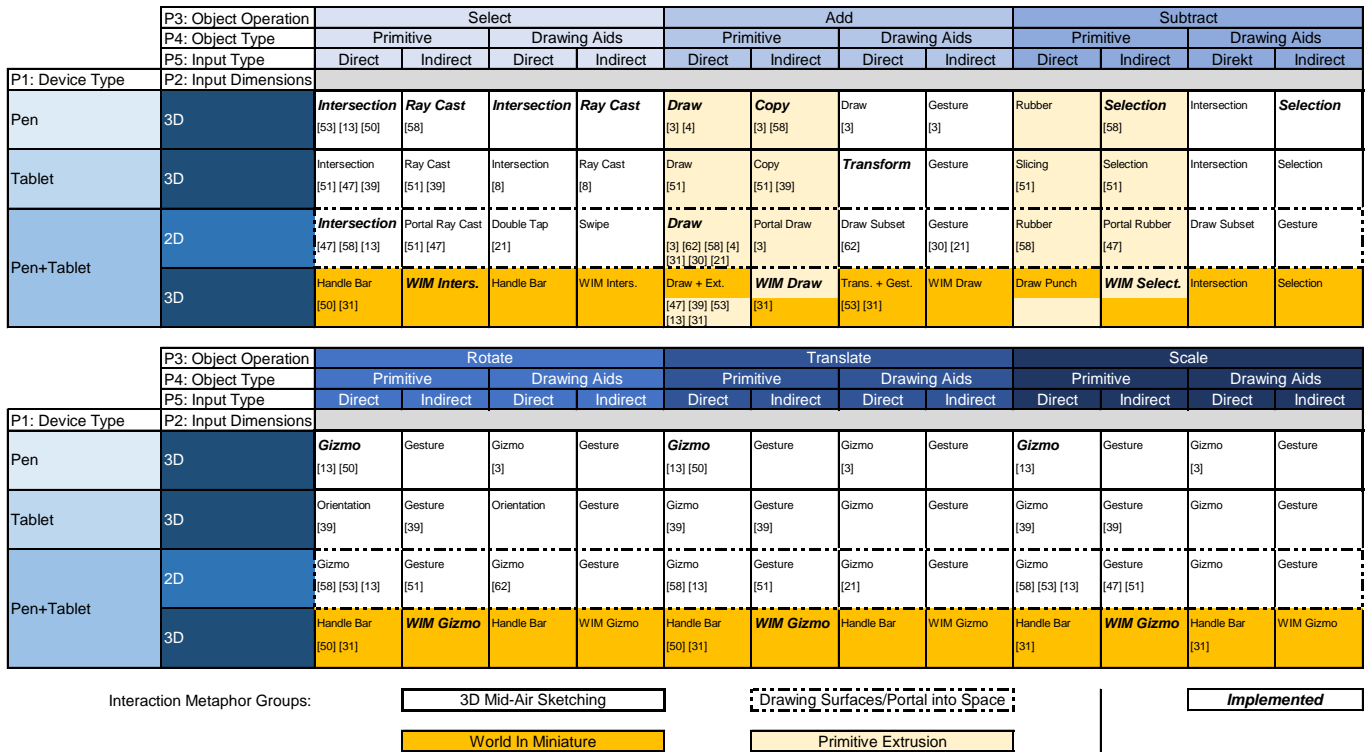World In Miniature | Primitive Extrusion

Figure 3. A populated version of our design space for pen- and tablet-based sketching that shows (1) the classification of interaction metaphors, (2) the classification of prior art, (3) the defined interaction metaphor groups, and (4) the interaction metaphors implemented in *VRSketchIn*. Due to space constraints, we had to split the design space into two parts. This is only a visualization.

parameter values of **D2 sketching operations** are supported, it spans a whole row in our design space that is highlighted orange in Figure 3. We define *WIM* interaction metaphors as *indirect* (**P5**) when the focus is on the manipulation of distant objects in the vicinity of the user even when there is direct feedback in the *WIM* (e.g., gizmo; see Figure 3; see [23]).

Portal into Space: The surface of the tablet can be used for multiple views and not only for pen strokes. As done in [56], it can be a see-through device, a window, or a lens that provides a different rendering of the scene (e.g., X-ray view, cut plane to look inside objects). We use it as a *portal into space* (see Figure 9a) that allows users to see distant and hidden objects inside the space. Furthermore, interaction metaphors exist that describe how to interact with these objects through the 2D *portal* (e.g., ray). It is mapped to the parameter values *pen+tablet* (**P1**) as well as *2D* (**P2**). All parameter values of **D2 sketching operations** are supported and it spans a whole row in our design space that is framed by a dotted black line in Figure 3. Despite this being the same row as the *drawing surfaces* group, they contain disjoint interaction metaphors.

Primitive Extrusion: Sketched primitives, like strokes, can be extruded to create solid objects, e.g., walls, floors, or sails (see Figure 9b) in the direction of one axis [13]. It is possible to add the extruded object to the scene or use them as a punch to subtract from existing objects. *Extrusion* is an easy way to create solid objects from primitives as they are difficult to create just by strokes alone. **Add** and **subtract** (**P3**) are supported and applicable to *primitives* (**P4**) in a *direct* and *indirect* way (**P5**). As this metaphor group is supported by every parameter value of **D1 device type**, it spans two columns in our design space that are highlighted yellow in Figure 3.

We described how interaction metaphors and interaction metaphor groups can be placed within the design space. The interaction metaphors and the interaction metaphor groups presented in this section and in Figure 3 are not complete and were created and positioned during joint brainstorming sessions. To widen our design space, we do not limit it to pen interaction and state that hand interaction such as gestures in mid-air or touches on the tablet are interaction metaphors that fit in our design space as well. This can be achieved by replacing *pen* in **P1** with the new value *hand*. Furthermore, it is not limited to VR and applicable to other environments such as AR and MR. An example would be that a mid-air hand gesture (e.g., a tap) is used for annotating physical objects in an AR 3D space. This interaction metaphor would be classified as *pen/hand* (**P1**) in *3D* (**P2**) and it *adds* (**P3**) a *primitive* (the annotation) (**P4**) in a *direct* (**P5**) way.

THE VRSKETCHIN SYSTEM

We created *VRSketchIn*, an artifact contribution according to Wobbrock et al. [61], to explore the combination of unconstrained *3D mid-air* and constrained *2D surface-based* interaction metaphors for sketching in VR. Based on our design space and our interaction metaphor groups, we selected several interaction metaphors for implementation that were interesting to further explore. Our selection criteria were (1) to cover 3D and 2D sketching operations and (2) implement at least one metaphor from each group. All implemented ones
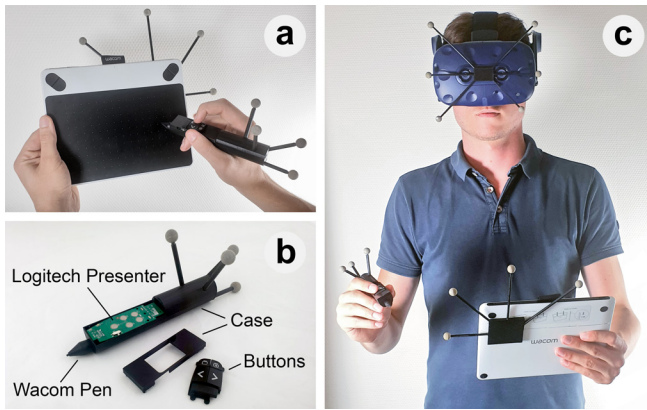
Figure 4. Our setup (c) consisted of an HMD, a tablet, and a pen (a). We 3D printed a pen case and combined the graphical pen with wireless buttons (b). All devices were motion tracked using OptiTrack [42].

are emphasized in Figure 3. In the following, we will present them using a pirate ship as an example sketch.

Prototype Setup
We used the HTC Vive Pro HMD attached to a workstation laptop with an NVIDIA GTX1060 graphics card and an Intel i7 processor. Our tablet was a Wacom Intuos Draw [57] with a weight of 325 grams (see Figure 4a). To enable 2D sketching on the tablet in combination with 3D sketching in mid-air, we needed to design a pen that is ergonomic, lightweight, and spatially tracked beyond the electromagnetic resonance (EMR) limits of the Wacom tablet. We went through several iterations and combined the graphical pen of the Wacom tablet with hardware buttons refurbished from a Logitech R400 Presenter [36] to provide wireless button input during mid-air sketching. Both parts were integrated into a custom 3D printed case (see Figure 4b). It had a weight of 46 grams. To ensure the low weight of our prototype, we refrained from using the HTC Vive tracker and used OptiTrack [42] instead. Pen, tablet, and HMD were tracked by an OptiTrack setup with 14 Flex13 cameras and Motive 2.1.2 (see Figure 4c). Our tracking space was 4x4 meters and we tracked with an accuracy of <1mm. To combine high-precision sketching in 2D, tracked via EMR of the Wacom tablet, with large scale *3D mid-air sketching* tracked via OptiTrack, we had to develop software combining both coordinate spaces into a fluent and seamless user experience (UX). We used Unity3D 2019.1.7f1 [55] in combination with open-source software (OpenBrushVR [41], uWintab [20], Icons © icons8.com. Used under CC BY-ND 3.0. [26]).

3D Mid-Air Sketching
The basic interaction metaphor for mid-air sketching is to direct-ly add a primitive in 3D by sketching a stroke in space (see Figu-re 5a/1b). This is implemented by all pen- or controller-based immersive sketching applications (e.g., [2, 3]) and spans an interaction metaphor group in our design space (see Figure 3). It is the most direct way for sketching in an immersive environment and we implemented it with a 6DoF-tracked pen.

When users want to add a flag to their pirate ship, they can press the upper right button of the pen to sketch a stroke in mid-air (see Figure 4a/5a). If they want to adjust the stroke

size, they have to click the right lower button (see Figure 4a) on the pen to increase and the left to decrease. The current size is visualized by a transparent sphere on the tip of the pen (see Figure 5a). When users are not satisfied with the position of their current stroke, they can select and move it. Users have to intersect the intended object with the pen tip and click the upper left button of the pen for selection (see Figure 4a). Only one object is selected at a time. If users want to get highlighting (yellow grid shader) for intersected objects, they can perform a double-click to enter selection mode. It is indicated by a red pen (see Figure 5b). Selected objects automatically have a translation gizmo. The user can grab and move it with the pen tip by pressing and holding the upper left pen button (see Figure 6a). Rotation (see Figure 6b) and scaling are supported as well. Selected objects are rendered with a red grid shader.
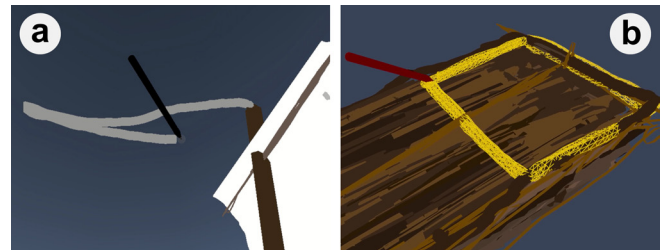

Figure 5. 3D Mid-Air Sketching. a) Pen-based mid-air drawing in the immersive environment. b) Pen-based mid-air object selection.
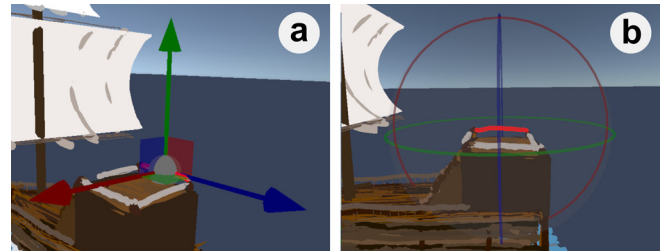

Figure 6. Gizmos. a) The translation gizmo activated for the selected stroke. b) The rotation gizmo for the same stroke.

Drawing Surfaces
Drawing surfaces provide constrained *2D surface-based sketching* in 3D environments (see [3, 62]). This allows to easily reduce dimensions and DoF in a *3D mid-air sketching* application. According to the interaction metaphor group in our design space (see Figure 3), we implemented *drawing surfaces* as drawing aids that can be placed in space by the tablet position and orientation. Primitives can be added on them by sketching with the pen on the tablet surface.

When users want to create the deck of their ship, a flat surface can support them by keeping all strokes on the same height. To place the drawing surface at the right position in space, users have to press and hold the surface button on the tablet (see Figure 10). This creates a new surface that floats in mid-air in front of the tablet (see Figure 7a). Users can now adjust the surface position by moving and rotating the tablet and by sliding the pen on the tablet vertically for distance changes and horizontally for scaling. *Drawing surfaces* snap in 5° steps to

provide guidance for e.g., 45° or 90° rotations. A preview on the tablet shows which objects in the 3D scene are sliced by the surface. When the surface is accurately positioned, users can sketch with the pen on the tablet surface and create strokes in the 3D space for the ship deck (see Figure 7b). If multiple *drawing surfaces* were created and users want to switch back to a previous one, they have to select it and press the drawing surface button on the tablet. Furthermore, users can select strokes on the tablet by pressing the upper left pen button when the pen tip touches a stroke on the tablet surface.
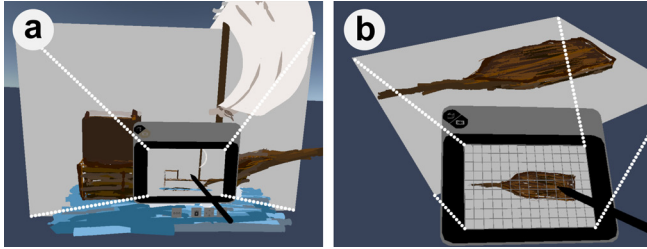
Figure 7. Drawing Surfaces. a) New drawing surfaces can be created by placing them in space with the tablet position and orientation. The scale and the distance are set by sliding the pen on the tablet. A preview of the sliced objects is provided on the tablet. b) Sketching on the tablet creates strokes in mid-air that lie on the defined surface. Gridlines can be activated.

World In Miniature

WIM, as introduced by Stoakley et al. [50], can provide a miniaturized overview of the whole space attached to a tablet. As immersive environments provide true scale, objects are not only in the vicinity of the user and it is difficult to see and interact with them if they are far away. Our design space defines *WIM* as a combination of 3D pen and tablet interactions (see Figure 3). We implemented a *WIM* by bringing the whole space in a miniaturized form to the user. Similar to Stoakley et al. [50], it is attached to the tablet and provides several interaction metaphors.

If users are standing in front of their pirate ship in the immersive environment and want to view it from every side, they can press the *WIM* button on the tablet (see Figure 10). This activates a *WIM*, which is attached to the tablet (see Figure 8a). It can be rotated by simply rotating the tablet. All interaction metaphors that are available such as drawing/sketching, selection, or gizmos, are available in *WIM* as well. To use a gizmo inside *WIM*, users have to enter the *WIM* with their pen. This detaches it from the tablet and freezes it in the last position to enable stable interactions. A detached *WIM* is visualized with white bounds (see Figure 8b). Gizmos are used inside *WIM* in the same way as in space. Changes in *WIM* are immediately synchronized with the space and the other way around.

Portal into Space

As done by Viega et al. [56], a tablet can be used as a see-through device that provides a different view of the scene (e.g., X-ray). This is another way to enable multiple perspectives or distant interaction compared to *WIM*, but our design space shows (see Figure 3) that it is constrained to 2D surfaces. We implemented *portals* as virtual cameras that can be placed using the position and orientation of the tablet.
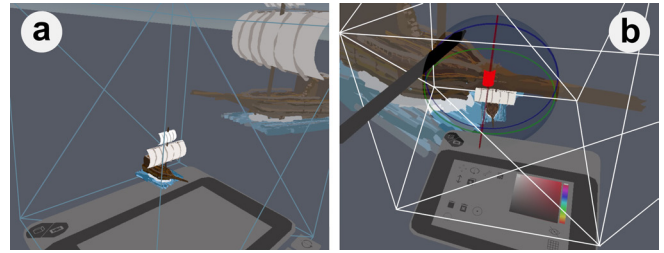

Figure 8. World In Miniature. a) WIM provides a miniaturized view of the whole space in the vicinity of the user and attaches it to the tablet. b) It is possible to use all interaction metaphors inside WIM such as the rotation gizmo.

When users want to permanently see their pirate ship from a defined perspective to perfectly set it in shape for that view, they can use *portals*. First, they have to open the configuration menu and click and hold the *portal* button (see Figure 10). *VRSketchIn* will provide a preview of the *portal* view on the tablet and visualize the *portal* itself as a wireframe in space. Users can adjust its position by moving and rotating the tablet. The *portal* stays at the current position when the pen is detached (see Figure 9a). If multiple perspectives are useful, users can create multiple *portals* and switch back to previous ones. Previous *portals* can be reactivated by selecting them and clicking on the *portal* button. This is similar to switching *drawing surfaces*.
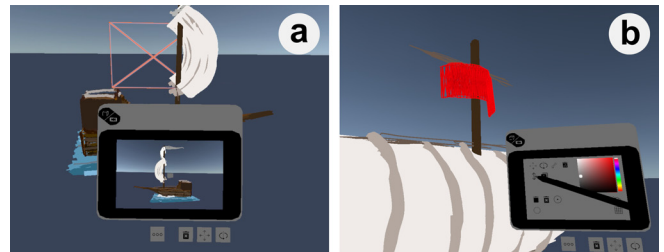

Figure 9. a) Portals can be places in space and provide a virtual camera that is visible on the tablet. b) Primitives can be extruded to create solid objects.

Primitive Extrusion

Solid objects like ground planes or walls are common in sketches, but creating them with multiple strokes is tedious and imprecise. *Primitive extrusion* is a common function for that use case [5, 13, 39] and according to our design space usable in 2D and 3D (see Figure 3). We implemented an *extrusion* function that allows users to extrude strokes on the y-axis.

If users want to create the sails of their ship, they can sketch a primitive shape and extrude it to a solid object. At first, they have to sketch the primitive and select it afterwards. In the second step, they have to open the menu and press the *extrusion* button (see Figure 10). *Extrusion* is now possible on the y-axis by sliding up and down on the tablet (see Figure 9b). A second click on the button exits the *extrusion* mode. If users want to extrude in other directions, they have to extrude their primitive on the y-axis first and use the rotation gizmo afterwards.

Configuration Menu

Besides the permanently available physical tablet with two hardware buttons and the floating buttons, we created a

configuration menu on the tablet to not permanently occlude the UI with all controls (see Figure 10). It is activated by selecting the three-circle floating button with the pen.
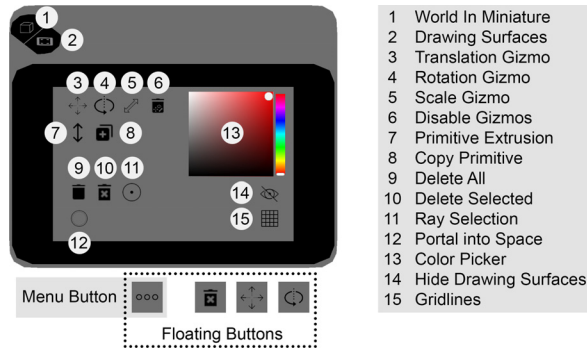

1	World In Miniature
2	Drawing Surfaces
3	Translation Gizmo
4	Rotation Gizmo
5	Scale Gizmo
6	Disable Gizmos
7	Primitive Extrusion
8	Copy Primitive
9	Delete All
10	Delete Selected
11	Ray Selection
12	Portal into Space
13	Color Picker
14	Hide Drawing Surfaces
15	Gridlines

Figure 10. Configuration Menu. Besides the permanently available physical tablet with two hardware buttons and the floating buttons, all other controls are accessible via the configuration menu on the tablet. Icons © icons8.com. Used under CC BY-ND 3.0. [26]

USABILITY WALKTHROUGH

To evaluate the implemented sketching metaphors for 2D as well as for 3D interaction, we conducted a usability walkthrough with six participants (age 22-30, 4 male, 2 female) recruited through convenience sampling. In a demographic questionnaire, participants reported if they have used VR HMDs (n=2) and VR sketching software like Tilt Brush [2] (n=0). Typically used sketching tools were pen and paper (n=4) and graphical tablets (n=1). The usability walkthroughs were between 90-150 minutes long.

Procedure

Introduction and Training (M=46 min, SD=6 min): Participants were introduced to *VRSketchIn* and the implemented functions following a script. The introduction was grouped by the interaction metaphors and at the end of each group, the participants had the task to sketch a crossed house puzzle using the presented metaphors. Proceeding was allowed when they solved the task successfully. They were encouraged to state comments and ask questions during the task. The researcher observed the usage of the system, asked questions when the behavior of the participant was unclear and offered help when necessary. Written notes were taken in addition to audio and video recording. After the first phase, participants could take the HMD off and answered a demographic questionnaire (M=13 min, SD=11 min).

Free Sketching (M=41 min, SD=13 min): Participants were told to freely sketch and use the introduced interaction metaphors appropriately to create a beach house on an island in the sea. We told them some possible objects to sketch (e.g., palm tree, boat, bridge). Each object was linked to an interaction metaphor, but this link was not communicated to the participants. There was no time constraint and participants were able to sketch as long as they wanted. Data recordings and instructions for the participants were similar to phase one.

Interview and System Usability Scale (SUS) (M=15 min, SD=02 min): In the end, we conducted a semi-structured interview with each participant and asked ten questions (topics:

system usage, use cases, improvements). Their answers were audio-recorded and written notes were taken. Furthermore, they rated the usability by answering the SUS questionnaire [12].

RESULTS

The lead author conducted a thematic analysis going systematically through the taken notes of all phases and grouped similar answers. Whenever the notes were not sufficient, the audio and video recordings were analyzed. Five out of six participants explicitly stated to like our system and that it works similar to known software (SUS=70, >=70 is in the range of good usability [7]). A selection of sketches created by our participants during free sketching can be seen in Figure 11. Most participants sketched in small scale, only P6 used true scale.

3D Mid-Air Sketching: Immersive *3D mid-air sketching* in VR was appreciated and fun for most participants (P1, P4, P5, P6) as shown by [29]. They liked the additional dimension (P2, P4) and that they are not constrained to a 2D surface (P5). Four participants (P1, P2, P3, P4) explicitly stated that precision in 3D is an issue, but it is sufficient for the sketching task they did during the free sketching phase (P2, P4, P5). The activation with one button press was a benefit. Therefore, it was frequently used compared to other interaction metaphors that would provide higher precision but need multiple interaction steps (P1, P2). This suggests that all interaction metaphors should be as easy to access as *3D mid-air sketching*.

Drawing Surfaces: P5, who is familiar with graphical tablets for desktop computers, stated that our implementation of a graphical tablet in VR is equally convenient and allows comfortable sketching in the vicinity of the user. *Drawing surfaces* were used to sketch straight lines or filled areas like the base of the beach house, the island, or a table (P1, P2, P3, P4, P6). Furthermore, they could be used as background planes (e.g., sky, clouds), as suggested by P1. Best results regarding the precision of connected lines were achieved when (1) a surface was positioned, (2) the sketch was drawn on that surface, (3) a new surface was positioned exactly on lines of the previous surface, and (4) a new connected line was drawn. This was especially useful for the crossed house puzzle.

Plane scaling and positioning was considered very useful (P2), but the snapping function should be improved to provide more common horizontal and vertical angles (P1, P3, P4) such as 45° or 90° (not only 5° steps) combined with automatic alignment as in [30, 37, 62]. Because 2DoF still can cause crooked lines (P6), the edges of the drawing surface were used for stabilization (P2, P3) whereas gridlines were never used. We observed that *drawing surfaces* were a feature for creating straight lines or filling areas and were not used for general sketching. A reason could be that the given task had few inorganic parts (only the beach house) and that *drawing surfaces* could be more useful for an architecture sketch (P1) or for writing text (P4). An improvement should be to simplify the process of creating surfaces to use them faster for just one line (P2, P5).

World In Miniature: *WIM* provided a good overview of the whole scene (P1, P2, P3, P4) and was used for easy perspective taking and verification of the sketches (P1, P2, P3, P4, P6). All participants stated that it is, due to the lower size, more difficult

Figure 11. Islands with beach houses created by our participants during the usability walkthrough (P2: (a), P1: (b), P5: (c)).

to sketch precisely in *WIM* than in mid-air. They used it, therefore, for sketching in distant areas (P1, P6), for sketching at the edges of the miniature space (P1), for large objects (P5, P6), and for filling areas (P5). Enhancements could be to enable *drawing surfaces* in *WIM* (P1), provide ground parallel freeze positions for the *WIM* when sketching (P5), and improve the occlusion of the menu due to the *WIM* floating above it (P6).

Primitive Extrusion: *Primitive extrusion* was used by the participants to create solid objects from strokes, such as floors, roofs, walls, palm trees, hammocks, or a chair (P1, P2, P3, P4, P6). Whereas rotating extruded objects with gizmos was easy (P2), *extrusion* itself should be possible in all directions (P1, P2, P3, P4, P6) so that an additional rotation step is not necessary. Our observations show that it is a useful interaction metaphor that should be implemented in immersive sketching applications.

Portals into Space: Like *WIM*, *portals* were used by some participants to quickly take a look from a specific perspective to verify the sketch without moving (P2, P5, P6). Besides the live view, P2 suggested to create snapshots. We observed that it is very complex to sketch in mid-air and look simultaneously on the *portal* (P2, P4, P6). Our design space proposes the addition of input metaphors to *portals* (e.g., ray through portal). This would solve the displacement issue between the interaction in mid-air and the output on the tablet.

Object Manipulation: Gizmos were a common tool and used by the participants for precise object placement (P2, P3, P4, P6) that should be available for *drawing surfaces* and *portals* as well (P1, P2, P3 P4, P6). Possible improvements can be to add uniform scaling to the scaling gizmo (P1, P2), adapt the gizmo size to the object size, and disable all gizmos automatically except for the selected object (P6).

DISCUSSION AND FUTURE WORK
We provide insights for pen- and tablet-based systems that fit into our design space, especially for the usage of the investigated interaction metaphor groups and the general usage behavior. The usage of *drawing surfaces* showed that they are useful for flat objects, but their usefulness depends on the topic. For *WIM*, we saw that it is a powerful tool to quickly verify a sketch from different perspectives, but that it is a minor content creation metaphor due to the lower precision resulting from the miniature scale. *Primitive extrusion* was useful to create solid objects and it is a powerful interaction metaphor when all axes are supported. The limited subset we implemented for the *portal into space* interaction metaphor should be extended by input interaction metaphors from our design space and evaluated further.

Our observations showed that there were specific use cases for *2D surface-based sketching* (e.g., straight lines, walls) as well as for *3D mid-air sketching* (e.g., 3D terrain, waves) interaction metaphors. Both were being used disjointly, and participants used one type over a longer period and did not frequently switch between them. This is an interesting outcome and points towards something more general as the participants were not explicitly instructed to follow certain usage patterns after learning everything during training. One possible explanation could be that *3D mid-air sketching* was easier to access than the other interaction metaphors, which needed more than one interaction step before a stroke could be sketched. Our observation was that participants accepted this overhead only when they could not achieve their goal in mid-air. It should be investigated further if a reduced overhead leads to frequent switching or if there is a fundamental reason for the observed usage behavior. We think that this is an important question and suggest that further research should be conducted to explore: (1) why there was no frequent switching between 2D and 3D interaction metaphors, (2) how this could be achieved, and (3) if this improves the system usability.

CONCLUSION
In this work, we presented *VRSketchIn*, a VR sketching application using a 6DoF-tracked pen and a 6DoF-tracked tablet as input devices, combining unconstrained *3D mid-air sketching* with constrained *2D surface-based sketching*. To explore what possibilities arise from this combination, we presented design dimensions that focus on pen- and tablet-based object creation and object manipulation and span the resulting design space. Inside the design space, we categorized prior art and defined metaphor groups of sketching interaction for VR. A subset of these metaphor groups *3D mid-air sketching*, *drawing surfaces*, *WIM*, *primitive extrusion*, and *portals into space* was implemented in *VRSketchIn* and evaluated with six participants in usability walkthroughs. Our observations show that 2D and 3D sketching metaphors were each used for distinct tasks, leveraging the benefits of the individual input device. *2D surface-based* metaphors were used for sketching straight lines or for flat objects, whereas *3D mid-air sketching* was used to shape volumes. Therefore, we argue that current input devices for VR are not optimized for sketching in immersive environments and that including traditional devices (pen and tablet) can open a large set of new opportunities and benefits to the user.

ACKNOWLEDGMENTS

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