Virtual Reality Data Visualization for Team-Based STEAM Education: Tools, Methods, and Lessons Learned

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Abstract. We present a discussion of tools, methods, and lessons learned from nearly ten years of work using virtual reality data visualization as a driving problem area for collaborative practice-based STEAM education. This work has spanned multiple universities and design colleges. It has resulted in courses taught to both students majoring in computer science and students majoring in art or design. Within the classroom, an important aspect of our approach is including art and design students directly in real scientific research, often extended beyond the computer science aspects of data visualization to also include the research of collaborators in biology, medicine, and engineering who provide cutting-edge data visualization challenges. The interdisciplinary team-based education efforts have also extended beyond the classroom as art and design students have participated in our labs as research assistants and made major contributions to published scientific research. In some cases, these experiences have impacted career paths for students.

Keywords: STEAM, art, science, computer science, education, virtual reality, visualization.

1 Introduction

Relevance to STEAM Learning. As we look toward the future of education in the 21st century, the importance of a strong STEM (Science, Technology, Engineering, and Mathematics) curriculum is unquestioned. Building upon this foundation, we join a growing chorus of educators and researchers in advocating for strong STEM + Arts or "STEAM"-based education. There are many possible benefits to combining STEM with Arts, and, in our experience, there is a great deal of interest in this combination from both the arts and scientific communities. However, the details of how to most successfully accomplish STEAM integration in the classroom as well as the details of how best to utilize the exciting new technologies that often characterize STEM fields remain underexplored

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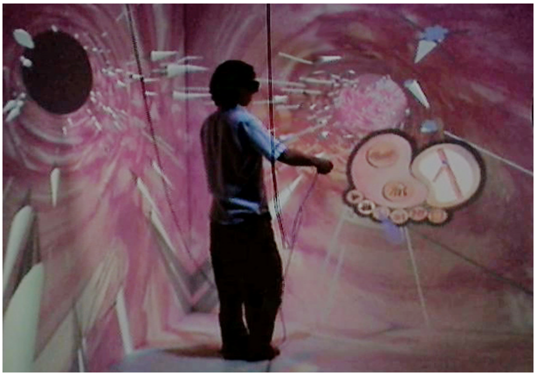

Fig. 1. A CAVE-based VR visualization of simulated blood flow through a branching coronary artery. The visualization and user interface were designed by a small group of art and computer science students as the final project for their course.

and underreported. In this paper, we present a discussion of tools, methods, and lessons learned from nearly ten years of work combining STEM with Arts for education, and in many cases extending beyond the classroom and into research.

We have used virtual reality (VR) technologies as a platform for much of this work. Since VR utilizes advanced technology and computing to create an environment that engages the senses (visual, auditory, haptic) in unique and exciting ways, we have found that it is a particularly engaging platform for students, regardless of whether their background is primarily in a STEM field or in the Arts. Thus, we believe VR may be uniquely positioned as a very powerful tool to facilitate STEAM education.

Bringing VR into the classroom in a way that works for students of all backgrounds also poses considerable challenges, both technical and methodological. We have refined a series of approaches and tools to use VR for team-based STEAM education and are keen to elaborate on a number of the ideas in this paper. Our approach is based in our core area of research, scientific visualization, which can be summarized as using computer graphics and human computer interfaces to understand scientific data, either in an effort to facilitate new discoveries based on the data or to explain data-driven insights to others. We have also found it useful to engage with a number of methods used in traditional art education, such as critique. The following sections provide some additional background on these core concepts.

Visualization. Figure 1 provides a motivating example of scientific visualization in virtual reality. The problem addressed by the visualization is to understand complex patterns in time-varying, three-dimensional fluid flow vector fields; in this case, the data come from a high-end computational simulation of blood flowing through a branching coronary artery [1]. In order for scientists to understand this complex phenomenon they must make sense of patterns across several 3D data fields at once: velocity, vorticity, pressure, shear stress, and so on. Since each of these data fields also changes over time, the amount and spatial complexity of the data make them extremely difficult to interpret, and nearly impossible to interpret without some visual aid. We use VR to create data visualizations for this problem because the increased spatial understanding that is achieved with head-tracked immersive displays can be extremely valuable for analyzing spatial relationships. But, designing effective VR visualizations is extremely challenging, and this is where a STEAM-based approach can be so valuable – not just for the students, but also for end product. For example, Figure 1 is the result of a small group (1-2 computer science students and 1-2 art students) final project for the course *Virtual Reality Design for Science*, taught and cross-registered at Brown University and the Rhode Island School of Design. For a computer scientist looking at this environment, the attention paid to the visual aesthetic of the visualization and user interface is immediately obvious and radically different than the norm. Even the menu (the organic shape to the right of the user's hand) was designed carefully and implemented using hand-painted imagery. The flow data are conveyed using 3D multi-variate glyphs that reshape and reposition themselves interactively in response to the flow data. Again, demonstrating a departure from the norm in computer science, these glyphs were designed with specific reference to forms in nature that respond to flow, e.g., the tentacles of a squid as it propels itself through water. This attention to shape, color, texture, form, narrative, and metaphor is one of the most exciting trends that we see resulting from STEAM efforts and has clear benefit to all who are involved in such collaborations.

Critique. We have found that using virtual environments for STEAM education also requires teaching methodologies that are mostly unfamiliar in computer science but are part of a strong educational tradition in art and design. One example is the use of critique, which we have now adopted in both the classroom and research labs. In the classroom, we have utilized critique in a traditional form. For example, class sessions often begin with students hanging drawings, printouts, or other artifacts from their work since the last meeting on the wall, and we follow with a traditional critique-style discussion of the work. During critique we discuss and teach about the same type of concepts one would encounter in an art class (e.g., shape, color, texture, form, narrative, metaphor) but these are discussed and evaluated with reference to the goal of moving from data to insight. Often, these group critique sessions are extended beyond the traditional classroom space and instead conducted directly in virtual reality environments, such as the CAVE facility pictured in Figure 1. As the problems we discuss often involve interpreting biological or other datasets, scientists from relevant disciplines have often joined these critique sessions as well. We have found this to be invaluable. In fact, the methodology has been so successful in our experience that we have begun to adapt critique to computer science classes, from first-year algorithms to graduate research seminars.

Collaboration. STEAM-based learning is interdisciplinary by nature. We believe one of the great benefits of the approach is that each student who think of

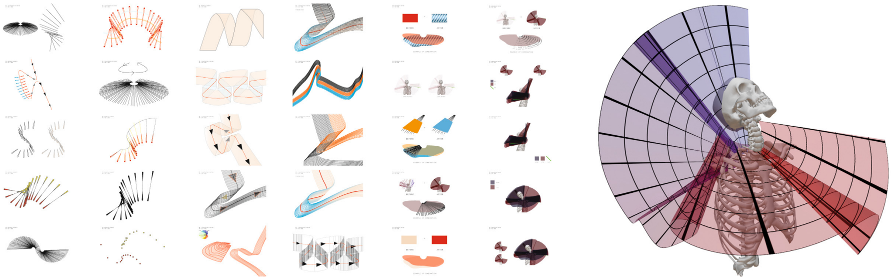

Fig. 2. Left: A selection of representative images from more than 300 sketches created by a graphic design student to explore the use of color, texture, form, narrative, and metaphor in depicting the biomechanics of the spine. Right: One frame from the resulting animated visualization of the data.

him/herself as belonging to a core STEM field becomes a bit more of an artist. Likewise, each artist becomes a bit more of a scientist, technologist, engineer, or mathematician. This isn't to say that these students will necessarily switch disciplines or become an expert in a new discipline, but to facilitate collaboration, students in STEM and Art fields need to learn to speak a bit of each others' language, only then than successful collaborations happen. In our courses and research this type of collaboration takes center stage. We teach students how to work across STEM and Arts disciplines as a starting point, but since the data understanding problems that are our focus involve real, active scientific research, both groups of students also find themselves in the same position of needing to understand how to speak the language of a third group of collaborators, typically from biology, medicine, or some related discipline. This is an excellent skill to develop, and, in the classroom, it helps us to focus on a problem and puts all the students, regardless of discipline, in a similar situation of needing to consider this third party as the user or client who will evaluate the ideas they develop.

2 Methods and Tools

One thing that has enabled our efforts to be successful is the new software tools we developed specifically to support collaboration across disciplines. Indeed, developing these tools has itself become an important area of research. Here, we describe a series of tools and approaches that we have used in the classroom and our research based around the concepts of sketching and prototyping.

2.1 Graphic Design and Traditional Prototyping

Sketching is a staple in arts education and is one of the most powerful design practices that has ever been invented. STEM education can learn from this. In computer science, for example, we find that students tend to be so excited to start programming that they jump right into the mode of implementing a new

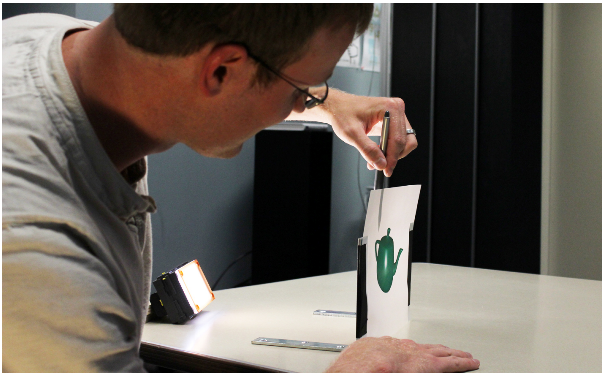

Fig. 3. A graduate student presents an interactive "sketch" of a new user interface idea

idea before it is fully thought out. Unlike sketching, programming is very time consuming; thus, there is a real danger of leaving important design refinements undiscovered when we jump right into programming. This is one concept that we try to teach. Borrowing from the arts tradition, we have found that sketching is an extremely effective method for demonstrating this to students.

To illustrate this, Figure 2 shows an example from our recent research on visualizing human spinal kinematics [2]. The selection of images on the left were created using Adobe Illustrator by a MFA student studying graphic design. At one point, this student generated more than 100 concept sketches in this style in a single week. Her goal was to explore the visual possibilities for how to depict the change over time in the instantaneous axis of rotation for the skull relative to the torso during a head rotation exercise. She refined the use of texture, form, color, and more through these sketches in order to visually emphasize the folds in the 3D surface swept out by these axes over time – our collaborators believe these folds correlate with neck pain, but they have never been analyzed before because it is so challenging to do a 3D analysis of these data. At the end, the goal is not a sketch but instead a data-driven computer graphics visualization. For this example, one frame from the 3D animated visualization result is shown in Figure 2 right. We find that even traditional paper and pencil sketches can be useful for this design and prototyping work; however, we next describe several extensions to the idea of sketching that can be even more useful and are particularly engaging for students.

2.2 Sketching User Experiences

Figure 3 demonstrates how our approach extends beyond traditional sketching to include "sketches" of user experiences. This is critical when the target medium in VR, since the experience of being in an immersive environment cannot really be captured on paper. Our approach draws heavily upon Buxton's notion of sketching user experiences [3]. For example, in Figure 3, a student acts out a

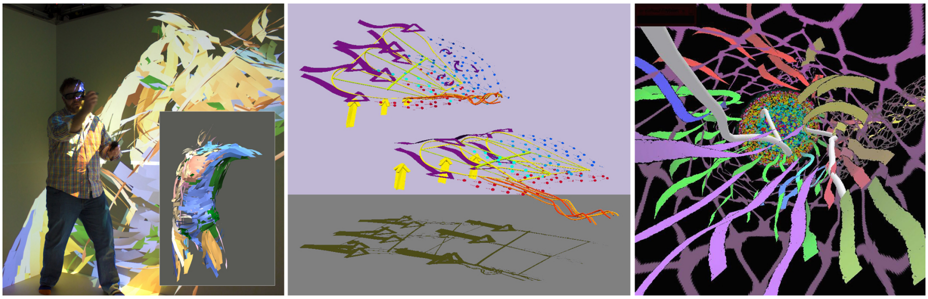

Fig. 4. New user interfaces make it possible to create virtual reality environments simply by sketching in 3D space using a tracked 3D input device

"sketch" of a user experience he has designed as part of a class assignment. He uses a flashlight, a pen, and a picture printed on a piece of paper to demonstrate how it would feel for a user to work with his idea for a new collapsable pen device that provides haptic feedback as it is inserted past the depth of the screen into a virtual world. The shadow of the pen substitutes in this sketch for a virtual pen that he proposes to program using 3D computer graphics. This physical prototyping method enables the class to explore and critique the user experience much more quickly than would be possible if virtual reality programming were required. Students in our courses have used short movies, modeling clay, paperclips, and even helium-filled balloons to sketch user experiences.

2.3 Sketching in Virtual Reality

Figure 4 shows work with the CavePainting virtual reality system [4], which has been used to support artists and designers in both coursework and research [5,6]. This is an engaging way for artists to create in VR without programming (see 3D gesture sketch of a human torso on the left). It can also be used as a 3D prototyping tool. The 3D sketches in the center and right were created by hand in virtual reality by students and depict their ideas for how multivariate fluid flow data (velocity, vorticity, pressure, etc.) could be represented in a virtual reality data visualization. This tool enables artists and designers with no knowledge of programming to design and create directly in virtual reality. In courses, this is critical because it gives artists an entry point to develop custom virtual reality applications, an opportunity that has previously only been available to advanced computer science students.

3 Next Generation Tools and Current Research

The interactive system called "Drawing with the Flow" [7] pictured in Figure 5 begins to address one of the limitations of our prior methodologies. Although we found sketching to be an exceptional entry point for bringing STEM and Arts

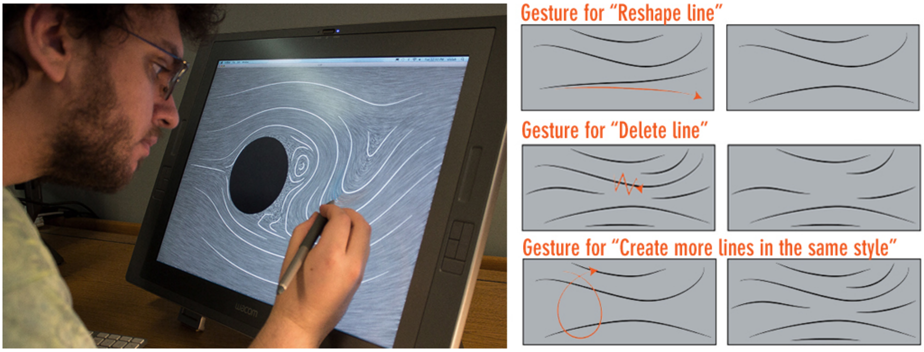

Fig. 5. Extending the productive uses of sketching described earlier, new tools developed through our research make it possible to sketch "on top of" data

together, the sketches discussed up to this point are not accurate with respect to the underlying scientific data. Thus, although they do provide excellent material for discussion and critique, the critique can only go so far until the ideas represented in the sketches have been implemented in an data visualization system. In contrast, the system pictured in Figure 5 is designed such that the user sketches on top of a data canvas. The data in this example describes a 2D flow field. As the user sketches a curve to depict flow lines in this field, the system interprets that sketch and rectifies the line that was drawn so that it remains as close as possible to the original while also staying true to the data. To the user, the result is that after sketching a flow line, he sees the line slowly morph into a line that is valid with respect to the underlying data. In this way, a number a visualization styles can be quickly explored (e.g., visualizations that use flow lines of different lengths, varying density, and so on) but at any point in time, the drawing on the user's screen is accurate with respect to the underlying flow data. The tool is in essence a step toward something like Adobe Illustrator, but for scientific data. We are now extending this concept to work with a variety of other data types and display environments. We believe the resulting tools will open up additional avenues and support for STEAM education.

4 Discussion

We have learned many lessons about how to include virtual reality technologies in new courses and research. Our focus has been on data visualization problems, and we believe this is a rich and productive focus area for STEAM education. Certainly, artists and designers can bring exciting new ideas to these problems, and solutions are often extremely exciting from the standpoint of the STEM concepts involved. The sketch-based tools and approach that we describe above has been a key to the success of our efforts, with one of the main reasons being simply that it makes doing real work (e.g., creating new visual environments) with VR technologies accessible to students trained in the arts. These methods also seem to teach students from STEM backgrounds an aspect of Arts education that can be seen as directly relevant to their work.

Reflections on Interdisciplinary Collaboration. Interdisciplinary collaboration is essential to all of the work reported here; thus, in addition to advocating for STEAM-based education, we hope that this report also serves to make explicit some of the fundamental benefits of this type of collaboration, especially with respect to the doors that it can open for students. As mentioned earlier, data visualization provides a particularly interesting platform for teaching and demonstrating this type of collaboration as it can often require involvement of not just artists and technologists but also "domain scientists" who act as the end users of the tools and techniques developed. Our students seem to benefit greatly from this experience. A graduate of the RISD design program recently reported, "The collaboration between science and art is exactly what my art is about... Much of the abstract work that I have been creating since my last few years at RISD is, in part, inspired by the work that we did in the Lab at Brown."

5 Conclusion

There are many benefits to STEAM-based education, but there are also important challenges relating to bringing together interdisciplinary groups and developing workflows that engage students from both STEM and Arts backgrounds. We believe virtual reality and related technologies can provide an exceptional platform for STEAM education, but our experience suggests that new tools and methodologies are required, especially when the goal is to support collaborative teams in the classroom. We have described several of the most important tools and methods we have adopted to make this work; many of them relate to sketching, which is perhaps not surprising since it is such a fundamental design activity. We encourage educators to think creatively about how sketching can be reinterpreted and integrated into classroom exercises and activities, especially when working with advanced visual technologies, such as VR. We have that doing so can completely change the classroom dynamic for STEAM education; it levels the playing field, empowering artists to create in virtual reality environments, while also teaching science students how to engage with core concepts in arts education. We see a profitable future in continuing to advance and disseminate these tools; when they are combined with methodologies, such as teaching with critique and interdisciplinary collaboration, the result can be a powerful approach to STEAM-based learning.

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