A User Study to Understand Motion Visualization in Virtual Reality

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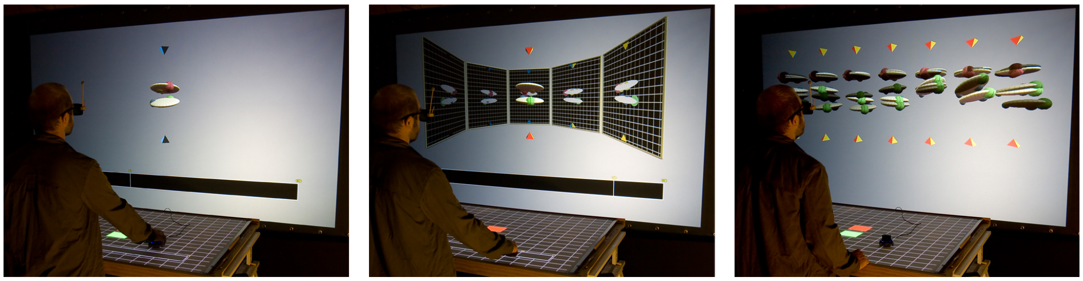

Figure 1: Three visualization designs for conveying motion data for two “bumpy discs” that rotate, translate, and eventually collide, an abstraction of data analysis scenarios encountered in biomechanics. **Left:** *Interactive Space, Animated Time* – A 3D input device controls scene rotation; the time dimension is controlled automatically via animation. **Center:** *Static Space, Interactive Time* – The scene does not move but 3D projection planes are included to facilitate spatial judgments; time is controlled interactively by touching a widget on the table. **Right:** *Animated Space, Static Time* – Space is animated by automatically rotating the objects back and forth; time is presented statically through a timeline of key 3D poses of the motion, reminiscent of stroboscopic photography.

1 Introduction

Studies of motion are fundamental to science. For centuries, pictures of motion (e.g., the revolutionary photographs by Marey and Muybridge of galloping horses and other animals, da Vinci’s detailed drawings of hydrodynamics) have factored importantly in making scientific discoveries possible. Today, there is perhaps no tool more powerful than interactive virtual reality (VR) for conveying complex space-time data to scientists, doctors, and others; however, relatively little is known about how to design virtual environments in order to best facilitate these analyses.

In designing virtual environments for presenting scientific motion data (e.g., 4D data captured via medical imaging or motion tracking) our intuition is most often to “reanimate” these data in VR, displaying moving virtual bones and other 3D structures in virtual space as if the viewer were watching the data being collected in a biomechanics lab (e.g., see [1]). However, recent research in other contexts suggests that although animated displays are effective for presenting known trends, static displays are more effective for data analysis [2]. Applied to the problem of analyzing motion, it could well be the case that VR environments that freeze time, for example, using depictions of motion inspired by the traditional stroboscopic photography of Marey, could enhance users’ abilities to accurately analyze motion. Also, outside of virtual reality, it has been shown for scenes that are complex spatially but do not include motion, that various combinations of automatic camera control, static imagery, and user interaction dramatically affect the utility of 3D data visualizations [3]. Thus, as we strive to harness the power of virtual reality as a data analysis tool, fundamental questions remain as to how to best visually depict and interact with motion datasets, especially in situations where the data require intricate analysis of both spatial and temporal relationships.

Visualization Design Conditions

SPACE \ TIME	Interactive	Animated	Static
Interactive	I_S,I_T -interactive camera -interactive timeline	I_S,A_T -interactive camera -animated timeline	I_S,S_T -interactive camera -multiple times in a single scene
Animated	A_S,I_T -auto camera movement -interactive timeline	A_S,A_T -auto camera movement -animated timeline	A_S,S_T -auto camera movement -multiple times in a single scene
Static	S_S,I_T -multiple camera views in a single scene -interactive timeline	S_S,A_T -multiple camera views in a single scene -animated timeline	S_S,S_T -multiple camera views in a single scene -multiple times in a single scene

Figure 2: Taxonomy of motion visualization design decisions.

To investigate the space of visualization design permutations we introduce a taxonomy of fundamental design variables for depicting these data. Based in this taxonomy, a formal user experiment is presented that evaluates the strengths and weaknesses of each combination. Finally, based on the results of this experiment and our own insights from iterative visualization development, we present a set of guidelines for designing virtual environments to depict motion.

2 Taxonomy of Motion Visualization Design Space

Consider using VR visualizations to analyze the motions of complex anatomical joints, such as understanding coordinated motions of multiple vertebrae in a neck kinematics study. It is critical to be able to analyze spatial relationships displayed in the VR scene, such as the proximity between multiple high-res 3D bone geometries, and it is just as critical to understand how proximity (and/or other quantities, e.g., pressure, velocity) change throughout the course of a motion. Figure 1 illustrates the types of visual and interactive design decisions that face developers of virtual environments. We have designed the two “bumpy discs” motion scenario shown as a representative abstraction of the types of patterns found in scien-

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tific studies of motion. Notice, there are several fundamental design choices that extend across both the space and time aspects of the data. We characterize these choices as involving either interactive user control, automatic animation, or static presentation, where each option can be applied to both space and time. Together, these form a taxonomy described by a matrix of fundamental design decisions for representing motion data.

In this taxonomy matrix, shown in Figure 2, there are three fundamental design choices regarding how to represent the time dimension of the data: (1) The user can have interactive control over time, e.g., via a knob or slider by which to advance the view forward/backward in time. (2) Time can be animated, with motion replayed in a loop. (3) Time can be shown statically, with multiple snapshots displayed in a single scene.

The space dimension has three analogous options: (1) The user can interactively control the camera, allowing for spatial judgments to be made from multiple viewing angles. (2) Automatic camera rotation can be used to rock or orbit the camera around the scene to create motion parallax. (3) A smart stationary camera position can be set and additional visualization widgets can be used to enhance depth cues (e.g., the ExoVis technique [3]).

3 VR Motion Visualization Experiment

Through iterative development we created an implementation for each row and column of the design matrix. Two input devices were used, a 6-DOF SpaceNavigator device and a multi-touch table. For the *Interactive Time* design, an touch timeline was placed at the front of the touch table. Designs with the *Animated Time* dimension featured motion playing automatically in a loop. In the *Static Time* designs, an even sampling of key frames was depicted by both overlying tinted keyframes along with horizontal separation to avoid excessive cluttering. For the *Interactive Space* design, users could rotate objects around their local vertical axis (1-DOF) by twisting the SpaceNavigator. In the *Animated Space* designs this same rotation motion was presented by automatically rotating the objects. Finally, the *Static Space* designs made use of the ExoVis[3] technique that introduces additional viewpoints projected onto smartly placed planes in order to depict multiple viewpoints simultaneuously.

Using the "bumpy discs" abstraction shown in Figure 1, a database of motions were generated algorithmically to emulate the types of data analyses tasks typical in scientific visualization. In these motions, the large protruding feature points (red on the top disc, green on the bottom disc) were precisely controlled to collide with the opposite disc an exact number of frames apart.

To evaluate the role interaction, animation, and static presentation have on VR motion visualizations we conducted a user study experiment. We used a 3x3 within-subjects experimental design with one missing cell for the Static Space, Static Time condition, which proved too complicated to implement in a controlled manner, and the following independent variables: design choice for time (Interactive Time, Animated Time, Static Time) and design choice for space (Interactive Space, Animated Space, Static Space). A set of 24 "bumpy disc" motions were used in the study. Each participant saw these same 24 motion sequences displayed in the 8 different visualization designs, with the order randomized for each presentation combination.

The motion analysis task users performed included two parts: first, detecting collisions of the two highlighted features (one shown in red on the top disc, and one in green on the bottom disc) with the opposite discs, and second, indicating which feature point was the first to collide by touching the appropriate button (colored red or green) on the touch table.

Participants were evaluated on two dependent measures: the mean time taken to complete the task and their accuracy, measured by the number of errors made. The results for each of the 8 design combinations is shown in Figure 3

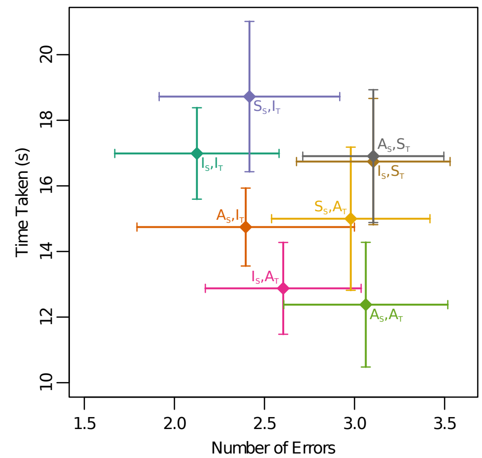

Figure 3: Each of the 8 visualization design conditions plotted in terms of time taken and number of errors. Error bars are +/- 2 SE.

4 Design Guidelines and Conclusion

Intuitively, the "best" visualization designs should appear in the lower, left corner of this plot. For scientific analysis, we typically prioritize accuracy, so we may favor designs that are plotted toward the left a bit more than those plotted toward the bottom. With this in mind, a number of the visualization designs seem promising. The most accurate combination is the one combining Interactive designs for both dimensions, but comes at the cost at the cost of slightly more time taken. Interactive Time appears to be the most critical design choice as all the combinations containing this element perform very well. However, Interactive Space, Animated Time also looks as though it may exhibit a strong combination of accuracy and speed. From the results of the experiment we suggest the following design guidelines:

- When possible, provide users with direct control of the time displayed in the visualization via an Interactive Time design.
- Animated Space, Interactive Time is likely to be the preferred design due to the faster speed of analysis, but the other Interactive Time designs are likely to be just as accurate.
- Static Time designs should be avoided, at least in generic cases that are not highly tuned to a specific analysis problem.

Together with other insights generated through the work, we believe these design guidelines can be useful in directing VR developers toward more effective presentations of motion data.

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