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Interdisciplinary Scientific Visualization

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Visualizing Self-Tracked Multivariate Time Series Data to Infer Sleep Cycle Patterns

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ABSTRACT

We present a novel technique for visualizing self tracked personal sleep data. We affirmed the success of an iterative prototyping process utilizing input from experts in the field and familiar analogs for visualization design in creating visualizations of multivariate time series and ordinal self reflection data that are intuitive and communicative. Our results show that these visualizations will aid sleep clinicians in gaining insight about a patient and subsequently motivating the patient to act on their recommendations.

1 INTRODUCTION

Our research lies at the cross section of scientific visualization, human-computer interaction, personal informatics and sleep science. By utilizing the closed feedback loop developed by SleepCoacher towards designing user-friendly visualizations for personal informatics data we can help sleep clinician generate recommendations more efficiently and improve the utility of personal informatics applications.

SleepCoacher SleepCoacher[2], was a sleep study conducted by our collaborators in 2015 using self tracked data. While many sleep tracking apps exist, such as [3], SleepCoacher was the first to explore the feedback loop between personal informatics and domain experts. In this process data was collected from the users using the SleepCoacher app, then put through an analyzer that calculated correlations which was then shown to sleep clinicians who measured impacts and delivered recommendations back to the users. This study's success is measured by the recommendations generated from the self-tracked data. Most sleep tracking apps give an attempt at visualizing the user's data and auto-generating recommendations, but it is rare that these match recommendations generated by domain experts. Because of this, our research focuses on visualizing this self-tracked sleep data in a way that communicates information to a sleep clinician in the best possible way, aiding them in making efficient recommendations. The initial visualizations created from that data were based on traditional actigraphy, the widely accepted method of viewing sleep measurements [1], and displayed just 5 of the key data points though SleepCoacher collected many more for each user each night. We found that these visualizations were not sufficient in aiding sleep clinicians with their recommendations, and believe a similar closed feedback loop to be a good solution for optimizing how this data is visualized and communicated. Our goal was to create visualizations that not only display all of this data, but scale in a way that promotes comparison and communicates trends.

Hypothesis Sleep Clinicians will create more effective insights and recommendations from visualizations of multivariate time series and ordinal self-reflection data designed in collaboration with a domain expert.

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2 METHODS

2.1 Data Processing

The data we received from SleepCoacher was processed using a python script that extracted the sleep types present for each 15 minute segment of sleep. The basic sleep types we looked at are no sleep (awake), normal sleep, oversleeping, naps, and early awakening. The noise and movement data received was sensor data taken every minute we used a median absolute deviation test to extract abnormally high values in three categories: noise anomaly, movement anomaly, and noise & movement anomaly. The visualizations were then built in d3.js and hosted on a web server for easy access.

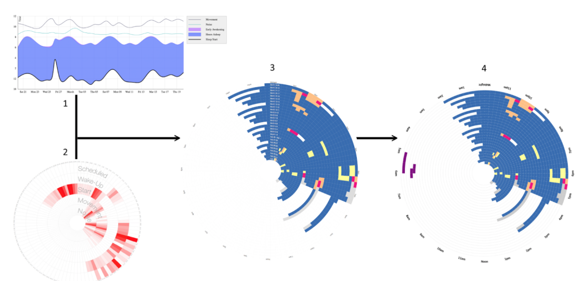

Figure 1: Iterative Visualization Prototyping.

2.2 Iterative Prototyping

In an initial meeting with our collaborator we established a set of introductory design requirements that these visualizations must cover to be of use to a sleep clinician. These included clearly showing the time spent in bed and how that relates to time spent asleep, number of awakenings, and general sleep and wake times. He is really looking for the consistencies within a patient's sleep patterns and what techniques work and don't work specifically for that patient. Additionally he is looking for a visualization simple enough for a patient to understand.

We created numerous prototypes over four iterations using feedback from a domain expert and collaborator to change, update and refine our strategies at each iteration.

The first iteration involves two separate strategies. One (Figure 1 vis 1) is based on traditional actigraphy a stacked area chart showing the data points for each night. This proves useful for displaying hours slept each night and varying sleep and wake times. Additionally its simplicity scales quite well. The second strategy (Figure 1 vis 2) involves a radial heat map showing concentrations of each quantity at each time of day. The appealing aspect of this from our collaborators point of view was its analog to a familiar household object the clock. This strategy scales perfectly and is especially useful for finding larger trends but does not show fine grained details about individual nights of sleep.

The second iteration (Figure 1 vis 3) combines many of the positive aspects of the first two prototypes taking the form of a radial stacked bar chart. This visualization portrays each day as its own concentric circle, lined up by time of day and with more recent days shown towards the outside of the circle. Each circular bar is split into 15 minute segments and these segments are color coded by type of sleep.

A noticeable shortcoming of this last iteration was its lack of a clear separation from one day to the next and the fact that adding one would inevitably split a sleep segment, so we pivoted to a spiral design (Figure 1 vis 4). This design kept the radial clock face analogy while retaining the linearity of time. To the best of our knowledge, a spiral design has never been used to visualize personal informatics data.

Figure 2: Final Visualization of Self Tracked Multivariate Time Series Data (left) and Final Visualization Including Ordinal Self Reflection Data (right).

The final spiralized block chart (Figure 2 left) has a number of interaction components, with the ability to highlight individual segments to show the date and hours slept on that date.

The final visualization incorporating ordinal data (Figure 2 right) utilizes an opacity-based filtering mechanism. This interaction highlights sleep segments in which selected keywords are present or segments that were rated above a certain threshold the threshold shown in Figure 2 (right) is 0.97.

3 Evaluation

3.1 In Person User Study

We conducted an in-person user study with a domain expert where we asked him to explore the visualization and describe his steps using a think aloud technique. He found the keywords to be especially compelling, commenting: I see every person as an individual, not just biologically but behaviorally and explaining that these keywords and their interactions with sleep segments show a lot about the individuals habits and tendencies, and aid dramatically in providing a recommendation. while simulating a patient consultation he leaned on the visualization quite heavily in explaining certain phenomena and his recommendations, commenting that this visualization would be of huge help in motivating patients to change their behaviors one of his most difficult tasks.

3.2 Survey

The second part of our user study involved evaluated via survey by three domain experts. This survey contained training tasks, likert scale questions and areas for feedback both on specific components and more generally. The survey acted as a comparison of three different types of visualizations each shown with the same three datasets. The types compares were (1) The original visualization used by SleepCoacher, (2) A visualization of the tracked multivariate data using our method (figure 2) and (3) A visualization mapping ordinal self reflection data onto multivariate data using our method (figure 3). The results of our survey (Figure 4) show that

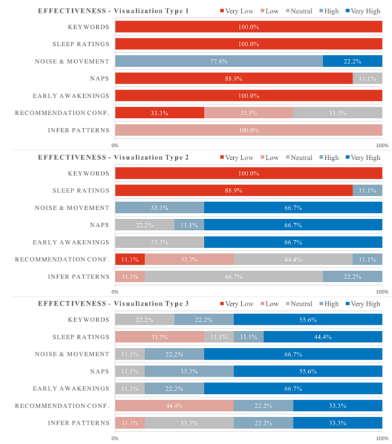

Figure 3: Survey Results

the third visualization type was by far the most effective at communicating information and generating insights, and was rated most likely to be used with patients. The second and third visualization types required the least amount of time to generate insights, and this first was least likely to be used with a patient.

4 Conclusion

Our visualization method that included ordinal data was consistently rated highest in evaluation by domain experts. This affirms not only our hypothesis and iterative process, but also the importance of working with domain experts in visualization practice.

Future Work Given that the iterative design process has no end the user study with our collaborator generated additional feedback about their domain-specific design requirements. This includes:

- adding intervention points to the visualization showing where an intervention was made and allowing the clinician to evaluate its effect
- adding a focus+context view allowing the user to zoom in on segments of the data
- posting average start and wake times across the visualization

Broader Impacts These visualizations can help sleep clinicians generate better recommendations much quicker and also aid in motivating these patients to translate their recommendations into action making their time more efficient and allowing them to help more patients in a more beneficial way. Additionally the process affirmed through our research can be extended to personal informatics data of all types and domain experts in any field.

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Interactive Visualization in Virtual Reality of T_2^* Measurements of the Anterior Cruciate Ligament More Beneficial than Desktop Environment

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ABSTRACT

We determine that a volume renderer in virtual reality is both easier to use and more useful for exploration of the healing process of the anterior cruciate ligament than a volume renderer in a desktop environment. Additionally, we present a new visualization method for separable 2D transfer functions, where the 2D transfer function is represented as a surface which changes in real time through user interaction. We evaluate our findings through a qualitative user study with our orthopaedics collaborators. Our results show that our collaborators find it easier to gain insights quickly using the virtual reality tool, but did not find the 2D transfer function visualization particularly helpful.

Keywords: Virtual reality, human-computer interaction, transfer function design, anterior cruciate ligament, volume rendering.

1 INTRODUCTION

Anterior cruciate ligament (ACL) damage leads to developing a higher risk for osteoarthritis in the knee. Current methods for repairing ACL injury include surgical grafting and scaffolding. Scaffolding, a non-surgical technique, could help minimize risk of the onset of osteoarthritis. To determine if scaffolding will yield these results, orthopaedics researchers currently compare the two methods in animal subjects. Testing of these methods in animals involves removing the healing ligaments to stretch them and test their integrity. Reasearchers are exploring the use of magnetic resonance imaging (MRI), an in-vivo imaging method, for future testing of ligament integrity in human patients.

Biercevicz et al. [2] have found that T_2^* measurements of the ACL from MRI act as predictors for the strength of the healing ligament. Our collaborators currently use histograms and colormapped 2D slices of their data to visualize the spread of T_2^* in the ACL (Figure 1). Our work gives orthopaedics researchers the opportunity to explore ACL datasets both more intuitively and in real time, unlike the current 2D imaging methods. Using our VR tool, researchers learn more about the healing process and the effects of different healing techniques. While our visualization is tested on animal data, in the future human patient data can be used.

To expand upon our visualization method in VR, we include a novel user interface for 2D transfer functions. Transfer functions are maps that take volumetric data to a 3D output with color and opacity values. Two-dimensional transfer functions encode gradient information as well as raw data values. Our visualization represents a 2D transfer function as a surface. This surface changes in both shape and color as the user edits the 2D transfer function using standard widgets. The goal for the visualization component of this work is to provide a pilot study of ways to improve user interface design for exploring transfer functions.

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We hypothesize that:

1. Orthopaedics researchers will find the VR tool both easier to use and more useful for their work than the desktop tool.

2. Our visualization of the 2D transfer function will make 2D transfer functions both easier to use and more useful.

When is VR beneficial for medical data analysis? To our knowledge, most volume rendering tools for medical data are made for desktop use. We seek to answer this open question in part by showing that VR is the more appropriate medium for initial data exploration of T_2^* spread in the ACL.

How can user interfaces for interacting with transfer functions be made more intuitive? This is an open problem in the volumetric rendering community [7]. As transfer function dimensionality increases, so too does the complexity of its corresponding user interface. This learning curve hurts the accessibility of these more powerful volume rendering tools. We seek to address this problem using our 2D transfer function visualization.

The main contributions of this work are as follows:

- Our visualization tool in VR helps orthopaedics researchers reach insights about the ACL more quickly and more easily than a desktop tool alone

- A novel visualization method for 2D transfer functions

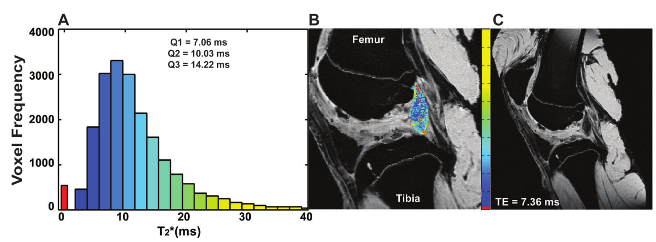

Figure 1: Current visualization method of T_2^* data for [2] using a histogram and colormapped 2D slices of the MR image cube.

2 RELATED WORK

The ACL is currently being visualized using different kinds of 2D imagery. Surgeons diagnose ACL injury using raw 2D MR images to qualitatively determine if the ligament or surrounding tissue appears damaged [1]. As for visualizing T_2^* data, orthopaedics researchers segment 2D MR images by hand, and apply a colormap to each of the images. They also look at a histogram of the T_2^* values in the volume (see Figure 1) [2]. Our VR visualization of the ACL makes it easier for researchers to quickly make insights about their data.

One-dimensional transfer functions assign color and opacity based on scalar data input. They are commonly used outside of visualization, and are the easiest transfer functions to implement.

(a) (b)

Figure 2: (a) Visualization of a 2D transfer function. Axes correspond to data values, their gradient magnitude, and opacity. (b) Rendered ACL corresponding to the 2D transfer function visualization. Note that the low gradient and low value regions of the ligament are most transparent.

However, they are not as effective with noisy data, such as medical data [7]. Higher dimensional transfer functions provide clearer boundaries between different substances in medical data, and can generally show more subtle variations in data than 1D transfer functions [5]. Semantics-based methods are a current way of visualizing higher order transfer functions. Salama et al. [8] use primitives such as parabolic curves and trapezoids to encode transfer function parameters, which reduces the perceived complexity of the editing process. However, their implementation is not intuitive for users who do not have experience with higher order transfer functions. Our work seeks to address this gap and open up more potent editors for novice use.

3 Methods

We use open source tools to create our VR and desktop environments. For our desktop tool, we use 3DSlicer [4]. 3DSlicer contains a volume renderer with a 1D transfer function split into two editors– one for opacity, and the other for changing bin sizes and colors. 3DSlicer also has slicing functionality. Please note that we only implemented the 2D surface representation in our VR application.

For our VR tool, we create an interface within Brown University's VR YURT using both VRUI and its complementary package, 3DVisualizer [6]. The tool allows users to interactively move around the ACL and slice it with a cutting plane at various angles. The user can view one volume, or multiple volumes side by side. There are two 1D transfer function editing palettes– one for mapping data values directly, and one for mapping the magnitude of the gradient. Together, they form a separable 2D transfer function. Figure 2a shows the implementation of a 2D surface representing a 2D transfer function. As the user edits the two 1D transfer functions, the surface changes appropriately, as can be seen in Figure 2b.

4 Results

We obtain qualitative feedback from our two orthopaedics collaborators via a questionnaire based on [3]. We explained how to use both the VR and desktop tools to both researchers as a group, then had them explore two healing ACL datasets using each tool individually. We find that the VR tool is both easier to use and more useful than the desktop tool for our collaborators. They would like to use the tool in the future for initial exploration of their ACL datasets, then transition to the desktop tool due to the overhead associated with scheduling VR use. In particular, they find visualizing volumes side by side to be a powerful utility. Ultimately, they do not find that our surface visualization of a 2D transfer function makes the transfer function easier to use or more useful.

5 Conclusion

We determine that our VR tool for exploring T_2^* spread in the ACL is initially more beneficial for orthopaedics researchers than a commonly used desktop tool for medical data analysis. Since our collaborators did not find our 2D transfer function visualization to be helpful, we postulate that much like in [8], users without experience with higher order transfer functions are more likely to prefer simpler and less powerful transfer function editors. It remains an open question as to whether it is possible to motivate the use of more powerful transfer function editors to novice users.

Acknowledgements

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Designing Interactive Visualizations for Atomistic Simulations

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ABSTRACT

In this paper, we will design the first multi-variable interactive visualization system to illustrate position, momentum, and energy in atomistic simulations. We will first replicate the traditional design and represent all three variables using phase spaces. We will then create an alternative design where we represent momentum and energy using vectors and opacity. To evaluate the design, we recruit 10 participants and conduct a questionnaire-based evaluation. The results show that the alternative design is preferred and the visualization is useful for both educational and research purposes.

Keywords: scientific visualization, visualization evaluation, physics visualization

1 INTRODUCTION

In the study of atomistic and molecular physics, researchers have developed a variety of tools to simulate atomistic-level phenomena. For example, Atomistic Simulation Environment (ASE) [1] uses a set of tools and Python modules for analyzing atomistic simulations. Amp [2] further uses machine learning technique to reduce the time of computation. While these tools precisely simulate the states and the behaviours of the systems and report the results as crunched numbers, they usually fail in offering intuitive understandings of the phenomena. Here, a visualization can be helpful as the visualization could illustrate the atomistic-level phenomena.

So far, most of the visualizations for atomistic and molecular systems are designed based on the concept of *phase space*, which describes all the possible states of a dynamic system. Each state is mapped to one unique point in this space. Based on this concept, different variables in the system, such as energy and momentum, are usually mapped to coordinates in the visualizations. We observed a lack of evidence that this design can intuitively and effectively represent the variables. Additionally, these visualizations for phase space are usually static and represent one of the states, which is counter-intuitive to the properties of a dynamic system.

In this paper, we will design a new interactive visualization to allow the intuitive and effective investigation of atomistic-level phenomena. In particular, we will use numerical integration to quickly and robustly calculate the force and velocity in the simulation. We will replicate the traditional design and further explore effective and intuitive visualizations using additional visual elements. Finally, we will evaluate our design in a questionnaire-based experiment.

The contributions of this paper are:

- We designed the first interactive visualization for multi-variable atomistic simulations.
- We confirmed that using vector and opacity to represent momentum and energy can be more intuitive for users than phase spaces.
- We demonstrated that building an interactive and effective visualize system can have both educational and research utility.

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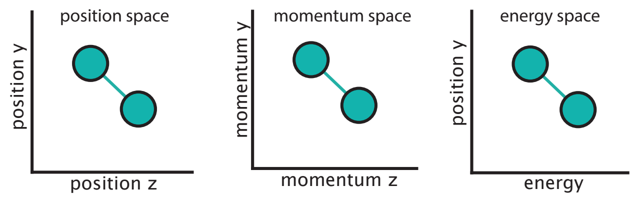

Figure 1: The first design: phase space, where the coordinates represent different variables in different phase spaces. Here we use 2D figures to explain the concept. However, we implement the system using 3D graphics.

2 DESIGNING VISUALIZATION

The goal of our design is to illustrate position, momentum, and energy of the atoms in a dynamic atomistic system. We first replicate the traditional design where we make use of phase space of a variable and follow the design in the existing tools such as Atomic Simulation Environment (ASE). We then create our alternative design and add interactions into the visualization.

2.1 Traditional Design

Following the traditional representation of atomic and molecular systems, we use a line to represent the bond between atoms and a sphere to represent an atom. The color of a sphere is consistent with the visualization in ASE and the radius of the sphere is scaled to the same ratio as what used in ASE.

We use coordinates to represent different variables in different phase spaces. Each of the spaces represents one variable: position space, momentum space, or energy space. For example, we use xyz coordinates to represent the value of momentum on each of the axes, and we use z coordinate to represent the value of energy. This design allows users to switch between different phase spaces to investigate different variables. Please refer to Figure 1.

The problem of phase space is that they could be very counter-intuitive. For example, momentum space doesn't present how an atom moves but only represents how momentum changes in different directions. We will address this issue in our alternative design and compare it to the traditional design.

2.2 Alternative Design

The alternative visualization we propose is to use different visual elements to represent different variables in the same phase space. We use position space as the baseline and add the representations of momentum and energy. We think that the position space is the most intuitive phase space because it is consistent with the intuition that coordinates equal positions.

We first proposed using axes-aligned vectors at the center of a sphere to represent momentum on each of xyz directions (Figure 2a) and using hue of a sphere (Figure 2c) to represent the change of energy. However, our collaborator suggested that axes-aligned vectors are confusing. One vector at the center of a sphere (See Figure 2a) to indicate the momentum would be more intuitive.

He also suggested that opacity of a sphere (See Figure 2d) should be more intuitive than hue to encode energy. We also found that for some of the color used in ASE system can be hard to differ in hue such as white color for Oxygen atom. Thus, we chose one vector to

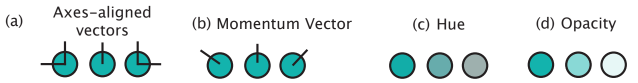

Figure 2: The alternative design: we can use axis-aligned vectors or one vector for momentum; hue or opacity for energy.

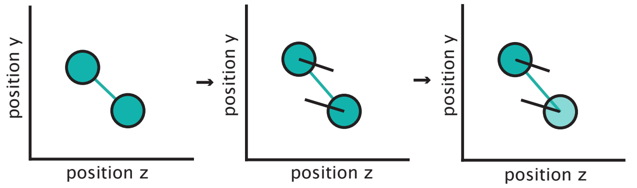

Figure 3: The final design: we use coordinates to represent position, vector to represent momentum, and opacity to represent energy.

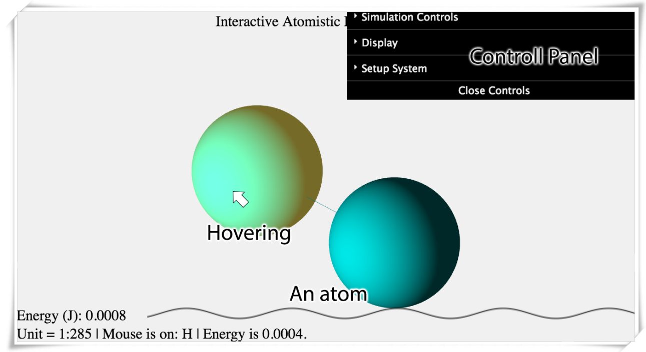

Figure 4: The screenshot of the visualization for Hydrogen system.

represent momentum and opacity to represent energy and then integrate them with the baseline visualization of position space. Please see Figure 3.

2.3 Interaction Design

We designed five types of interactions for our system: hovering, dragging, zoom, and selecting menu items. The hovering operation highlights an atom and displays the name and the energy of the atom. The dragging operation allows users to change the position of the atom in the phase space and shows the corresponding effects in energy and momentum. The zoom operation lets users look at the visualization at different scales. Finally, the menu items enable users to switch between different phase spaces, load another atomistic system and determine whether to display the representation of a variable.

2.4 System Design

We use Javascript and Three.js to implement the system. The system can run in a modern browser. In this prototype, we set up three atomistic systems, including Hydrogen, Oxygen, and Water. A screenshot of Hydrogen system can be found in Figure 4.

3 Evaluation

To demonstrate that the alternative design is preferable and an interactive visualization system for atomistic and molecular systems can be successful, we conducted a questionnaire-based evaluation. Our hypotheses for the evaluation are:

- We think that our alternative design is more intuitive than the phase space design for users.
- We think that such an interactive tool for visualizing dynamic systems can be useful for researchers and students.

We recruited our collaborator and nine students as our participants.

3.1 Questionnaire

The questionnaire is organized in three sessions.

- Demographics. We collected participants' educational background and their familiarity with atomistic simulation.
- Visualization. We aim to evaluate our alternative design in this session. We ask our participants about their thoughts about the phase space design and the alternative design. We explicitly ask them to compare the energy-opacity to the energy space and compare the momentum-vector to the momentum space.
- System. We aim to collect comments and potential improvements in this session. We ask what other features would be useful to implement and how can the participant foresee using such a tool.

3.2 Results

We had 5 participants from Physics department, 2 from Mechanical Engineer, and 3 from Chemistry or Chemical Engineering. We found that 4 participants reported that they had worked with atomic simulations.

We found that all participants reported that they like the alternative design. First, all of them prefer the energy-opacity over the energy space. They reported that opacity is more intuitive than the energy space, especially for users without experience. Second, participants tend to believe that the momentum vector could be helpful. We found that 8 participants prefer the momentum vector over the momentum space; 1 participant reported that they are equal; 1 participant prefers the phase space over the momentum vector. The concerns about the momentum vector focus on it is too small and difficult to see.

When being asked about phase space, 7 participants reported that phase space is very confusing and not useful. Two of them reported that they like that phase spaces exist as on option. We also found that 1 participant reported that she likes phase spaces because they can be very useful.

Comments on the prediction of the usage of our design are very positive. We found that 4 participants reported that this tool would be useful for educational and research purposes. For example, one of the participants reported that the visualization could help understand the overall effect of small forces and changes in an atomic system. If we are able to integrate it with ASE or Amp, the tool can be used further for research purposes.

4 Conclusion

We built the first interactive visualization system that allows users interactively and effectively investigating position, momentum, and energy in atomistic simulations. We confirmed that our alternative design is more intuitive for users to understand. However, it may not be the most accurate way to investigate the value of the variable. We are confident that an interactive visualization for atomistic systems can be useful for both education and research.

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My CS237 Final Report

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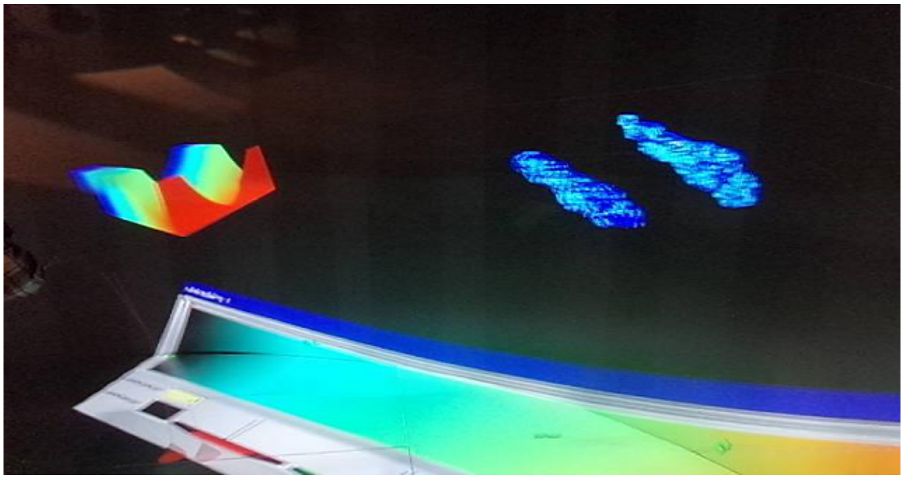

Figure 1: An overview image of the virtual reality system we implemented for visualizing the healing of the ACL. The top right is a pair of ACLs at different stages of healing (12 and 24 weeks). The top left is a visualization of the 2d transfer function being used to visualize the ACLs. The bottom is a window for editing the 1d transfer functions which make up the 2d transfer function.

Abstract

We present a user study evaluating the effectiveness of virtual reality and transfer function visualization in volume rendering of T2* values in the ACL. We found that for this particular application our transfer function visualization did not help make exploration of the data easier. We did find that virtual reality is helpful for initial exploration of this data and determining what to focus on in more traditional desktop visualizations.

1 Introduction

The Anterior Cruciate Ligament (ACL) is a major ligament in the knee and tearing it is one of the most common sports injuries. Unfortunately, studies have shown that standard ACL reconstruction surgery leads to an increased risk of osteoarthitis. Our collaborators have designed a new method of performing this reconstruction surgery that they believe will reduce this risk.[4] In order to evaluate the successfulness of this, they are studying how the ACL heals under the different techniques. The primary way they are evaluating the strength of the ligament is through T2* relaxation times obtained through MRI scans, which has been shown to correlate to structural properties. [1] The current ways of studying this are making histograms showing the spread of these values throughout the ligament compared over time (via multiple MRI scans taken over many weeks) and looking at 2d slices to determine how the rate of healing changes in different parts of the ACL. An example of this method can be seen in figure 2

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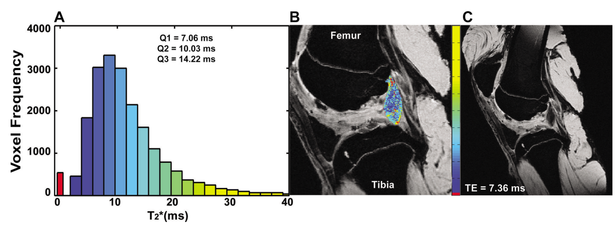

Figure 2: The traditional method of comparing T2* values in the ACL.

In this work, we look to the visualization technique of volume rendering in order to provide an alternate method of studying this data. In particular, we create a 3d volume rendering of the ACL in several different environments in order to evaluate the effectiveness of different transfer function techniques and virtual reality on the analysis of this data. Transfer functions are the way that a volume renderer converts the data value (in our case a T2* value) at a location in 3d space to the color which should be shown there and how opaque the visualization is at that point. Standard techniques involve defining the transfer function based purely on the data value at the point. Higher dimensional transfer functions take as input more information, such as the gradient of the value at that point. [3] We choose to focus primarily on the difference between 1d and 2d transfer functions, as well as the addition of a more advanced visualization of the 2d transfer function. One significant classification within multidimensional transfer functions is whether they are *separable* or not. A separable transfer function is one which can be represented as multiple 1d transfer functions that are then combined in some way.

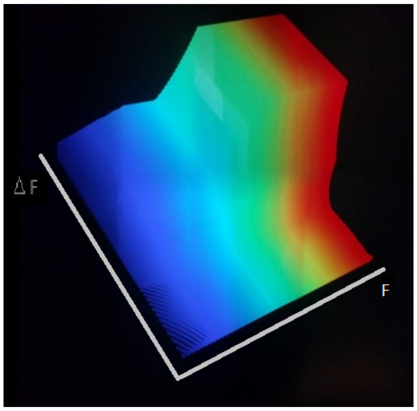

Figure 3: Our method of visualizing transfer functions. The axis labels were not present in the original visualization, but the meanings of the axes were explained to the users. They are added here for convenience.

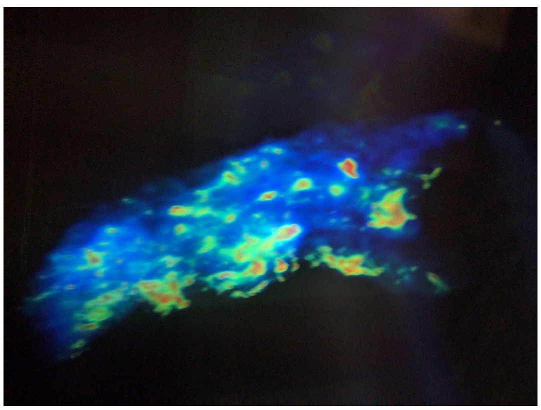

Figure 4: A rendering of the ACL with our system and a transfer function designed to highlight spots of high T2*.

2 Approach

We based our visualization on the 3dVisualizer program included with the VRUI virtual reality toolkit. [2] This gave us a volume renderer to build off of that had implemented a basic one dimensional transfer function already. We adapted the included renderer to allow the use of separable multidimensional transfer functions, in particular we used a 2d transfer function with color defined by a 1d transfer function on the T2* values and opacity defined multiplicatively between 1d transfer functions, one on the T2* values and one on the gradient magnitude. Interaction with these transfer functions was done via the builtin interface, which has an editor that allows you to easily define piecewise linear 1d transfer functions.

We also created a visualization of this 2d transfer function, showing the color and opacity for combinations of T2* and gradient values. We did this by visualizing a 3d surface, where one axis is T2* value, one axis is gradient value, and the heightiswas the opacity. It is a colored surface, with the color corresponding to that of the transfer function. We also fill in the volume below the surface in order to help orient the user. An example of this visualization can be seen in figure 3.

We also have the ability for users to interactively rotate and move the rendering to be able to look at it from different views. Additionally there is a slicing tool that allows users to look at slices through their data along any axis.

An example rendering can be seen in figure 4.

3 Experimental Setup

Our user study consisted of 2 users: the medical experts we were collaborating with. We had 2 conditions, the setup described above as well as a well known desktop environment for volume rendering, 3DSlicer. We desired to evaluate using the same setup on the desktop as in VR, but ran into technical issues. We used data provided to us by the participants that they were interested in seeing in 3d. In VR we showed them 2 volumes side by side and in the desktop we had 2 separate windows available, one for each volume.

We explained both platforms to the users ahead of time, then divided them so each went to one initial platform. We were available to answer questions as they explored the data using the tools. When they were satisfied with their exploration of the data/tool, they switched to the other platform. We recorded verbal feedback as they were using the tools. Finally, we had them answer a questionnaire to rate the quality of their experience with each system, with a particular focus on the visualization of the 2d transfer function.

4 Results

Our users were both very impressed by the ability to see their data in 3d. They both thought that VR was a very useful tool for the exploration of their data, particularly in the ease of looking at the data from different directions and slicing it. They did express hesitation about using the VR setup for most of their data analysis, citing concerns about ability to communicate results and time overhead required in communicating with us to schedule meetings and get data into VR. They were still very optimistic about using it to get an iniitial overview of their data and identifying ways of looking at it in a desktop tool.

The feedback they provided indicated that they did not feel the 2d transfer function visualization was effective in helping them to look at their data. Anecdotally, most of their use of the transfer functions were to remove things they were less interested in seeing. Additionally, a significant portion of their time was spent with the entire ACL fully opaque, using the slicing tool instead of a transfer function to see inner structure. Both of these modes of looking at the data do not benefit very much from the presence of a visualization of the transfer function, so it is still possible that our visualization could be useful for other datasets.

Acknowledgements

The authors wish to thank our collaborators Braden Fleming and Jillian Beveridge. We would also like to thank Hua Guo and Johannes Novotny for providing guidance in CS1951-J throughout the semester for this project.

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Visualizing Self-Tracked Data to Infer Sleep Cycle Patterns

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ABSTRACT

This work introduces two novel visualization methods for self-tracked sleep data. These methods combine multivariate time series data and ordinal self-reflection data to help sleep clinicians. We conduct an iterative design process to achieve our collaborator's domain specific goals for visualizing self-tracked sleep data. The final visualizations feature a unique spiral clock radial design and interactive controls for ordinal data. We run a survey with three sleep clinicians to assess the effectiveness of each visualization type. In our user study a sleep clinician also performs a mock in-patient session with the new visualizations. The new visualizations prove more effective for all design requirements in comparison to the original visualization from SleepCoacher. They also visualize double the number of sleep states and associated information.

Keywords: sleep visualization, multivariate time series, ordinal, design, prototyping, personal informatics

1 INTRODUCTION & RELATED WORKS

The main contribution of this work is the validated design of two new visualization methods for self-tracked sleep data. These novel methods combine multivariate time series data and ordinal self-reflection data to achieve domain-specific goals of sleep-clinicians. The design consists of an iterative prototyping process in collaboration with a domain expert. The first visualization features multivariate time series data from raw sensor data such as movement, noise, start, and end time. Another visualization integrates multivariate time series data with ordinal data. Ordinal data consists of sleep quality ratings and keywords tracked daily. To the best of our knowledge, there is no pre-existing work that attempts to integrate ordinal data and multivariate times series visualizations.

This work seeks to build on the previous efforts of sleep clinicians and Personal Informatics researchers who collaborated on the mobile application SleepCoacher [3]. SleepCoacher uses a closed feedback loop to deliver personalized sleep recommendations to users outside of a clinical setting. Sleep clinicians play a vital role in this closed feedback loop between data collection and personalized recommendation stages. They generate recommendations for users by inferring sleep cycle patterns from visualizations and raw ordinal data. SleepCoacher is the first system that involves experts in the feedback loop to build and deliver recommendations from self-tracked data. The visualizations used to generate recommendations were not built to scale, omitted all ordinal self-reflection data, and were not designed based on the goals of sleep clinicians. The inclusion of sleep clinicians in the feedback loop has garnered significant results for positive changes in user behavior. Other Personal Informatics applications such as Lullaby [4] use visualizations to engage users by mapping single variable time series data. Authors of similar systems in addition to other researchers [2] state the need to develop visualizations that generate more effective insights. Furthermore, neither system involves domain-specific experts to review or help design the visualizations. The work presented here demonstrates how engaging domain-specific experts in the design of scientific visualizations can provide new knowledge in the design of effective visualizations in Personal Informatics.

Figure 1: Final radial spiral design featured in V2 & V3. Hover for date & hours slept. *Key normally placed above visualization.

In the past, sleep clinicians have effectively used actigraphy to visualize and infer sleep patterns. [1] Actigraphy consists of single variable time series data. This proved ineffective in motivating patients to modify behaviors to improve sleep. In contrast, SleepCoacher enhanced this relationship between clinician, recommendation, and patients. SleepCoacher used visualizations of multivariate time series data stacked in columns to infer patterns over a series of days. This visualization along with user's self-inputted daily reflection data were sufficient for sleep clinicians to build recommendations. SleepCoacher demonstrated that clinical insights could be pattern matched into a collection of recommendations [3]. However, these recommendations might lack key insights due to the omission of daily self-reflection data, such as ordinal sleep ratings and keywords. Our contributions can help bridge this gap between visualizations of sleep data and clinical insights.

2 METHODS

Our work involves several iterative steps to design and evaluate new visualization methods for self-tracked sleep data. The data used is from SleepCoacher users. Our collaborator and two other survey respondents worked on SleepCoacher. First we conducted an interview with our collaborator to gather design requirements and patterns they look for in sleep data. We built four prototypes, **P1** to **P4**, through an iterative design process to explore and satisfy our collaborator's goals and design specifications.

2.1 Iterative Design Process

We built P1 and P2 simultaneously. **P1 is a multivariate time series area chart**. It shares the strengths of traditional actigraphy to appeal to sleep clinicians. Our collaborator felt it was scalable and made a clear depiction of patterns over time. They felt it did not adequately visualize noise, movement, or ordinal data. They also felt this visualization might be confusing for a patient. **P2 is a radial heat map**. Our collaborator wanted to explore clock

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based interfaces to communicate changes over time that would be familiar to patients. The radial design represents a 24-hour clock. It features five distinct rings that represent an average data value at 15-minute intervals for noise anomalies, movement anomalies, sleep start time, actual wake-time, and scheduled wake-time. The collaborator had a favorable impression of the clock design and the concept of noise and movement anomalies. Sleep clinicians infer patterns from noise and/or movement anomalies, not the baseline measurements. The collaborator felt this visualization lacks the ability to infer daily patterns. This is pertinent, since patients often engage in behavioral and environmental interventions to help improve their sleep patterns per clinician advisement. P1 and P2 did not visualize naps, oversleeping, or ordinal data. P3 is designed to combine the strengths of P1 and P2. P3 also visualizes additional sleep states per our collaborator's requirements.

P3 is a stacked radial bar chart. Rings represent a two day segment. Each 15-minute interval represents the patients current sleep state. The collaborator outlined various sleep states to visualize: normal sleep, oversleep, nap, noise anomaly, movement anomaly, noise & movement anomaly, awake, and early awakening. Each sleep state is mapped to a unique color. Noise and movement anomalies are computed with the median absolute deviation test. The classifier is trained per sleep segment and then each 15-minute interval is tested for anomalies. A slider is used to change opacity by sleep rating per sleep segment. P4 addresses remaining ordinal data requirements by mapping keywords to check boxes. If a sleep segment did not contain one of the keywords its opacity is reduced. **P4's major design revision features a spiral design to represent the data.** This is essential because only a spiral allows for linear segments of time to be wrapped around a radial interface. This matches the concept that time is linear. Without the spiral users with abnormal sleep patterns, such as shift workers, can not be accurately depicted across days. This key requirement allows for the accurate visualization of naps and other odd sleep patterns.

2.2 User Study & Survey

We ran a survey to measure the effectiveness of the three visualization types, **V1** to **V3**. The original visualization from SleepCoacher **V1**, the new multivariate times series visualization **V2** (see Figure 1), and the new multivariate times series visualization with ordinal data **V3**. V3 is the same as V2, except it has interactive controls for keywords and sleep ratings. The survey used 9 visualizations, three for each type. First, respondents performed training tasks and gave recommendations to ensure realistic engagement with the visualizations. Then they answered ten 5 level Likert scale questions and gave comments per visualization. Likert Scale questions were modelled per design requirement. Respondents answered open ended questions per visualization type. We also ran an in-person user study with our collaborator.

3 Results & Conclusion

The survey yielded 9 responses per visualization type from 3 respondents. All three visualization types rate similar in their effectiveness to depict anomalies in noise and movement data. This can be seen as a positive result for the new visualizations since they visualize 12 to N data points in contrast to V1's 5 data points. V2 and V3 are more effective in all other measurements compared to V1 (see Figure 2). V3 was also more effective than V2 in all other measurements. V2 and V3 proved to require less effort to generate recommendations. All respondents chose V3 as most likely to use in a patient session. These results support the realization of the goals for this work, to create new validated designs of multivariate time series and ordinal visualizations for self-tracked sleep data.

We also conduct a user study with our collaborator. First they interact and review basic functions with the new visualizations with the think-aloud method. After that, they conduct a mock patient

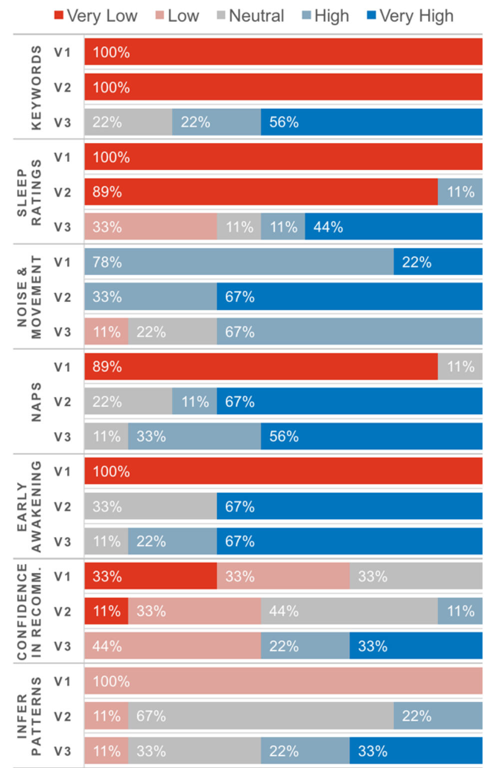

Figure 2: Survey Results for Effectiveness. (V1 old, V2 & V3 new)

session to give recommendations using the new visualizations. The collaborator commented *"I love the visual depiction, I think it's incredibly compelling."* The keywords garnered strong insights. They were used to inform the clinician of lifestyle choices, such as neck pain, work, or school. The collaborator uses keywords and sleep ratings to isolate and find unique correlations per patient. These directly determine patient recommendations.

Future work with these visualizations could include a study with SleepCoacher. This can help answer long standing questions in Personal Informatics around the use of visualizations to modify behavior. In contrast to previous efforts this study would be the first to include visualizations designed in collaboration with a domain expert. This study show the potential impact of these visualizations for clinicians and patients in and outside of a clinical environment.

Acknowledgements

Special thanks: John McGeary, Nediyana Daskalova, & Jeff Huang

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Trajectory Clustering for Dinosaur Track Visualization

Josh Tveite* Eleanor Tursman †

Brown University

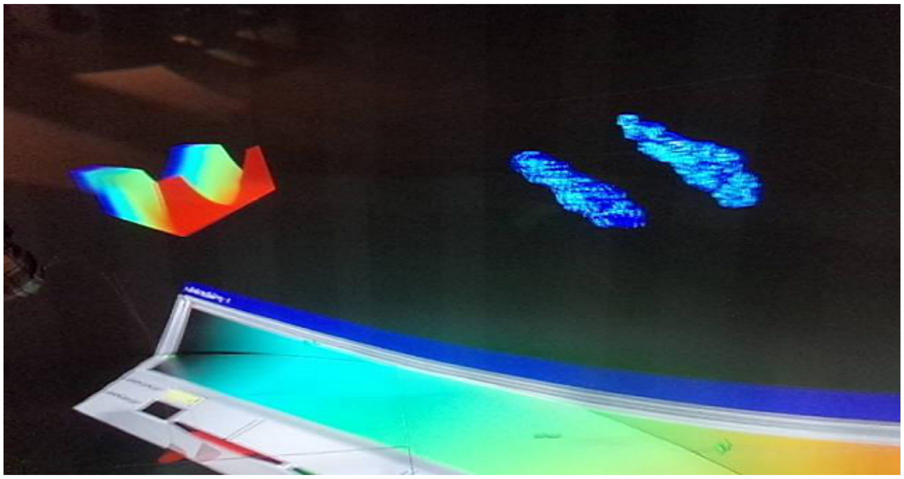

Figure 1: An overview image of the virtual reality system we implemented for visualizing the healing of the ACL. The top right is a pair of ACLs at different stages of healing (12 and 24 weeks). The top left is a visualization of the 2d transfer function being used to visualize the ACLs. The bottom is a window for editing the 1d transfer functions which make up the 2d transfer function.

Abstract

We present a user study evaluating the effectiveness of virtual reality and transfer function visualization in volume rendering of T2* values in the ACL. We found that for this particular application our transfer function visualization did not help make exploration of the data easier. We did find that virtual reality is helpful for initial exploration of this data and determining what to focus on in more traditional desktop visualizations.

1 Introduction

The Anterior Cruciate Ligament (ACL) is a major ligament in the knee and tearing it is one of the most common sports injuries. Unfortunately, studies have shown that standard ACL reconstruction surgery leads to an increased risk of osteoarthitis. Our collaborators have designed a new method of performing this reconstruction surgery that they believe will reduce this risk.[4] In order to evaluate the successfulness of this, they are studying how the ACL heals under the different techniques. The primary way they are evaluating the strength of the ligament is through T2* relaxation times obtained through MRI scans, which has been shown to correlate to structural properties. [1] The current ways of studying this are making histograms showing the spread of these values throughout the ligament compared over time (via multiple MRI scans taken over many weeks) and looking at 2d slices to determine how the rate of healing changes in different parts of the ACL. An example of this method can be seen in figure 2

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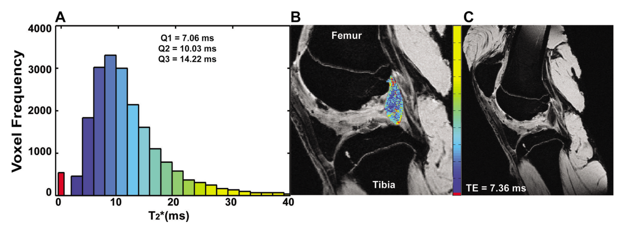
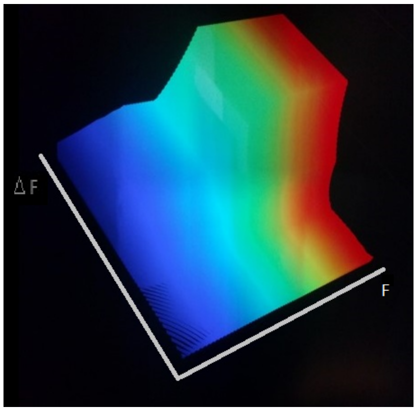


Figure 2: The traditional method of comparing T2* values in the ACL.

In this work, we look to the visualization technique of volume rendering in order to provide an alternate method of studying this data. In particular, we create a 3d volume rendering of the ACL in several different environments in order to evaluate the effectiveness of different transfer function techniques and virtual reality on the analysis of this data. Transfer functions are the way that a volume renderer converts the data value (in our case a T2* value) at a location in 3d space to the color which should be shown there and how opaque the visualization is at that point. Standard techniques involve defining the transfer function based purely on the data value at the point. Higher dimensional transfer functions take as input more information, such as the gradient of the value at that point. [3] We choose to focus primarily on the difference between 1d and 2d transfer functions, as well as the addition of a more advanced visualization of the 2d transfer function. One significant classification within multidimensional transfer functions is whether they are *separable* or not. A separable transfer function is one which can be represented as multiple 1d transfer functions that are then combined in some way.



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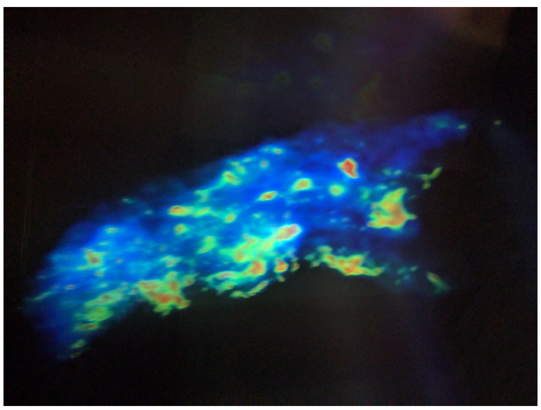

Figure 4: A rendering of the ACL with our system and a transfer function designed to highlight spots of high T2*.

2 Approach

We based our visualization on the 3dVisualizer program included with the VRUI virtual reality toolkit. [2] This gave us a volume renderer to build off of that had implemented a basic one dimensional transfer function already. We adapted the included renderer to allow the use of separable multidimensional transfer functions, in particular we used a 2d transfer function with color defined by a 1d transfer function on the T2* values and opacity defined multiplicatively between 1d transfer functions, one on the T2* values and one on the gradient magnitude. Interaction with these transfer functions was done via the builtin interface, which has an editor that allows you to easily define piecewise linear 1d transfer functions.

We also created a visualization of this 2d transfer function, showing the color and opacity for combinations of T2* and gradient values. We did this by visualizing a 3d surface, where one axis is T2* value, one axis is gradient value, and the heightiswas the opacity. It is a colored surface, with the color corresponding to that of the transfer function. We also fill in the volume below the surface in order to help orient the user. An example of this visualization can be seen in figure 3.

We also have the ability for users to interactively rotate and move the rendering to be able to look at it from different views. Additionally there is a slicing tool that allows users to look at slices through their data along any axis.

An example rendering can be seen in figure 4.

3 Experimental Setup

Our user study consisted of 2 users: the medical experts we were collaborating with. We had 2 conditions, the setup described above as well as a well known desktop environment for volume rendering, 3DSlicer. We desired to evaluate using the same setup on the desktop as in VR, but ran into technical issues. We used data provided to us by the participants that they were interested in seeing in 3d. In VR we showed them 2 volumes side by side and in the desktop we had 2 separate windows available, one for each volume.

We explained both platforms to the users ahead of time, then divided them so each went to one initial platform. We were available to answer questions as they explored the data using the tools. When they were satisfied with their exploration of the data/tool, they switched to the other platform. We recorded verbal feedback as they were using the tools. Finally, we had them answer a questionnaire to rate the quality of their experience with each system, with a particular focus on the visualization of the 2d transfer function.

4 Results

Our users were both very impressed by the ability to see their data in 3d. They both thought that VR was a very useful tool for the exploration of their data, particularly in the ease of looking at the data from different directions and slicing it. They did express hesitation about using the VR setup for most of their data analysis, citing concerns about ability to communicate results and time overhead required in communicating with us to schedule meetings and get data into VR. They were still very optimistic about using it to get an iniitial overview of their data and identifying ways of looking at it in a desktop tool.

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IntAE: Interactive Atomistic Environment for Visualizing Multivariate Simulations

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ABSTRACT

We present a proof of concept of IntAE (Interactive Atomistic Environment), the first robust, interactive, multivariate atomic simulation visualization software. Interactivity has previously been shown to facilitate effective learning, and multivariate visualization allows users to visualize the different variables, such as energy and momentum, associated with atoms in atomic simulations. To assess different multivariate visualization options and the overall potential usefulness of our software, we had ten users evaluate a simulation of a hydrogen molecule in IntAE. All users liked the software and could foresee themselves using it for educational and/or research purposes. Our evaluation also found that encoding variables into the visualization of each atom was more intuitive and thus nearly unanimously preferred by users over phase space visualizations.

Keywords: multivariate visualization, interactive simulation, atomic simulation

1 INTRODUCTION

Atomic simulation visualizations help scientists study complicated systems at atomic and molecular scales. Heterogenous catalytic reactions, which create a majority of the commodity chemicals and fuels used in today's society and which are a focus of our collaborator Dr. Andrew Peterson, are one example of the important reactions that can be studied with simulations. Beyond these reactions, however, atomic simulation visualizations impact all atomic research by facilitating investigation into the atomic world of physical systems.

Currently, the most widely used atomic simulation visualization software is Atomic Simulation Environment (ASE) [1]. In ASE, users can visualize atomic systems and the results of simulations, but the software does not provide real-time interaction or multivariate visualization. Additionally, a few interactive chemical environments exist which have demonstrated how interactivity can facilitate learning [3, 4], but they are all for strictly educational purposes and lack robust calculations. Interactive simulations with robust calculations have never before been possible because calculating accurate electronic structures takes too long to permit real-time interaction.

We addressed the lack of robust, interactive, multivariate atomic simulation visualization software by developing IntAE (Interactive Atomistic Environment). In this paper, we present a proof of concept of IntAE, focusing on the interactivity and the multivariate visualization. We also evaluate the visualization and overall potential usefulness of the software.

2 THE ENVIRONMENT

IntAE will be the first robust, interactive, multivariate atomic simulation visualization software. Novel machine-learning techniques

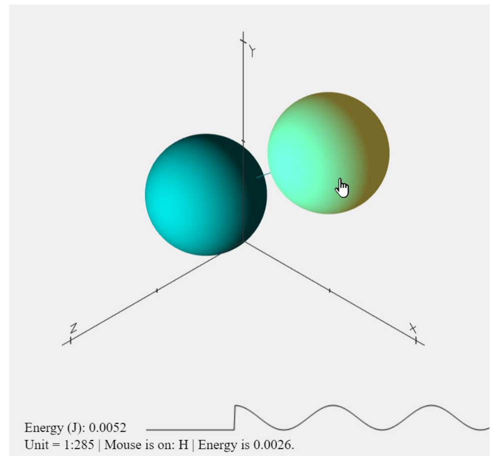

Figure 1: A hydrogen molecule in IntAE. The right hydrogen atom has been selected and displaced from equilibrium.

developed by our collaborator's research group allow for quick calculations of atomic forces and energies [2]. Using these techniques, we will be able to produce simulations that support real-time interaction. Because the machine-learning techniques require further development before we can quickly calculate forces for large systems, however, the forces are currently calculated with only Hook's law, a simplification based on atomic vibrational modes. IntAE will also provide multivariate visualization. This feature has been left out of other simulation software, but it is important because atomic simulations have multiple variables (position, energy, momentum, force, etc) associated with each atom that can provide insights into how and why the system is evolving.

2.1 Interactivity

After an atomic system has been loaded into IntAE, the user can interact with the system by clicking an atom and dragging it in the space, displacing it from equilibrium (Fig. 1) and manipulating the positions. All variables (forces, energies, positions, etc) are calculated for every user-specified timestep using Verlet integration. Users can rotate the space and zoom in and out to view the system from different angles and distances. IntAE is also browser-based to ensure accessibility[1].

2.2 Multivariate Visualization

We created options for visualizing the energy and momentum of each atom (Fig. 2). The first option for visualizing energy involves encoding the energy of each atom into the atom's opacity; high opacity corresponds to high potential energy. The opacity of each atom dynamically changes as its energy changes, allowing users to glance at the system and identify which atoms are most energetic. The first option for visualizing momentum displays a dynamic momentum vector at the center of each atom that corresponds to the magnitude and direction of the atom's momentum.

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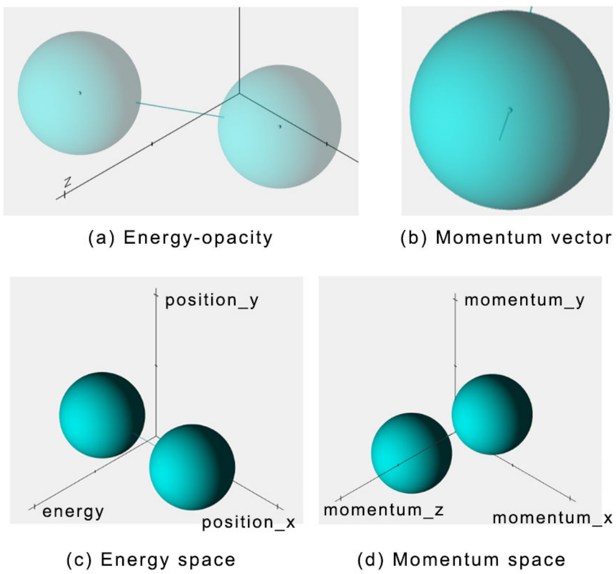
[1] View the proof of concept at www.fmyang.com/iae/

The other options for visualizing energy and momentum involve changing the coordinates of the space in which the system is displayed. By default, the atoms are plotted according to their position. We created the option, however, to change to energy space (Fig. 2c) or momentum space (Fig. 2d); these are called phase spaces. To provide simultaneous visualizations of different variables, the phase spaces could be displayed side-by-side or the opacity and vector visualizations could be used together.



(a) Energy-opacity (b) Momentum vector

(c) Energy space (d) Momentum space

Figure 2: Different visualization options. (a) and (b) encode energy or momentum into the visualization of each atom, while (c) and (d) plot the atoms into energy or momentum phase spaces.

3 Evaluation

To evaluate which multivariate visualization options were most effective and what features users would find useful in our system, we conducted an interview with our collaborator and surveyed nine fourth-year undergraduates in Chemistry, Engineering, and Physics. The themes of the questions can be seen in Table 1.

Responses were overwhelmingly positive with all participants saying that they liked the system and could foresee themselves using it in an educational and/or research capacity. A few participants cited specific problems that they would be interested in investigating with such a system, e.g. determining how stresses and forces in a carbon sheet change in response to small atomic displacements. Participants also had numerous ideas for other useful features such as moving multiple atoms at once, exporting videos, and allowing other types of interaction (e.g. applying electromagnetic fields).

Participants were nearly unanimous in preferring the opacity and vector visualizations over the phase spaces, as seen in Table 2. Seven out of the ten of the participants said that they preferred the opacity and vector visualizations because they found them more intuitive than the phase spaces; as one participant said about the momentum visualizations, ”vectors are more intuitive for someone without experience in momentum space.”

The phase spaces are likely unintuitive because atomic simulations have previously only used position space. One participant who had experience with momentum space actually preferred momentum space over the vector visualization, saying the phase space ”could be a bit more useful to see patterns.” Thus, while participants overall strongly preferred the opacity and vector visualizations, this could be because users are unacquainted with using phase spaces

Table 1: Themes of Evaluation Questions

Section	Question Themes
Demographics	What is your specialty? Highest degree? Experience?
Visualization	What are your thoughts on the visualization options?
	Which visualizations do you prefer and why?
General	What are other useful features to implement?
	How would you use such software?
	Do you have any other feedback?

Table 2: Multivariate Visualization Preferences

Energy-opacity	Energy space	No preference
10 users	0 users	0 users
Momentum vector	Momentum space	No preference
8 users	1 user	1 user

in atomic simulations and not necessarily because the phase spaces are inherently worse multivariate visualization options. Additionally, we evaluated these options using a small system (hydrogen), so the results may not map to systems with many atoms. We would like to re-evaluate the visualization options later with a large system and participants who have worked more with phase spaces.

4 Conclusion

We produced a proof of concept of the first robust, interactive, multivariate atomic simulation visualization software, IntAE (Interactive Atomistic Environment), focusing on interactivity and multivariate visualization (for energy and momentum). Interactivity has been shown to facilitate effective learning, and IntAE will be the first simulation software to combine interactivity with robust atomic calculations thanks to novel machine-learning techniques [2]. IntAE will also be the first software to provide multivariate visualization of the different variables associated with atoms in simulations. The different options for visualizing the energy and the momentum of each atom can be seen in Fig. 2.

Ten users, our collaborator and nine students, evaluated the system and could all foresee themselves using it for educational and/or research purposes. They also reported that encoding energy and momentum into the visualization of each atom is more intuitive than phase space visualizations. This caused them to nearly unanimously prefer the opacity and vector visualizations (Fig. 2a and b), but this could be due to a lack of familiarity with phase spaces and not because the phase spaces are inherently worse visualizations.

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Using Photorealism to Represent Uncertainty in Historic Architecture

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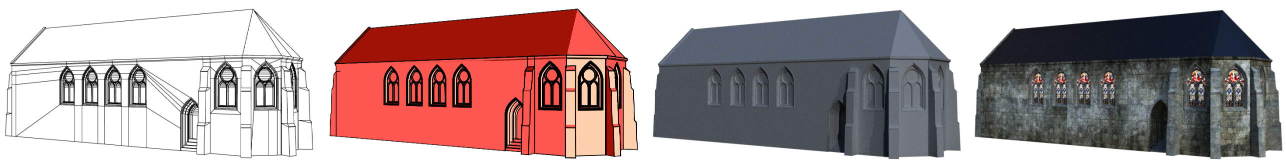

Figure 1: A medieval cathedral represented using four different rendering techniques. We hypothesize that it is possible to rank these rendering techniques by their perceived level of certainty.

Abstract

We present the results of a user study conducted to test whether varying levels of photorealism offer a more intuitive way of visualizing uncertainty in recreations of historic architecture than past techniques based on color and transparency. Our results show that photorealism is as effective as those techniques at representing uncertainty. Moreover, we show that it is possible to classify a combined set of photorealistic and non-photorealistic rendering techniques based on their perceived level of certainty. Together, these results introduce photorealism as a medium for communicating uncertainty in scientific visualization.

Keywords: User study, archeology, non-photorealistic rendering, NPR, perception

1 Introduction

Historians recreate pictures of past architectural sites by piecing together information from a variety of documentary and archeological sources. Depending on the reliability of a given source, the recreation may have a variable level of certainty associated with each architectural component. Although modern historians have a wide choice of media for visualizing and sharing their mental recreations, challenges remain in visualizing non-pictorial data, such as the aforementioned uncertainty. While previous work has used color and transparency to address this issue, the results are often not visually intuitive, requiring either prior knowledge, or reference to a legend for interpretation.

The goal of our study is to test whether representing uncertainty through levels of photorealism can help overcome the shortcomings of existing representations. Our choice of photorealism as a metric is based on past studies that show humans naturally associate realism with veracity of underlying data [4]. However, while we may associate realism with certainty, deciding what defines "realism" in the first place proves to be a difficult question with no universally accepted answer. For instance, in what order of realism is one to rank the large array of non-photorealistic rendering (NPR) techniques? Nonetheless, our daily experience with visual media suggests that while a complete ordering of such rendering techniques by level of realism may not be possible, a *partial* ordering may still be imposed: it may be difficult to decide whether a highly detailed computer generated model is more, or less "real" than a living actor, it is certainly obvious that they are both more real than a hand-drawn cartoon.

Hence, our first hypothesis is that *it is possible to impose a partial ordering on the set of all rendering techniques - both photorealistic and non-photorealistic - with respect to their percieved level of certainty (H1).* Then, once we know whether such an ordering of realism exists, we can test our original hypothesis that *photorealism offers a more intuitive medium for the visualization of uncertainty than color or transparency (H2).*

2 Methodoloy

An online user study with 46 participants was conducted to test our hypotheses. All participants were graduate students responding to an email request. Twelve did not complete the entire study and, hence, their results were discarded. Of the remainder, 24 participants were female and 14 male. Participants were classified as *experts* if their area of study was history, archeology, or architecture. Seven of the considered participants identified as experts.

Groups

Each participant was randomly assigned to one of three groups: transparency, color, or photorealism. The name of each group suggests the within-subjects variable that was used to represent different levels of uncertainty. For the current study, the number of levels was set to four. The number of participants in each group was 13, 12, and 13, respectively. The number of expert participants in each group was five, one, and one, respectively.

The four levels of photorealism (Figure 1) were selected based on visual cues of realism and spatial understanding in images as identified by existing work [1]. Moreover, each of these levels may be assigned a hypothetical level of certainty based on the amount of empty space in each representation [2, 3]. For the color group, the levels were represented by the colors red, yellow, green, and blue, with blue corresponding to the highest certainty level. For the transparency group, opacity levels of 40%, 60%, 80%, and 100% were used.

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Tasks

Each participant was shown renderings of two historic buildings in random order. In each rendering, different components of the building were represented by varying the within-subject variable for the group. Each level of the variable corresponded to a ground-truth certainty level, and this correspondence remained constant across both tasks. Participants were asked to rank the components based on their percieved level of certainty. Each component to be ranked was assigned a unique label x^k. No key or legend was shown. Participants who were identified as experts were presented with an additional set of three questions at the end asking how easy they found the ranking tasks, whether they would have preferred a legend been shown, and what strategy they used to rank the components. The two historic buildings selected for the experiment were the medieval and early-modern reconstructions of a 13th century cathedral at Bourgfontaine in Southern France (Figure 2).

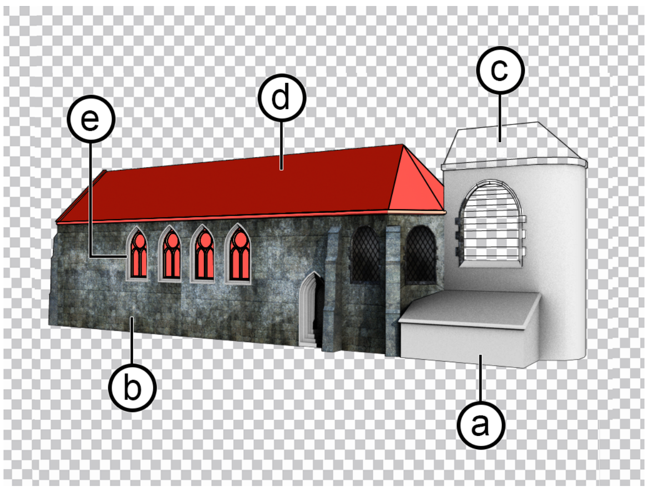

Figure 2: The early-modern reconstruction showing the labelled components which are to be ranked

Scoring Responses

The response of participant number i for the ranking tasks was scored by calculating its Kendall-Tau distance D_k from the ground-truth ordering. This was done by converting the response across both tasks to a string representation $X_i = x_i^1 x_i^2 x_i^3 \dots x_i^n$ based on the label of ranked components. The Hamming distance between two strings was initially considered. However, as the Kendall-Tau distance is more effective at accounting for global order, it was selected as the metric for our study. Welch's t-test was used to find whether any significant difference existed between the mean Kendall-Tau distance of the three groups and, hence, to test *H2*.

To test *H1*, the variance in responses within each group was studied. If a universal partial ordering of rendering techniques according to perceived realism is possible, then most participants in the photorealism group would have ordered the components in a similar way. Hence, the variance within the photorealism group should not be higher than the other two groups. To find the within-group variance, a *mean* response was calculated for each group as

$$X_\mu = M_i(x_i^1)M_i(x_i^2)\dots M_i(x_i^n)$$

where M_i represents the mode over all participants in the group. The variance was then calculated as

$$\sigma^2 = \sum_i D_k(X_i, X_\mu)$$

3 Results

The within-group variance of responses was highest for the transparency group (205), and approximately equal for the color (129) and photorealism (136) groups. Since everyday experience suggests that most people have developed similar associations of color with meaning (red is bad, green is good), the small difference in the variance of the color and photorealism groups would suggest that a similar association of meaning exists in the case of our chosen rendering techniques. The high variance of the transparency group can be attributed to the fact that distinguishing between different levels of opacity is not always easy. In fact, the layering of opacity levels may entirely confound the desired representation. These results, therefore, show that our first hypothesis cannot be disproved.

On the other hand, our second hypothesis was disproved as no significant difference was found between the mean Kendall-Tau distance of the photorealism group (M = 10.61, SD = 2.46) and transparency group (M = 10.76, SD = 1.92); t(-0.17) = 22.64, p = 0.86, or the photorealism and color groups (M = 11.58, SD = 3.08); t(-0.86) = 21.07, p = 0.39. Nor was there any significant difference between the means of the transparency and color groups; t(-0.78) = 18.14, p = 0.44. These results suggest that photorealism is as effective as color and transparency at communicating uncertainty.

Three of the five experts in the photorealism group preferred the inclusion of a legend, with the remainder being unsure whether a legend would prove more useful. Three out of five found the task of ranking the components slightly difficult, one found it slightly easy, and one extremely easy. While the latter did not respond to the question about the strategy used for ranking, the expert who found the task *slightly* easy, however, indicated that she had based her ranking on her knowledge of architecture, and the use of "photorealistic texture for the walls and only solid colors/outlines of less certain elements." Those who had found the task slightly difficult did not rely on any visual cues and, instead, based their responses on their intuition about "what would be most logical for archeologists to find," and "which is more in the ground." The expert in the transparency group found the ranking tasks slightly difficult, basing her responses on what was "most likely to remain in the material record." The expert in the color group, who found the tasks neither easy nor difficult, did not state her ranking strategy.

4 Conclusion

While photorealism may not necessarily be more effective at representing uncertainty, our results show that it is certainly not less effective than color or transparency either - two representations that are widely used at present. Moreover, our work, for the first time, shows that it is possible to rank rendering techniques, including NPR, according to their perceived level of certainty. Hence, in addition to introducing photorealism as a new medium for the visualization of uncertainty, our work provides insights into the human visual system, and perceptual psychology.

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