ABSTRACT
Virtual reality provides a heightened sense of immersion and spatial awareness that provides a unique opportunity for designers to perceive and evaluate scale and space. At the same time, traditional sketches and small-size physical models provide tactile feedback that allow designers to create, comprehend, and explore complex geometric relationships.

Through the development of vSpline, a modeling application for virtual reality, we explore the potential for design within a virtual spatial environment to blur the boundaries between digital and physical stages of design, and seek to combine the best of both virtual and analog worlds. By using spline-based closed meshes created directly in three-dimensional space, our software provides the capabilities to design, modify, and save the information in the virtual world and seamlessly convert the data to evaluate the printing of 3D physical models.

We identify and discuss important questions that arise regarding relationships of perception of scale, digital-to-physical domains, and new methods of input and manipulation within a 3D immersive space.
INTRODUCTION
Motivation
Virtual reality (VR) creates an immersive virtual world where the perception of space and scale can be manipulated. Analog models and drawings typically require abstractions of scale or projective distortions, producing a disconnect between the design tool and the constructed project. Our interest was to study opportunities for designing in a virtual world while still producing models, artifacts, or sculptures in the physical world.

VR head-mounted display systems have become increasingly prevalent in the design field. Advanced systems provide room-scale experiences and tracked hand motion controllers, allowing for the potential to not only move through, but also create and design within a virtual space.

The perceptual qualities of an immersive 3D space, the relationship between the physical and virtual world, as well as the use of tracked input controllers raise a variety of questions regarding new modes of human–computer interaction and novel relationships of scale between a designer and a model. As the development of design tools within VR continues to expand, these relationships will influence the design process from creation, to iteration, to fabrication of prototypes.

Precedent Work
Rock and Harris demonstrated that the perception of one’s own body had a significant effect on the evaluation of the size of objects, and that visual cues could dominate tactile cues when the two conflicted (1967). Tcheang, Gilson, and Glennerster investigated the relative perception of body versus object motion within immersive virtual spaces, finding that users had difficulty discriminating the rotation or translation of objects without an additional stable visual reference frame (2005). The potential for three-dimensional immersion into a virtual scene has been studied to visualize and communicate design alternatives (Heydarian et al. 2014).

In the area of design tools, Schubert et al. explored ways to bridge the gap between physical and digital environments for sketching (2012). HoloSketch was an early development tool for sketching within a virtual 3D space (Deering 1995). DDDoolz used a cube-based method for additive creation of geometry and explored the use of VR in early design phases (Achten, de Vries, and Jessurun 2000). These tools began to explore interface design and creation within 3D spaces, but the technology and computational power was limited compared to modern VR systems. SculptVR, released more recently, uses a similar geometry of cubes. Medium provides “sculpting” capabilities by using volumetric mesh based on voxels. Tilt Brush and Quill are two applications that use planar mesh based geometry to allow a user to draw and paint in a three-dimensional space. Gravity Sketch, currently under development but not publicly available as of the writing of this paper, is a NURBS-based application that can create surfaces and splines.

vSpline
To explore the blurred boundaries between drawing and modeling, both digital and physical, as well as the perception of scale, we developed vSpline, a custom VR application for the HTC Vive (Figure 2) that provides the flexibility and simplicity of creating and editing geometry within virtual space. We focus on a specific use-case of geometry that could be 3D printed directly without additional processing. This approach allows us to explore the relationship of the virtual and the physical, as well as the actual and perceived scale of the geometry, along the entire pipeline from creation to production.
METHODS
Here we discuss the core implemented features necessary to explore the aforementioned relationships. Our prototype software has three crucial modules: input, modification, and output methods. Additional supplementary features are provided through a UI that enhances the design and user experience.

Input
We implemented two primary modes of input, the "brush" and the "pen," both of which have the option to use NURBS or handle curves. Brush mode allows the user to draw continuously in space, comparable to sketching, while pen mode allows the user to manually place individual control points to create the spline.

In the first mode, a user presses a button on the motion controller to produce a preview geometry along the path of the drawing. When the button is released, a curve-fitting algorithm calculates the control points of a best-fit spline. Information recording the pressure of the button and the rotation of the controller is saved as well.

This information is used to create a closed triangulated mesh around the centerline of the parametric spline (Figure 4). The pressure parameter is used to determine the width of the mesh while the controller rotation controls the twisting of the resulting mesh.
In the second method, the user places control points manually, allowing for the creation of both straight-line and curved segments (Figures 5 and 6). Options for varying the surrounding volumetric mesh increase the flexibility of possible geometry. Several cross-section shapes are provided, including squares, circles, or triangles, which can be scaled horizontally or vertically. The scale of the cross section can also be varied while drawing, producing a mesh with varying thickness along the spline (Figures 7 and 8).

**Modification**
Geometry can be modified through multiple means. Meshes can be moved, rotated, and scaled by using the controllers to “grab” the curves. The control points of the underlying curves can be accessed and moved in a similar way. Additionally, the thickness at any position along the curve can be increased or decreased to “inflate” or “deflate” the enclosing mesh (Figures 9–11).

The user can also modify the positioning and scale of the digital environment. Operations analogous to panning, zooming, or orbiting a model are accomplished by pressing and holding grip buttons on the sides of the controllers. These operations allow the user to move through and around the designs at different scales and different orientations.

**Physical Output**
To ensure that the resulting geometry can fit within the print bed of a 3D printer, the user is provided with a guide-bounding box in which to work, as well as the ability to change the scale of the space to match real-world scale. For printing purposes, each individual mesh drawn is a closed mesh.

**Technical Information**
The software was developed using Unreal Engine 4 and designed for use with the HTC Vive VR headset and controllers. The Geometric Tools Engine library was used for best-fit spline algorithms.

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7 Geometry drawn with different cross sections.
8 Curve drawn with variable thickness.
9 Variable thickness along a spline can be ‘inflated’ or ‘deflated’ for increased formal flexibility.
10 The points of handle curves and NURBS curves can be moved, inserted or deleted.
11 Editing a spline with a variable thickness.
RESULTS

vSpline was periodically tested by student users, providing feedback on the ease of use, suggestions for potential features to enhance the perception of scale, and streamlining the process of virtual design to 3D printing. Users were observed to understand how they would move through and work within a virtual space. We found that the ability to edit the geometry in simple intuitive ways was necessary to allow a user to quickly create iterations of basic concepts and forms. Allowing the user to edit the cross-sectional dimensions and thickness of mesh geometry along a one-dimensional spline produces a system that is simple, since it is based on a single set of control points, but still flexible enough to produce a wide variety of forms (Figures 12–15).

Virtual Scale vs Real-World Scale

A distinguishing feature of working in a 3D virtual environment is the relationship between the user and the scale of the space. With room-scale VR systems the user is physically in the same space as the “drawing,” imposing a human scale into the perception of the environment. At the same time, similar to any 3D modeling software, an arbitrary scale can be imposed on the modeled geometry.

This discrepancy between the physical size of the geometry and the represented dimension of an object can cause perceptual ambiguity when the user changes the scale of the model. This action can be perceived either as an object getting physically smaller or as the user themselves getting larger (Figure 17). This is an experiential result of the user inhabiting the same perceptual space as the digital model, as opposed to designing on paper or a screen where the model space and the physical space are clearly separated.
We found that this ambiguity of perception can result in significant disorientation within a virtual modeling environment, both with respect to the scale of the modeled objects, as well as the physical position and rotation of the user within the physical room. We explored several different features to address this disorientation. The most basic is a reference box to indicate the bounding area of a 3D-printing bed. Initially implemented simply as a guide to indicate how large the printed object would be, we found that it also provides the user with a scaled reference frame to indicate the relative real-world size of the digital geometry. We also added a simple grid at the origin of the model space to maintain orientation relative to position and rotation.

A second feature implemented to address the issue of orientation was a series of viewports. These provide two-dimensional views of the model area (Figure 18). The associated camera positions are fixed relative to the print area bounding box, while the viewports themselves are fixed relative to the world space of the user. When a user zooms, pans, or rotates the model geometry, both the viewports and the views remain constant (Figure 19).

16 A sequence of screenshots showing a user zooming into a space. The bounding box provides a frame of reference.

17 The process of “zooming out” within the immersive virtual space can produce the perceptual effect of either the user growing larger or equivalently the geometry getting smaller, creating disorientation and perceptual ambiguity.
These viewports allow the user to maintain a real-world fixed reference frame while also zooming into a model and working at arbitrarily fine levels of detail. We found this additional feature to be extremely useful in reducing the ambiguity of the model space scale and orientation. By remaining stationary relative to the physical room and user, the viewports additionally provide useful visual frames of reference for the users to maintain their own orientation, thus reducing perceptual ambiguity.

**Drawing vs Model**

There are many potential options for input methods into a 3D virtual space. We chose to implement methods such as the brush and pen in order to imitate the processes of sketching and drawing and bring them into a spatial environment. The combination of spline-based geometry with volumetric meshes begins to blend concepts of drawing and modeling together. In vSpline, line weight becomes a physical thickness, and can be increased to the point where it is no longer understood as a one-dimensional line, but rather as a spatial volume.

**CONCLUSION**

vSpline allows a designer to sketch within a 3D environment and provides the ability to edit the resulting sketch. The uni-variate spline-based geometry allows for simple and intuitive creation while maintaining the flexibility necessary to produce complex and versatile forms. This begins to describe a fundamentally new paradigm of “drawing,” one in which the drawing is both hand drawn and parametrically defined. This software can be used to create an immersive digital representation of a concept, form, or prototype, but the resulting 3D printed object also serves to narrow the gap between the digital and the physical.

The spatial nature of VR encourages a different understanding of scale, as compared to two-dimensional drawings or displays. The relationship between the physical inhabitant of the virtual environment and the represented scale can produce ambiguous perceptual experiences. Our results indicate that reference frames of dimensions and scale can help orient users and allow them to form mental models within a dynamic virtual environment. Future work in this area would observe and evaluate the practical use of this tool within a design studio in order to better understand how these preliminary results can be integrated into existing design heuristics. We are especially interested in the effects of ambiguity in scale and orientation with respect to both the perception of a modeled space and the creation of geometry within a virtual environment.

Although VR provides a powerful tool to create and visualize designs, there is still inherent value in the tactile qualities and materiality of a physical prototype or drawing. Ultimately, the use...
of VR as an interface for computational design should be understood as complimentary to existing tools rather than replacing methods such as physical sketching, modeling, or digital input with a mouse and keyboard.

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REFERENCES


IMAGE CREDITS
All images are original content by the authors.