Scientific Sketching for Collaborative VR Visualization Design

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Abstract—We present four studies investigating tools and methodologies for artist-scientist-technologist collaboration in designing multivariate virtual reality (VR) visualizations. Design study 1 identifies the promise of 3D interfaces for rapid VR design and also establishes limitations of the particular tools tested with respect to precision and support for animation. Design study 2 explores animating artist-created visualization designs with scientific 3D fluid flow data. While results captured an accurate sense of flow that was advantageous as compared to the results of study 1, the potential for visual exploration using the design tools tested was limited. Design study 3 reveals the importance of a new 3D interface that overcomes the precision limitation found in study 1 while remaining accessible to artist collaborators. Drawing upon previous results, design study 4 engages collaborative teams in a design process that begins with traditional paper sketching and moves to animated interactive VR prototypes "sketched" by designers in VR using interactive 3D tools. Conclusions from these four studies identify important characteristics of effective artist-accessible VR visualization design tools and lead to a proposed formalized methodology for successful collaborative design that we expect to be useful in guiding future collaborations. We call this proposed methodology Scientific Sketching.

Index Terms—Visualization methodology, design study, critique, artistic interface, art, virtual reality.

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1 INTRODUCTION

One of the most challenging aspects of developing scientific visualizations is designing effective visual codings and abstractions for the data. Unlike technical challenges in simulation, data processing, and developing interactive rendering algorithms, this is best described as a *visual design* problem, and it is made particularly challenging by the unusual visual characteristics of several of our most prominent visualization media, including virtual reality (VR).

As customary in visualization, we turn to visual guidelines [29], insights on human perception [31], and the study of time-tested artistic techniques [19] for direction in solving these visual problems. Guidelines are often difficult to interpret however, and they rarely describe how we can handle the conflicting requirements imposed by multivariate visualizations. Even when we find relevant guidelines to direct our work, applying them to the unusual immersive visual space that we find in VR is rarely straightforward. We are left with a difficult visual design problem that typically requires an iterative solution of the form: design, evaluate, redesign, reevaluate, etc.

The underlying premise of the work presented here is that collaborations with visual experts such as illustrators, designers, and artists have great potential for addressing these challenging *visual* problems. After several successful collaborations between our visualization research laboratory and artists from the Rhode Island School of Design, we have become convinced that this collaboration can be an important aid to science. Indeed, this idea is not without precedence. Cox pioneered the development of "Renaissance teams," where experts in art, science, and technology come together to make effective illustrations of science [3]. Sorensen's work describing an artist's contribution to scientific visualization presents a noteworthy account of artistic collaboration for solving visual problems in scientific domains [26]. Our work builds on these early examples of successful artist-scientist collaborations.

We address the question: Given that we want to collaborate with visual experts such as artists, how do we most effectively leverage their skills when working with real computer-based scientific visualization media such as VR? We believe that new refinements in methodologies and tools intended to support collaboration will lead to increased roles for artists during the design process, making more significant design contributions by artists possible and ultimately leading to more effective visualizations.

Our primary contributions are the presentation of a series of four design studies and resulting insights. We report on refinements across the studies in terms of both design methodology and tools, and we discuss the impact of each of these on artists' ability to contribute to VR visualization design. We also present a formal methodology for collaborative VR visualization design derived from conclusions of the design studies.

One way that artists and designers often work when designing visuals is by sketching [2]. Designs begin as rough

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Fig. 1. Designs for scientific visualizations intended for VR described using traditional artistic media. While artists can clearly contribute to visualization problems using these media, they can contribute additional insight if given appropriate tools for creating and refining visual ideas within target visualization environments.

pencil line drawings and, through visual experimentation via sketching, become much more refined over time. Physical noncomputer media such as sketching, drawing, and painting are all relatively quick, accessible, and expressive, which makes them excellent tools for this iterative design refinement.

Fig. 1 shows some examples of designs for visualizations created entirely with traditional media. How effective are designs such as these when we target visualizations using contemporary computer media such as VR? Clearly, traditional media plays an important role in nearly all visual design tasks, but in this case, we find that it is difficult to evaluate how well even the most sophisticated concept drawings will work when translated to a VR environment. Traditional media such as drawing, painting, Photoshop, and even desktop-based 3D modelers simply do not capture the unique VR experience: head-tracked stereo vision, multimodal interaction, and the sense of presence and immersion. As such, it is difficult to critique these traditional designs accurately without seeing them at least partially realized in VR.

We presented these observations about the difficulties inherent in visual design for VR based on our early collaborations first in a poster at the 14th IEEE Visualization 2003 Conference (VIS 2003) [11] and then in a *Visualization Viewpoints* article [14]. In these venues, we first posited the idea that artist-accessible VR modeling tools such as CavePainting [13] could be used for design directly in VR, in a sense, moving the traditional act of sketching, with which artists are quite familiar, to a 3D VR setting.

In this paper, we bring insight from this early work together with more recent results achieved after significant refinement of tools and methodology. From the analysis of the complete work, which now spans multiple years and scientific applications, we pose a new prototyping-driven methodology for collaborative design called Scientific Sketching. Our presentation follows from the recent dissertation results of Keefe [12].

We begin with an overview of related work. We then present Scientific Sketching, followed by the series of four design studies. Next, we present additional details of the custom tools developed to support design tasks during the studies. Finally, we present the discussion and analysis of design tool and methodology refinements and the results of the studies as a whole.

2 RELATED WORK

In this section, we describe related approaches to collaboration with artists, and we compare our work with techniques in software engineering and prototyping.

2.1 Artistic Collaboration for Scientific Visualization

Many researchers in the visualization community have recognized the important role that art and artists can play in informing effective visualization strategies. One important subarea of this research involves developing visualization techniques from the study of successful artistic techniques. For example, Kirby et al. provide an overview of painting techniques applied to 2D multivariate visualization [17], [18]. Many other techniques for art-based or nonphotorealistic rendering have been demonstrated in both the visualization [7], [9], [19], [20] and graphics communities [6].

Other approaches that are more applicable to our methodology involve significant collaboration with practicing artists rather than the study of artistic techniques. Many of these follow a Renaissance-team model, in which experts from art, science, and technology work together to produce scientific imagery [3]. The distinguishing characteristic of much of this work is the particular role that artists play in the collaboration. Sorensen outlines several possibilities for these roles in a collaborative scientific process [26]. We often think of artists only when we reach the dissemination stage of scientific research. While artists can certainly contribute at this point, this is a very limited use of artistic insight. As Sorensen explains, artists can play key roles throughout the scientific process, notably in the design and conceptualization stages that come early in the scientific process. We hope to make more significant contributions from artists in early visualization design stages possible.

Another recent research area in artistic involvement in visualization has been in evaluating visualization techniques. Jackson et al. show that expert visual designers can predict user performance with different visualization techniques on tasks required for the analysis of 2D fluid flow [10]. This work makes a quantitative case for the efficacy of incorporating artistic critiques of visualizations in an evaluation process. Our goal is to take this role for artists a step further. In addition to helping us evaluate visualizations, we want experts trained in art and design to collaborate in posing new visualization designs and refining existing ones.

2.2 Software Rapid Prototyping

In software and usability engineering terms, our methodology is closely related to development via rapid prototyping, which also embraces an iterative approach to design and recognizes the costly nature of implementation via programming [1]. Learning by evaluating rough (not completely functional) prototypes early in the development process is the premise of this approach.

One of the most successful application areas for this style of software development is in user interfaces. The benefits of incorporating feedback from user testing have been well documented in this context. In some cases, the prototypes are minimally functional and may even be constructed from paper.

In a related approach, the functionality of prototypes can be faked for the purpose of user testing in what has been termed a "Wizard-of-Oz" approach [5], [16]. Here, a technician or "wizard," who is typically hidden from the user, controls the system so that it responds to user feedback, simulating the effects of features that are challenging or costly to implement, for example, speech recognition. Our methodology incorporates Wizard-of-Oz techniques for prototyping aspects of the VR visualizations that respond to user interaction.

While the idea of this design style is not new, several researchers have recently called for a renewed focus on design strategies, particularly in visual and interface-centric applications. Notably, Buxton, in his recent book on the importance of design techniques in interface development, cites Wizard-of-Oz techniques as among the chief means of achieving something akin to a design sketch, specific to interactive situations [2]. Similarly, a recent special issue of the *IEEE Pervasive Computing* was devoted to rapid prototyping for ubiquitous computing [4]. Ubiquitous computing and VR pose similar problems for software development in that in both, a user's experience is simply very difficult to capture via traditional design media.

Our main technical contribution in this area is combining these interactive prototyping techniques with tools for drawing out design ideas in VR, thus allowing us to explore by drawing within the complex space of possible interactive VR visualizations and leverage the artistic skills of our collaborators.

2.3 Toolkits for Rapid Visualization Development

Several tools based on visual programming [30] and more conventional programming [24] can facilitate rapid development of visualizations. While these ease the burden of programming visualizations, they are limited in their ability to directly support artistic involvement in design. Tools like these likely fit nicely into the later (implementation) stages of our framework.

3 SCIENTIFIC SKETCHING DESIGN METHODOLOGY

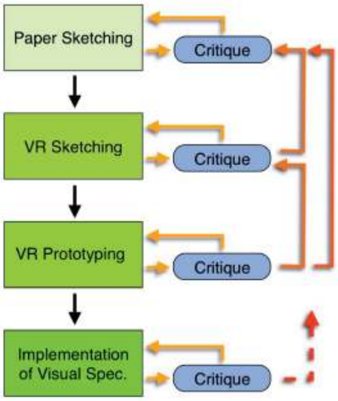


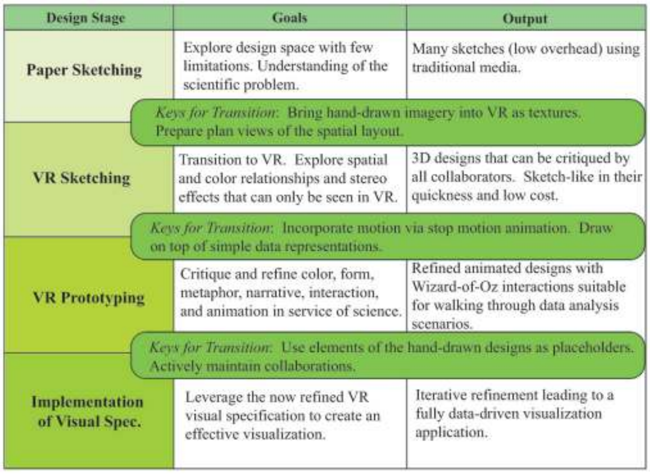
Fig. 2. Overview of the Scientific Sketching methodology.

In this section, we present Scientific Sketching, a methodology for designing VR visualizations, with significant contributions from collaborators with visual expertise such as artists. As we have mentioned in the Introduction, the development of this methodology is warranted by several factors, including the unique qualities of VR. The second factor is the multivariate nature of the data that we expect to encounter. Scientists wish to draw connections between multiple variables in their data sets and hence wish to see the connections between these variables expressed within a 3D view of their data. Designing such a display is hard. It requires balancing multiple constraints, including avoiding problems of occlusion when displaying multiple variables. As we encounter new data sets, new solutions are typically required. We hope to engage our collaborators in finding these hard-to-design solutions.

The methodology that follows was generated from a synthesis of insights gained through the series of design studies described in Section 4. In forming the methodology, our approach was to extract the elements of the design process in each study that were most successful and note the roles of each team member in these processes. As we proceeded through our investigations, less successful portions of the process were refined or replaced in successive design studies. The resulting methodology reflects our current understanding of the most successful collaborative design process to take, given our emphasis on using sketching as a tool to drive design.

Scientific Sketching contains four distinct stages of design, described in detail in the following. With each stage, the design becomes increasingly refined as it moves from rough initial sketches toward implementation in VR. Fig. 2 contains a flowchart for the entire process. High-level goals and the intended output of each stage, along with keys for transitioning between stages, are detailed in Fig. 3. As shown in Fig. 2, iterative loops are a part of the process. Iterations within each stage and, to some extent, between the initial stages are encouraged. We try to avoid the loop from a partial or full implementation back to the earlier design stages, since implementation is far more costly than design via sketching or prototyping.

Evaluation of the visuals and interactive techniques proposed during each design stage is performed using a critique, which is repeated multiple times within each design stage. We provide additional background in evaluation by



Design Stage	Goals	Output
Paper Sketching	Explore design space with few limitations. Understanding of the scientific problem.	Many sketches (low overhead) using traditional media.
	Keys for Transition: Bring hand-drawn imagery into VR as textures. Prepare plan views of the spatial layout.	
VR Sketching	Transition to VR. Explore spatial and color relationships and stereo effects that can only be seen in VR.	3D designs that can be critiqued by all collaborators. Sketch-like in their quickness and low cost.
	Keys for Transition: Incorporate motion via stop motion animation. Draw on top of simple data representations.	
VR Prototyping	Critique and refine color, form, metaphor, narrative, interaction, and animation in service of science.	Refined animated designs with Wizard-of-Oz interactions suitable for walking through data analysis scenarios.
	Keys for Transition: Use elements of the hand-drawn designs as placeholders. Actively maintain collaborations.	
Implementation of Visual Spec.	Leverage the now refined VR visual specification to create an effective visualization.	Iterative refinement leading to a fully data-driven visualization application.

Fig. 3. Goals and deliverables for each stage of design.

a critique in the next section before continuing to describe each stage of the design process in detail.

3.1 Background in Artistic Critique

Critiques are a primary teaching tool used in art and design education. They are also used outside academia in a variety of fields where visual design is important. The critique is a careful critical detailed group discussion, with the goal of evaluating a visual artifact. The discussion is oriented around specific aspects of the visual being studied and how well each "works" to support the goals of the piece. Good critiques involve detailed comments backed up with a basis for each evaluation [28]. The comment, "I don't like the colors..." must be followed with an explanation, "... because the use of primary colors dominates the visual field, leaving little room for perception of the subtleties that are really the most important concept in this piece."

In our use of critique, scientists, visualization experts, and artists participate together. As customary in illustration, art, and other visually oriented fields, our visualizations have a purpose behind them: in our case, it is scientific understanding. Thus, the visual questions explored during the critique evaluate how well the visualization design functions in effectively representing the science. Scientists must be involved in making this evaluation. Together, the design team works toward posing the scientific problem as a visual problem, allowing visual concepts such as color, texture, form, composition, metaphor, and narrative to be discussed as tools in service of the science.

Consider an example from an application area discussed later in the paper. In studying bat flight, scientists now know that the wing bones bend considerably during flight. Furthermore, a recent study of the mechanical properties of the individual bones has revealed considerable between-bone variation as compared to other mammals. These results lead to follow-on hypotheses regarding the role that this variation might play during flight.

During the critique of a design intended to investigate this issue, the methods used to depict the bat anatomy will be an important discussion point. If additional variables are also to be conveyed in the visualization, for example, aerodynamic forces or vortical structure in the wake of the bat, then methods for striking an appropriate visual balance between these elements and the bones will need to be discussed. For example, the choice of color may be discussed as a tool for controlling visual emphasis. If understanding the particular form of the bones is critical, then discussion in the critique may turn to novel visual strategies for clearly depicting this form. For example, to address this problem, an artist in our group composed a design in which the bones were depicted relative to straight reference lines connecting the joints in the wing. The critique of the design established that the ability to contrast shape changes relative to a consistent reference geometry made visual comparisons within animated VR displays much easier.

3.2 Stage 1: Paper Sketching

We now describe the first stage of the Scientific Sketching process, namely, paper sketching. Almost all successful design processes begin with sketching on paper. Paper is quick, easy, accessible, and disposable, so it is easy to explore many possibilities quickly and engage in visual thinking [2]. Each team member plays an important role during this stage of the process:

Role of artists. The artist's role is to present many visual ideas. Quantity is important at this stage, because variety in design sparks new thinking. Artists should ask questions to learn enough about the science in order to pose the problem visually: What needs to be depicted? What portions might change in response to data? What stays constant?

Role of visualization experts. Visualization/Computer experts play a key role in facilitating discussion between the artists and scientists. Sketching ideas is also important. In this early stage, sketching good visual ideas without regard for the difficulty of implementing the ideas is often useful. There is a good chance that a critique may lead to a simplified version of the design that is much easier to implement.

Role of scientists. The scientists' chief role is to explain the scientific problem and data sufficiently for others to understand at a level of potential cause-and-effect relationships and the relative importance of variables. If one variable can be identified as the first thing to look for in a visualization, that information is important to convey. Landmarks in the data are also useful to identify: for example, in brain visualization, the ventricles often provide a landmark for understanding spatial orientation. Landmarks will provide common ground in the critique of designs and a starting point for discussion that can be useful for introducing the process of critique to the group.

3.3 Stage 2: VR Sketching

After several paper designs have been proposed and refined, it is important to begin to evaluate the ideas within VR. This is done primarily through a process that we call "VR sketching." Like paper sketches, VR sketches are quick to construct, but unlike paper, the resulting designs exist within the target visualization medium, allowing critique sessions to focus on VR-specific aspects of the design. Custom tools that support sketchlike construction in VR are needed to support this and the next stages of the design process. Section 5 describes these tools in more detail.

Role of artists. While working in VR to “sketch” 3D versions of the designs from the previous stage, the artist should work as she would with any new brush and color palette, i.e., learn the medium through experimentation via drawing in VR. How do colors interact, and how does computer-generated lighting on the forms interact with artist-specified color? What stands out? What fades to the background? We have found that the answers to these questions often change when moving from traditional media to VR and from one VR-form factor to another. Artistic experimentation is a valuable tool for determining the visual properties of the intended medium.

Role of visualization experts. Initial VR sketches should also be created. One issue to explore in particular is visual simplification. Designs from stage 1 that are promising from a visual standpoint but are daunting from an implementation standpoint are good candidates for visual simplification. Experimentation coupled with critique is needed to arrive at designs that preserve visual effectiveness while also addressing potential implementation difficulties.

Role of scientists. During a critique, it is useful to speak with reference to specific visuals that are being presented. How would the data be interpreted if presented exactly as sketched now? How well do the visual forms reflect the underlying scientific concepts? While other team members likely have more background in topics of color theory and composition, discussion of visual techniques such as the use of metaphor and narrative in the design requires insight from the scientists. In addition to being valuable in refining the design as presented, the critique of metaphor and narrative also likely serves as a continued introduction to scientific concepts.

3.4 Stage 3: VR Prototyping

Stage 2 yields several VR design sketches and a variety of insights gained through the critique of visual ideas in VR. In Stage 3, the best of these designs will be investigated as VR prototype applications. In this stage, many of the same design tools from the previous stage are used, but the drawing of forms becomes deliberate and exact rather than quick and sketchy. Prototypes, especially those including interactive scenarios, may be created over several days rather than the hours needed for paper and VR sketching. Only the most promising one or two designs should advance to this level. This is the stage at which Wizard-of-Oz interaction techniques should be explored. Additionally, some effort should be made to establish connections to the underlying data.

Role of artists. The artist should focus on refined VR designs. Picking a very specific hypothesis and then creating a view that is useful for investigating it is a focused way to proceed.

Role of visualization experts. While the visualization/computer expert should do some of the same design drawing and visual refinement as the artists, the need for limited programming may also emerge. In the design studies discussed in Section 4, simple markers for motion-capture data were imported into the design application, requiring less than 3 hours of programming time. The ability to design in relation to this real data, even in an extremely simple form, made a tremendous difference in the team’s ability to critique time-varying designs with confidence. Another possibility for simple programming is adding controls to features that the artists have drawn. If a feature is intended to rotate in response to data, simple scriptlike additions to the program can be used to mock up these visual effects for critique. Making a design element rotate may involve an hour of programming, while making it rotate in response to vorticity values in a pulsating time-varying flow may take days or weeks. At this stage, the non-data-driven version is likely to be nearly as valuable as the data-driven version in determining how well the design functions visually.

Role of scientists. The team is converging upon a specification for a fully implemented visualization. It is imperative to address during critique whether the necessary quantities are visible in this visualization in order to investigate the driving scientific questions.

3.5 Stage 4: Implementation of the Visual Specification

Most visualizations, especially exploratory ones, target a final result of a fully data-driven visual display. At some point, a programmer must take the lead in building this type of application, but the transition to implementation can be difficult to navigate.

Role of artists. The artist must advocate for the visual decisions made in the earlier design stages. It is easy for artists to be left out of the process as the programmer assumes responsibility for what actually ends up displayed on the screen. Implementing the design is bound to necessitate some design changes. The artist needs to stay involved in discussion and redesign through smaller scale repetition of earlier drawing-based design stages.

Role of visualization experts. The visualization/computer experts lead the implementation of the visual specification devised in previous stages. A conscious effort must be made to maintain collaborations. One of the best ways to do this with respect to the artists is to build the implementation on top of the prototypes established in previous stages. This way, hand-drawn elements of the design can live on in the “final” presentation as placeholders or annotations. The artists should be encouraged to continue drawing on top of the latest state of the visualization to continue refining the specification for the yet-to-be-implemented portions.

Role of scientists. Scientists also must take care to stay involved in the process during implementation. An important role is to help determine intermediate goals and set priorities for features to be implemented. What is the next hand-drawn placeholder that should be replaced with a data-driven visual element? Estimates of the relative difficulty of implementing features should be used collectively to determine the most important next steps to be taken.

4 DESIGN STUDIES

In this section, we describe the series of four design studies that led to the methodology posed in Section 3. These were conducted over the course of several years. During this time, our research collaborations grew to include an interdisciplinary course cotaught by professors of computer science, biomedical engineering, and evolutionary biology from Brown and of illustration from RISD. Several of the results pictured in this paper have come from students that began in this course and have continued on to become involved in research. Each study led to an important refinement in artist-accessible visualization design tools; collectively, they led to insight that informs the Scientific Sketching methodology presented in Section 3.

Designs created during studies 1, 2, and 3 also appear in [11], [14], and [15]. New in this treatment are more detailed descriptions of these studies and the discussion of how insights from this work come together to inform Scientific Sketching. Study 4 is presented in the most detail within this section, as it employs a methodology very similar to our proposed formalization. As such, the comparison of results obtained in study 4 to the other studies is useful in evaluating the success of design processes based on Scientific Sketching.

4.1 Study 1: CavePainting Visualizations

Design study 1 is an initial exploration into using CavePainting [13], an artistic free-form modeling tool based on 3D drawing interactions for visualization design. CavePainting provides several styles of 3D "paint strokes" (ribbons, tubes, and other shapes) with which the artist draws in space by using 3D tracker-based input. Like sketching or painting, the complexity of form in CavePainting comes directly from sweeping movements of the hand. As with other VR modeling systems based on 3D drawing-style interactions [23], CavePainting is easily understood and adopted by artists for artistic work. Thus, there are reasonable expectations that artists and designers will quickly engage with this system, but it is unclear how well these artistic tools translate to tasks in scientific visual design.

4.1.1 Hypothesis and Methodology

The hypothesis is that using CavePainting, artists will be able quickly to sketch out prototype visualizations that can then be critiqued directly in VR, eventually leading to visual insight and quick VR design iteration times.

Four artists involved in our collaborations were asked to create designs for one of the 3D fluid-flow visualization problems described in the following. Some of these were quick initial designs, whereas others advanced to more refined states. In all cases, the process began with hand-drawn sketches on paper or by searching for inspiration in paintings and photography that exhibit patterns of fluid flow. In some cases, elements of this preparatory work were scanned in and imported into VR to be used as textures in the CavePainting program.

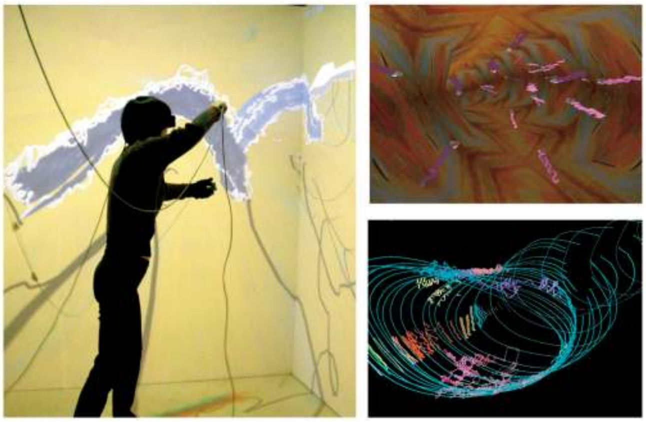


Fig. 4. Design study 1: a free-form 3D modeling tool CavePainting was used to sketch designs for visualizations directly in VR.

To guide the design task, two active scientific visualization research problems within our group were targeted. The first visualization scenario is examining blood flow through a branching coronary artery [25]. Scientists are studying the depositing of plaque on the arterial walls. To investigate this phenomenon, they need to understand time-varying pulsatile blood flow in various conditions. Variables such as velocity, vorticity, pressure, shear stress, and residence time are of importance, particularly near the arterial walls. The visual challenge is designing a visualization that highlights local relationships among these multiple variables while preserving a global sense of the time varying flow.

The second visualization problem is investigating airflow around a bat's wings during flight [27]. Scientists are studying the evolution of flight in bats and its potential implications for future unmanned aircraft design. The 3D complexity of this problem is considerable, as bats have as many degrees of freedom in wing movement as the human hand, and their flexible wing membrane changes shape drastically during flight. The challenging visual problem is depicting the complex geometry of the bat's anatomy, along with multiple variables describing the flow detail that may hold keys to understanding the formation of lift.

4.1.2 Results

Images from the work of two artists are shown in Fig. 4. In the left image, we see the VR design tool in use. An artist is working with the CavePainting system on a design for the bat problem. The right images are snapshots from within VR. The viewer is standing inside a scaled-up version of the artery model. Two different representations for flow data have been sketched in 3D by using CavePainting. Each design attempts to capture multiple flow variables, for example, velocity, pressure, and shear stress.

4.1.3 Study 1 Conclusions

While we confirmed that artists were able to quickly adopt and work with CavePainting, this study helped us establish two key limitations of the CavePainting-based approach to visualization design. First, the lack of animated views connected to data makes it difficult to evaluate designs based on flowing icons or glyphs, as in the proposed artery visualizations. Second, the lack of control over the form drawn using CavePainting makes it hard to create illustrations that look scientific. While the loose quality of Cave-painted designs is exciting for artistic purposes (it makes a hand-crafted aesthetic possible, which is rare in computer graphics), it is inappropriate for depicting scientific subjects that demand precision. Tool refinements found in the next studies and in Scientific Sketching will address these two issues.

Fig. 5. Artists designed several data-driven flow glyphs for use with the artery problem. This one, inspired by the natural forms of sea creatures, changes shape in response to both velocity and pressure as it moves through the flow.

4.2 Study 2: Data-Driven Glyph Sketching

In design study 2, a new software system was developed to incorporate a tighter connection to the underlying scientific data within the artistic design tool. The scope of visualizations was limited to the design of glyph-based flow visualizations like the ones proposed in study 1 for the artery problem. The goal of this study was to address directly the animation limitation discovered in study 1.

4.2.1 Hypothesis and Methodology

The hypothesis is that animating artists' drawings in response to real data will improve our ability to evaluate the success of glyph-based visual techniques for 3D flow visualization.

A designer works with the revised software by drawing a legend describing how a glyph should change in response to data. Based on the specification that the legend provides, the system automatically produces a visualization of animated data-driven glyphs moving through a flow volume. The artist begins by drawing several instances of a 3D glyph using CavePainting. These are then associated with specific data values by using a 3D selection technique to grab the drawing and drag it to a legend describing the variables in the data.

For example, to use a change in the geometry of the glyph to describe the variable *flow speed*, the artist would draw what the glyph should look like at low speeds and link this drawing to the slow end of the *flow speed* legend. Then, she would draw the second representation for high speeds and link it to the fast end of the legend. The system computes a 3D morph between the two representations that is used to continuously vary the form of the glyph as it moves within the flow volume. Multivariate glyphs are constructed by adding additional legends to the specification. For example, additional drawings could be used to make the color or texture of the glyph change in response to *flow pressure*. Once the specification is complete, a seeding algorithm for particle-based visualization of time-varying flows [25] is used to distribute and advect a set of glyphs through a visualization of the flow data set. This visualization is then critiqued directly in VR.

Working together with one illustration student and several of the designs posed by her peers, we evaluated this system by creating test cases targeted at the artery problem. One driving example of a data glyph that we tried to capture using the system is shown in Fig. 5. In this design proposed (here, as the initial design sketches) by illustration students in our course, an organic squidlike glyph changes shape in response to velocity and pressure as it moves through the flow.

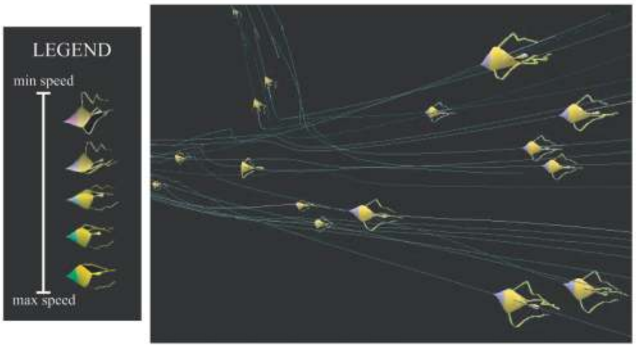


Fig. 6. Design study 2: an animated data-driven visualization sketch can be automatically created from a few keyframe glyphs drawn in 3D and attached to a data legend.

4.2.2 Results

The complexity of the motion available through this method is impressive and hard to capture in any other way. A view of the artist-created legend and resulting data-driven visualization for the squid case is shown in Fig. 6. While it is difficult to convey in the static images here, when seen in VR, designs created using this method clearly capture a sense of flow that is entirely lacking in the results of study 1.

Despite this advantage, we found significant limitations in this approach. Establishing correct correspondences between multiple drawings of a glyph composed of an unlimited number of 3D "brushstrokes" is a challenging algorithmic problem. In order to simplify the problem, our implementation required artists to keep the glyphs used in the system very simple, severely limiting their power to use CavePainting as intended. A good Cave-painted glyph would be suggested, as in traditional painting, by many tiny brushstrokes oriented in space, but the geometries that we could explore were of the form of those in Fig. 6, relatively simple geometric forms.

4.2.3 Study 2 Conclusions

While the tight connection to the data gave artists a powerful tool, it also forced them to work within a framework that often limited their ability to convey the new insights and sophisticated visual thinking that motivates our collaborations. We also discovered that these relatively large multivariate glyphs are less appropriate for flow visualization than what we had originally thought. Dense simple particles yield a much more understandable representation of flow patterns in VR.

These conclusions, together with the follow-on investigation in study 4, lead to adopting an alternative strategy of connecting to experimental data in Scientific Sketching, which avoids the constraints identified here while preserving benefits to our ability to critique designs, also observed during this study.

4.3 Study 3: Appropriate Artistic Control for Science

In design study 3, we return to another limitation identified in study 1: the inability of artists to control 3D drawing tools

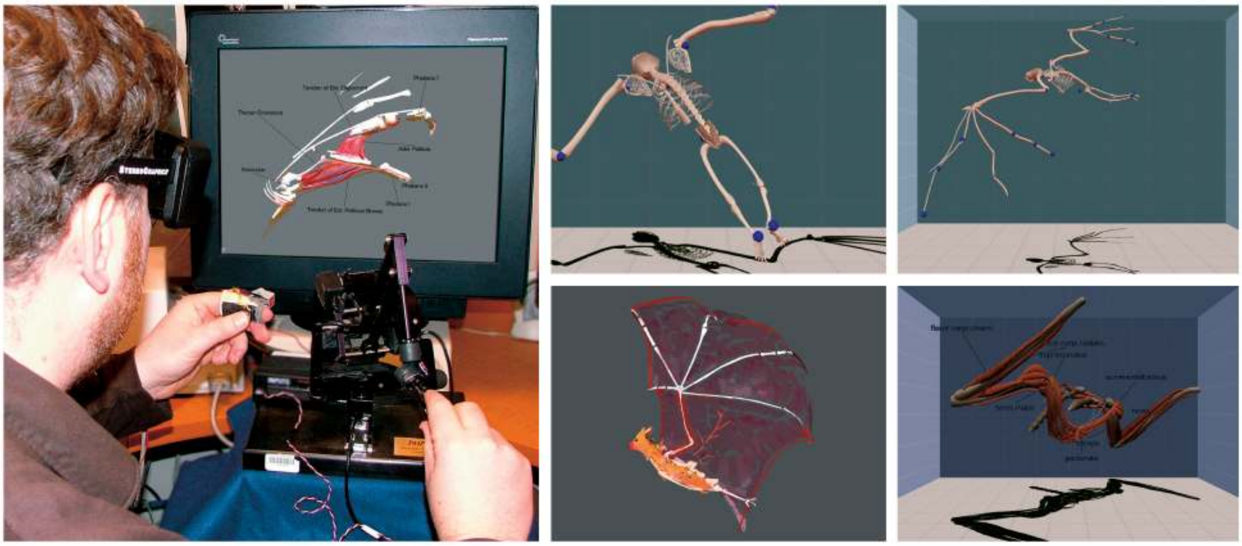


Fig. 7. Design study 3: the additional control provided by the Drawing-on-Air haptic-aided drawing interface lets artists address scientific subjects, with the necessary level of precision.

with the precision required for science. This problem has fueled several investigations into new techniques and models for understanding 3D computer input [12]. One result of this work is a more precise haptic-aided 3D drawing tool called Drawing on Air [15]. As compared to previous VR systems such as CavePainting, Drawing on Air increases control while maintaining the immediate exploratory qualities of modeling tools based on 3D drawing. Thus, it remains accessible to artists with minimal computer training but increases precision and control. In this study, we explore the use of this new tool for depicting complex scientific problems.

4.3.1 Hypothesis and Methodology

The hypothesis is that the improvement in precision seen with Drawing on Air is significant enough to let artists combine the strengths of modeling tools based on a 3D drawing paradigm with the precision required to address difficult visual subjects in science. If this requirement is met, these tools should be useful for generating finished 3D scientific and medical *illustrations*, as well as intermediate visualization designs.

Two artists within our collaborative group worked closely with us and with the evolutionary biologist leading the bat flight project to create 3D illustrations of bats posed in flight using the Drawing-on-Air tools. In some of the illustrations such as the top two in Fig. 7, drawings were created “on top of” experimentally collected bat flight data. The blue sphere markers at the joint positions in these images were positioned inside the 3D drawing system to correspond with motion-capture data collected from flying bats in a wind tunnel. The artists used these guides to create anatomical illustrations within the reference frames provided by the experimental data. Together with the evolutionary biologist guiding this project, we hypothesize that this style of 3D illustration will be superior to traditional 2D representations for several purposes, including studying which muscles are likely to be active at particular points in the wing-beat cycle.

4.3.2 Results

Significant improvements in the 3D drawing precision using this new technique were observed as compared to previous results created with tools in the spirit of CavePainting. The additional control clearly has significant ramifications for depicting scientific subjects with precision. For example, the smooth curves of the wing bones in Fig. 7 would be impossible to draw with CavePainting or similar freehand tools.

4.3.3 Study 3 Conclusions

With tools of this level of artistic control and expression, artists can combine the benefits of hand-drawn 3D modeling with the control needed to address scientific subjects. While clearly useful for 3D illustration purposes, the additional level of control is also useful for intermediate stages of design for multivariate exploratory visualization. Without sufficient control over form, the science is confused rather than clarified, visual critiques are less accurate, and scientists are less willing to engage in serious discussion of visual designs.

These conclusions shaped the formation of the VR Sketching and VR Prototyping stages of Scientific Sketching. In the VR Sketching stage, quick sketches that may not exhibit the precision seen in this study are made. These lead to the first sense of how a design functions in a VR environment. In the next stage, VR Prototyping, a more refined drawing, as exhibited in this study is used, allowing the critique to focus more seriously on the discussion of the visuals in service of the science. While the tools employed in study 1 may be sufficient for the VR Sketching stage, they fail when we desire the refinement of the VR Prototyping stage. This study establishes that we can reach the level of refinement necessary while still employing tools based on the drawing-style interactions that we believe are so appropriate for design work.

4.4 Study 4: Design via Scientific Sketching

Like the other studies, design study 4 builds significantly upon its predecessors. This study is particularly important,

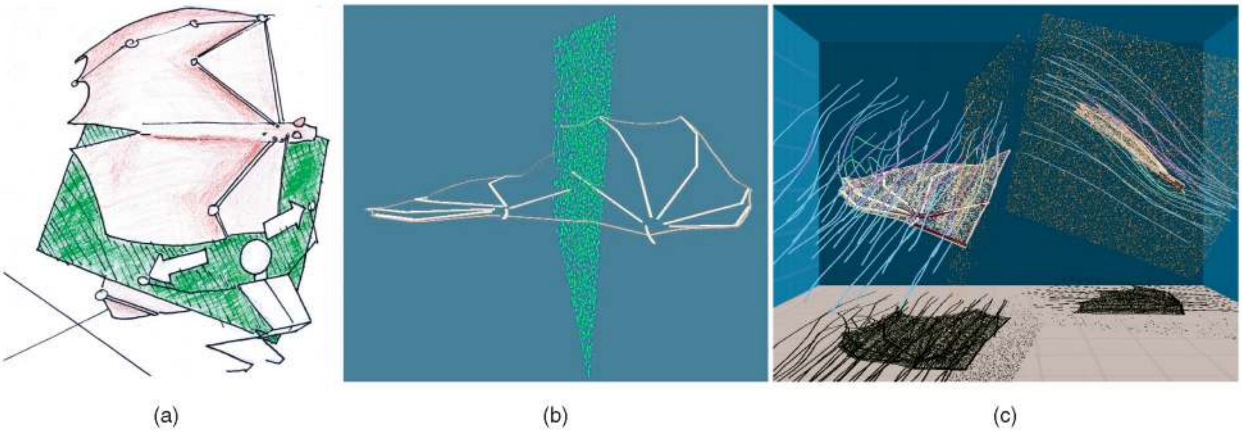


Fig. 8. Design study 4: the addition of Wizard-of-Oz interaction prototyping techniques and stop-motion animation controls enables artists to sketch the *experience* of VR and the visual artifacts. (a) A design for a cutting-mirror technique for exploring multiple bat flight data sets was proposed first on paper. (b) and (c) Then, it was refined during multiple VR sessions, in which the interactive and visual characteristics were critiqued.

because the process taken most closely reflects our current formulation of Scientific Sketching. With the advances in artists' ability to clearly represent complex scientific subjects using 3D drawing established in study 3, the key remaining shortcomings of the methodologies explored so far are the inability to represent time-varying data without thoroughly constraining the designer and the inability to capture the *experience* of VR visualization, that is, the ability to interact with one's data rather than just view it. These limitations are explored in this final study.

4.4.1 Hypothesis and Methodology

The hypothesis is that a substantial number of the time-varying and interactive properties of VR visualizations can be captured through two extensions of the tool: 1) support for stop-motion animation of data and hand-drawn elements and 2) support for Wizard-of-Oz-style interaction prototyping.

To provide a role for time-varying data, drawing on top of motion-capture markers (first explored in the previous study) is extended to support multiple frames of data. Wizard-of-Oz prototyping is implemented by adding drawing layers that can be turned on and off by using keys on the keyboard. Designs are created in such a way that during critique, a "wizard" operates the keyboard to cycle through frames of an animated drawing and toggle drawing layers on/off to simulate visual changes in the scenario that result from user interaction. Further details of these extensions to the design tool are presented in Section 5.

The resulting system was incorporated into the toolset used for teaching the course Virtual Reality Design for Science, as mentioned in the introduction to this section. The results discussed here come from the various final projects that art and computer science students prepared as part of that course. Each design went through several sessions of artistic and scientific critique and revision, as outlined in the Scientific Sketching methodology. Initial designs were created with traditional media and were critiqued in paper form, while later VR sketches and VR prototypes were evaluated in multiple collaborative VR critiques.

4.4.2 Results

Fourteen designs for VR visualizations were created as part of this study. We describe one of these in detail here, and several others are featured in the video accompanying this paper, which can be found on the Computer Society Digital Library at www.computer.org/tvcg/archives.htm. Fig. 8 shows the results from three stages of the design for the visualization technique "Cutting Mirrors for 3D Flow Visualization" developed during this study. These cutting mirrors are an interactive visualization tool for comparing multiple bat flight data sets. It is hypothesized that such a tool will be useful for comparing the flight of different species of bats and the same species performing different maneuvers. Comparison of these different situations is an important method for generating insight regarding flight mechanics and, ultimately, the evolution of flight.

Fig. 8a is an initial sketch on paper from a design storyboard for the project. During the critique, this sketch sparked a discussion about the visual effectiveness of the technique as presented. It was agreed that several changes would improve the readability of the data, and these were incorporated into the design before it was investigated in 3D. One of these changes was a move from displaying both data sets within a shared coordinate system to displaying the flight data in separate but correlated axes.

In the next stage of design (Fig. 8b), a VR sketch of the technique was created. Multiple drawing layers were used in conjunction with a Wizard-of-Oz approach to investigate the interactive scenario of placing a cutting mirror within the visualization and moving it around near the wing in order to compare a portion of the wing as seen during the upstroke to the same portion of the wing during a downstroke.

Again, the discussion at the critique identified a visual problem, also relating to the coordinates of the two visualization spaces. The strength of this version of the technique from a scientific standpoint is the ability to quickly adjust the visual to view two corresponding sections of the wing, one from each data set. The "mirror" identifies the correspondence, so as noted during the critique, the most interesting data tends to lie right along the mirror, where the closest correspondence occurs. After seeing the design within VR, team members noticed that data displayed near the mirror, although likely the most important in the display, were probably also the most difficult to see, as occlusion and additional clutter in this area complicates the view. Furthermore, the discussion identified that it would be difficult for the scientist to "step into" the data in the region of the mirror for a closer look, since there was so much visual activity in that area. A suggestion was ultimately made for the next refinement, which will treat the mirror as a book that could be opened for closer visual inspection.

The design was refined to a VR prototype (Fig. 8c) and again presented for critique. At this point, the design had advanced significantly from both a visual and an interactive standpoint in a matter of weeks. This VR prototype is far more complete than the previous VR sketch. Immediately obvious are the new streakline flow visualization elements, which are colored according to mock pressure data. Additional anatomical features are also specified, including insertion and attachment points for the primary muscles hypothesized to be responsible for wing movement during this point in the wing beat. From this more advanced visual, a scientist is able to perform mock analysis of the data as sketched out, which is a great aid during the critique.

An interesting observation was made during the critique of this project: since the coordinate space in which the data was to be visualized evolved from a simple regular grid to a space that could be cut with a mirror and then opened up like a book, several probable assumptions in the strategies for programming the original design were now no longer valid. Had the technique been implemented via programming after the first set of sketches, incorporating the later refinements would involve changing major assumptions about the data structures and rendering techniques, likely requiring large portions of the code to be redesigned and programmed again.

4.4.3 Study 4 Conclusions

By drawing on top of motion-capture data, artists created stop-motion animations that are tied to real scientific data. However, unlike the very tight data constraints in study 2, the strategy used in this study allows considerable artistic freedom in the design. We conclude that linking design sketches to data can be an important aid in capturing a more realistic view of the goal visualization, but the constraints imposed by the data must be balanced with the goal of artistic freedom. This insight is reflected in Scientific Sketching, where simple connections to data involving minimal programming is encouraged in the prototyping stage, and the gradual merger of data-driven elements with hand-drawn elements is encouraged during the advance toward implementation.

The ability to cycle through drawing layers to prototype user interactions in a Wizard-of-Oz style was also explored in this study. Prototyping these interactions allowed important design explorations that could not be captured by our previous tools. We conclude that the ability to capture these interactive scenarios is critical to design efforts targeting VR.

These tool advances lead to an ability for artists to express much more complicated visual designs, which, in turn, leads to more valuable critique sessions. The example of the likely change to data structures necessitated by changes in the visual design highlights how it is often difficult to predict design refinements until the design is seen in VR and how relying on programming to produce designs in VR can necessitate long waits between design iterations. The strategies posed in this study help maximize the impact of the evaluation during a critique while also minimizing the time between design iterations, two goals carried forward to the Scientific Sketching methodology.

5 TOOLS TO SUPPORT SCIENTIFIC SKETCHING

Additional details of the custom tools used to support the VR-based stages of design in Scientific Sketching follow. These implementations were used within design study 4.

5.1 Interactive 3D Drawing in VR

The key technology required for making "sketching" VR visualizations possible is interactive 3D drawing in VR. Building expressive and controllable modeling tools based on 3D-drawing-style input proves to be a considerable research challenge with its own body of literature and advances. See [12] for an overview.

The 3D drawing tools used in study 4 make use of the interfaces of the Drawing-on-Air system [15] and a nonhaptic implementation of the drag and tape-mode interfaces of Drawing on Air adapted to work in the larger VR environment of the Cave. Since the interfaces used to generate hand-drawn 3D models with these tools have been described in detail elsewhere, we limit our discussion in the next sections to new specific extensions to support Scientific Sketching.

5.2 Prototyping Interactions and Animation

Prototyping interactive and animated visualizations is achieved through two constructs—drawing layers and animation frames—as discussed in the following.

5.2.1 Drawing Layers

Each visual object in the VR design application exists within a particular drawing layer. As in the layers commonly found in 2D bitmap manipulation programs such as Photoshop, drawing layers can be selected, created, deleted, and hidden using a widget within the design application. Additional operations such as copying or repositioning the contents of a layer relative to other layers may also be performed.

Drawing layers bring important functionality to the problem of design for interactive VR visualizations, particularly in their ability to group a set of visual primitives and assign a visible or a hidden state to them. In anatomy-based visualizations, drawing layers may be arranged such that layer 0 contains guidelines and scaffolding useful to the designer but not intended to be viewed during the critique. Layer 1 contains bones or other anatomical context, layer 2 contains muscles, membranes, or other secondary anatomical features, and layers 3, 4, 5, etc., are used to describe variables such as velocity, vorticity, pressure, and shear stress via streaklines, icons, and widgets sketched by the designer. Interactively setting individual layers to visible or hidden allows for simulating different views that might occur within a multivariate visualization application. The question of how the addition of a streamline widget affects the legibility of the visualization can be quickly examined by drawing the widget in its own layer and toggling its display during the critique.

5.2.2 *Stop-Motion Animation*

Time-varying data and interactive scenarios described in the VR prototyping stage of Scientific Sketching are created by using drawing layers in combination with stop-motion animation. Each visual object in the design is contained within both a drawing layer and an animation frame. Only one animation frame is visible at any point in time, but multiple drawing layers may be displayed as controlled by the user. Using the example in Section 5.2.1, a design can be constructed to produce an animated sequence that displays the movement of the bones only (by advancing frames while viewing layer one only) or the movement of the bones in conjunction with velocity and vorticity values (by advancing frames while viewing layers 1 and 3). Interactive techniques may also be described in this fashion. For example, the visual changes that occur when a data probing widget is interactively moved through the visualization space may be captured using a series of hand-drawn animation frames.

5.2.3 *Interfaces*

For the designer working in VR, onscreen 3D widgets are used within the design application to control drawing layers and animation frames. These are activated from a palette of 3D menus that serve as the primary design application interface. Input is captured in VR from the six-degrees-of-freedom trackers, which are also used for drawing and modeling.

During the critique, an alternative keyboard-based interface is usually preferred. Depending on the particular design, one designer may talk through an interactive scenario while simultaneously advancing the display by using the keyboard, or more often, a team member acts as the "wizard," advancing the display by using the keyboard as the designer presents a visualization scenario. Arrow keys are used to advance and rewind the stop-motion animation, while number keys are used to toggle the visibility of drawing layers. Programmers have implemented several other simple keyboard controls (toggling the display of shadows, activating a virtual laser pointer, etc.) as needed to enhance the prototypes.

As designs advance toward implementation, programmatic access to hand-drawn designs is also useful. Properties of the visual objects that designers have drawn (for example, position, orientation, shape, texture, and color) can be accessed via programming on an individual object level or on a layer level. Thus, both an individual object and a collection of objects drawn within a single layer can be easily made to move according to data or some other programmatic control. Also useful within the programmatic interface is the ability to import data upon which designs may be drawn. For the motion-capture data of flying bats, this has been done by reading data from the disk, generating an object such as a simple sphere that may be rendered at the position of each motion-capture marker and then assigning these objects to a particular layer and a sequence of animation frames. Thus, as the frames are advanced during use, the display advances through the time-varying data and hand-drawn design elements.

5.3 Artist Accessible Color and Texture Inputs

A common refinement suggested during the critique is a change in the color scheme. To facilitate rapid exploration of alternatives, all the colors used in a design are stored within the columns of a color palette texture, which is used as a lookup table when rendering 3D geometry. Alternative palettes can be swapped in as the application is running with the press of a keystroke, and consequently, new colors will be assigned to the geometry in the scene. New palette files are automatically discovered from a special directory, where artists easily place new files, providing artists with the ability to make program-level changes to the VR design tool without assistance from a programmer.

Textures to be used as patterns on hand-drawn 3D objects or on planes interactively placed in 3D space are also loaded automatically from a special artist-accessible directory. Alpha mask textures are also supported and used often for prototyping effects similar to Interrante's "shape-via-texture" concentric shells [8], which are quite useful in depicting complex 3D forms of scientific interest.

6 ANALYSIS AND DISCUSSION

The following serves as an evaluation of the design studies and methodology with respect to the scientific understanding generated, refinement across studies, and comparison to alternative design approaches.

6.1 Gauging Scientific Understanding

Scientific understanding resulting from the design studies takes two forms. The first is domain-specific insight gained from viewing a visualization. The second is insight gained from comparative evaluation of visualization designs during the critique. As our focus is on the early design stages and expanding the role of the artist, our results are primarily of the second form, which tends to be more anecdotal.

For example, during critiques in study 4, scientists made comments such as, "Yes, seeing these variables together will help me evaluate hypothesis X much better than in the previous design," and "the display of actual numbers within the VR environment, as shown in this design, is very important, because it will help me make a quantitative comparison." Artists, in turn, described how colors and forms could be altered to increase the understanding of the data and posed ideas for new visual techniques.

It is difficult to quantify the scientific impact of this type of insight and even more difficult to compare these insights to those reached through some alternative, perhaps non-collaborative, visualization methodology. We note, however, that critiques during study 4 generated far more scientific evaluations of this form than in the other studies. We attribute this to an improved capacity to create science-appropriate designs, which leads to an improved capacity to collaboratively evaluate those designs. Thus, we believe that this methodology meets one of our primary goals, that is, increasing the role (and, consequently, the contributions) of artists in visualization design.

In the future, it may be possible to perform more sophisticated comparisons of scientific insight obtained through various visualization design methodologies. For the type of hard-to-design (multivariate, immersive VR) visualizations, which are our focus, qualitative insight analysis based on the type of open-ended protocols posed by North et al. [21], [22] may be most helpful, since the goals of these visualizations are complex and deeply rooted in application domains. A similar analysis might also apply to the more intermediate scientific insights obtained during a critique. For example, coded analysis of recorded comments made during a critique, in the style of the work cited above, might lead to more quantitative assessments of the value that artists bring to visual problems in science.

6.2 Refinement Across Studies

When viewed as a whole, the four design studies reveal an increased ability for designers, including nonprogrammers, to capture more visually complex designs. The methodology of study 1 was adopted by artists, but it is inappropriate for advanced depiction of science. The methodology of study 2 moved closer to addressing scientific concerns, but at the cost of limiting artist contributions to the process. In study 3, tool refinements advanced the potential contributions of artists by making it possible to more appropriately depict scientific subjects with design tools based on sketching-style interactions. However, the methodology and tools of study 3 still fall short in terms of an ability to capture designs of time-varying data and interactive scenarios, both of which are typical of complex VR visualization. The advances employed in study 4 address these concerns, and the resulting designs are more sophisticated from both visual and interactive standpoints, allowing team members to address additional visualization scenarios and be more precise in their critique.

6.3 Common VR Design Practice

It is useful to contrast the design tools used in study 4 to common alternatives such as quick programming, scripting, or visual programming tools. In general, these programming-based alternatives do an excellent job at capturing the visual complexity of a design and consequently provide excellent material for collaborative critique. The downside of such tools is that they have a high cost in the sense that the time taken to realize or even partially realize a design is typically much larger than the time taken to make a sketch of the design. Thus, time between iterations can be long. The other downside is that these tools are less accessible to artists and other visual experts with little programming experience. If the artist cannot be significantly involved in content creation, then the artist's role is limited to evaluation and suggestion during a critique. We believe that the more the artists become involved in serious design at the level of sketching, refining, and prototyping, the more valuable their contributions will be in addressing visual problems posed by science.

7 CONCLUSIONS

In this paper, we have presented four design studies of process and tools for collaborative design of VR visualizations and discussed how insight from these studies leads to a proposed formal methodology for collaboration, called Scientific Sketching. A primary conclusion from the series of design studies is that effective artist-accessible design tools must support quick sketch-like visual exploration, sufficient control over form to represent complex subjects in science, and an ability to capture the animated views and interactive scenarios that are critical to VR experiences. The Scientific Sketching methodology incorporates each of these elements while also drawing upon traditional design tools such as work with traditional media and evaluation via critique.

As our methodologies have evolved, we see evidence of an ability for artists to capture, without programming, increasingly complex visual designs in VR. We conclude that as our ability to design and critique more sophisticated visualizations improves, so does the additional insight that we are able to obtain through collaboration with artists. As we and many artists and researchers before us have demonstrated, artist-scientist collaboration has great potential. In looking toward the future, we believe that questions of methodology are of great importance in learning how we can best leverage the visual expertise of our collaborators within the context of driving scientific questions.

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