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Use of Stereoscopic Virtual Reality for Online Atmospheric Nucleation Research and Education

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***Abstract* — Molecular-level understanding of complex atmospheric nucleation processes is crucial for modelers and researchers who are studying the mechanisms of atmospheric aerosol nucleation. To promote collaborative research and online education in this field, we developed a web-based nucleation data analysis and visualization platform. We have learned that the success of our effort largely depends on the effectiveness of user interface design and data visualization. In this paper, we study the potential of incorporating stereoscopic virtual reality (VR) technologies into our web-based system to achieve our goal. We implemented three different VR enhanced data visualization solutions and conducted a thorough user study and comparison. Our findings could be valuable to anyone who is interested in developing an online 3D virtual world for research and educational purposes.**

***Index Terms* — Atmospheric Aerosol Nucleation, Data Visualization, Virtual Reality, Web-based System.**

I. INTRODUCTION

Newly formed atmospheric aerosol particles have a considerable impact on global climate by affecting the Earth's radiation balance. Understanding how particles nucleate in a multi-component gas mixture is important not only for climate and weather studies but also in wide-ranging technological applications including gas separations, pollution control, and nanotechnology [10][18]. However, many fundamental questions about atmospheric nucleation pathways remain unanswered due to the complexity of nucleation. For each type of gas-to-particles nucleation process, particle-based simulations generate huge amounts of digital data. Although existing data visualization and analysis algorithms provide a feasible solution for researchers to gain better understanding of the nucleation process, due to vast amounts of data produced by a typical nucleation simulation, keeping multiple copies of data at different locations is impractical. With advances in web technology, developing collaborative applications on the web has become a promising solution to encourage data sharing and avoid redundant copies.

On the other hand, over the years we have observed a tremendous growth in undergraduate research. At large research universities, undergraduates can easily get involved in cutting-edge research and have opportunities to work with top researchers in the field. However, it may not be the case at primarily undergraduate institutions where faculty members devote most of their time to providing a superior, student-centered learning experience and do not have enough time to develop high quality research projects that expose the realities of working in research to the undergraduates. As strong supporters of the belief that "undergraduate research is the pedagogy for the 21st century [1]", we are interested in studying the possibility of developing a web-based collaborative research and education environment through which more undergraduates at primarily undergraduate institutions are able to study and work on research projects with professors and researchers at large research institutions and access educational resources that are usually not available at their own institutions.

Mode	Hardware	Software
Standard	PC	Google Chrome or Mozilla Firefox
Anaglyph	Anaglyph glasses	WebGL enabled
NVIDIA 3D Vision	3D monitor 3D graphics card	WebGL enabled
Oculus VR	Oculus Rift LM Controller	Oculus-Bridge LM software

Table I. Hardware and software requirements for different visualization modes on the user side. The requirements for the standard mode also apply to other modes

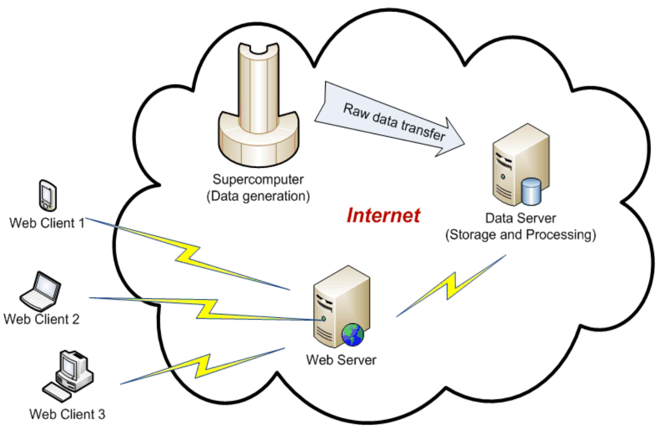

Figure 1. The complete process from data generation to exploration.

As we were developing the web application to support collaborative nucleation research and online teaching, we found the great potential of using the up-to-date stereoscopic virtual reality technology on the web to further enhance distant teaching and learning experience. In this paper, we present a stereoscopic virtual reality enhanced data analysis and visualization solution for online atmospheric nucleation

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research and education. Figure 1 describes the complete process from data generation to exploration. Researchers and students at geographically distributed locations are able to mine the wealth of data generated from a particle-based nucleation simulation through interactive visualization of nucleation processes and pattern search in the molecular self-organization of the aggregates. Considering users with different levels of hardware and software support, four different visualization schemes, as listed in Table I, were implemented. For users who use a 3D capable monitor and a PC with a NVIDIA 3D graphics card, the "NVIDIA 3D Vision" mode could be enabled. For users who wish to use an Oculus Rift and a Leap Motion (LM) Controller, the "Oculus VR" mode is enabled. For users with access to anaglyph glasses, the "Anaglyph" mode is enabled. For all other users, only standard 3D visualization results will be displayed with minimum hardware and software requirements. To evaluate the effectiveness of these different schemes, we conducted a thorough user study. Our findings could be valuable to anyone who is interested in developing a 3D virtual world for research and educational purposes.

The rest of the paper is organized as follows. We first go through previous work on collaborative visualization and stereoscopic virtual reality in Section II. We then present three different stereoscopic VR solutions for our web-based nucleation data analysis and visualization platform in Section III. After that, the user study as well as our observations and findings are discussed in Section IV. In the end, we summarize our contribution and future directions in Section V.

II. RELATED WORK

Over the years, advanced middlewares and frameworks have been developed to facilitate collaborative data analysis and visualization. For example, Brodlie et al. [9] assessed a selection of visualization systems and frameworks for their use in a collaborative environment. Grimstead et al. [13] presented a collaborative grid enabled visualization environment that supports automated resource discovery. Many Eyes [25], a public website for uploading data and creating interactive visualization, supports collaborative visualization at a large scale.

With the increasing challenges of data analysis and visualization, collaborative problem solving has started to draw more attention from visualization researchers. For example, Park et al. [21] explored collaboration issues for a CAVE-based virtual reality environment. Waldner et al. [26] discussed design considerations for employing multiple-view visualizations in collaborative multi-display environments. Bresciani and Eppler [8] analyzed the impact of visualization on knowledge sharing in situated work groups and showed that interactive visualization could bring positive and productive for group work.

Similarly, many efforts have been made to develop techniques to create 3D virtual worlds on the Web. In 1994, the Virtual Reality Markup Language (VRML) was developed to represent 3D virtual worlds connected through the Internet [2]. In 2003, Second Life [3], an online virtual world that currently has about 1 million regular users, was launched. As the virtual reality (VR) technology became more and more mature, researchers began to build web-based 3D VR systems for various research and education purposes [11]-[12], [14]-[15], [20], [23]-[24], which greatly inspired our work.

As stereoscopic virtual reality techniques being widely used, some researchers put their efforts into comparative study [22] and the potential side effects [7]. Their work gave us many valuable insights that were applied to our user study.

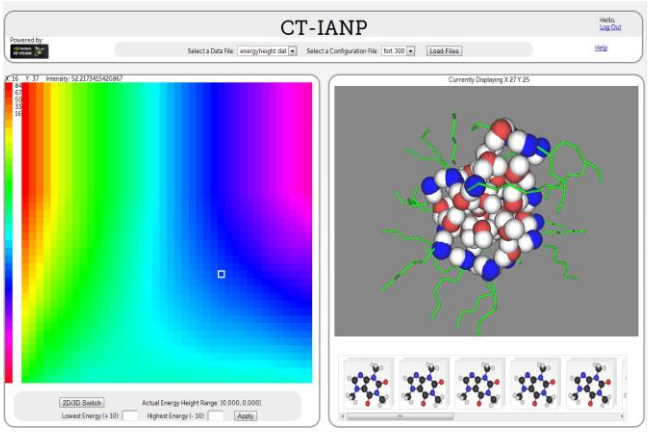


Figure 2. The graphical user interface of our web-based collaborative system. The 2D image on the left shows the nucleation free energy map. The color at each pixel implies the magnitude of nucleation free energy for the particular aggregate that this pixel refers to. When the user moves the cursor over this interactive map, the top side bar would show the aggregate composition (i.e., number of water and hexanol molecules) as specified by this point on the map and its nucleation free energy. On the right, molecular structures of all possible configurations for this aggregate are displayed. Web-based folders with graphic thumbnails group these aggregates based on the similarities of their molecular topologies.

0	1	21.577
0	2	30.622
1	0	17.286
...	...	...

Table II. Free energy height data. Three columns represent the number of water molecules, the number of hexanol molecules, and the corresponding nucleation free energy respectively. The data is used to generate the nucleation free energy map shown on the left display panel in Figure 2.

III. SYSTEM DESIGN AND IMPLEMENTATION

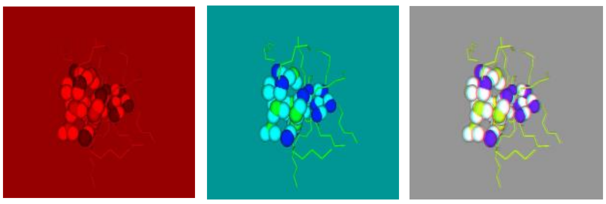
Our web-based collaborative system was developed mainly for investigating atmospheric nucleation processes, although the design ideas should be applicable to other similar web-based applications. Our goal is to develop an easy-to-access platform that links researchers and students from different departments and institutions into a collaborative teaching and learning team. As our targeted users are nucleation researchers and college students studying in relevant fields, the system is designed and developed in a way that users do not need to be experts in computer science or networking or visualization in order to interactively analyze their data. That is, the system must exhibit good usability.

In this research, each particle-based nucleation simulation produces two types of data sets. Table II shows the partial data set for generating the nucleation free energy map. Three columns represent the number of water molecules, the number of hexanol molecules, and the corresponding nucleation free energy respectively. Table III describes the format of aggregate structure data that contains the coordinates of each molecule (and its atoms).

Figure 2 shows the user interface design of our web-based collaborative system. The main screen on the left-hand side displays the 2D nucleation free energy map [10], [16]-[19] using an adjustable color range. The main screen on the right hand side displays the visualization results of molecular structures using one of four different visualization modes: standard, anaglyph, stereoscopic using NVIDIA's 3D Vision, and virtual reality using an Oculus Rift with a leap motion sensor. In the standard visualization implementation, aggregate structures are displayed to users as an interactive model created using the Three.js API, which has minimum hardware and software requirements. As our main focus here is on studying the potential of incorporating stereoscopic virtual reality technologies into our online platform to further improve user experience, we will limit our discussion to other three non-standard visualization implementations.

1 (1st configuration)		
19 (num of molecules)	0 (Water)	19 (Hexanol)
1 (1st molecules)	3 (hexanol)	8 (num of units)
219.49	-202.69	118.25
219.00	-201.67	119.12
219.39	-200.30	118.55
...	...	...

Table III. Aggregate Structure Data.



(a) (b) (c)

Figure 3. An example showing anaglyph visualization using AnaglyphEffect.js API for Three.js: (a) Left eye's image; (b) Right eye's image; (c) Combined image displayed to the user.

A. *Anaglyph Visualization Using Three.js*

For users who own anaglyph glasses, our system provides a VR solution implemented using the AnaglyphEffect.js API for Three.js [4]-[6]. Each frame is rendered by two offset cameras. As shown in Figure 3, the left eye's image is tinted red and the right eye's image is tinted blue. These two images are then combined and displayed to the user.

Because of the color tinting used in the anaglyph method, some of the red and blue molecular structures in visualizations became indiscernible. As a result, water oxygen molecules are now assigned a green material, which appears yellow in the final combined image.

The anaglyph implementation has minimal impact on system performance, and therefore might be the best solution for older and slower systems. Users can toggle the anaglyph visualization on and off with the "*a*" key. Given the simplicity of the molecular structures, shaders, and lighting scheme utilized by the visualization, the extra rendering should not adversely impact most users. As a result, users can switch between anaglyph and standard visualization modes instantaneously.

The anaglyph display can be rotated and zoomed with mouse controls or finger controls on mobile devices. Users can rotate the image by clicking and dragging anywhere. Zooming is achieved by scrolling in and out. Mobile users can rotate the image by dragging with their finger and can zoom by pinching with two fingers.

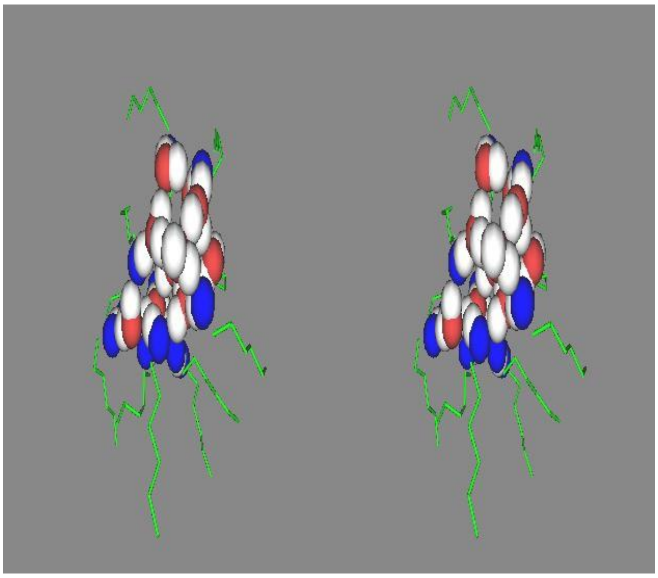


Figure 4. An example frame showing the images captured from two cameras.

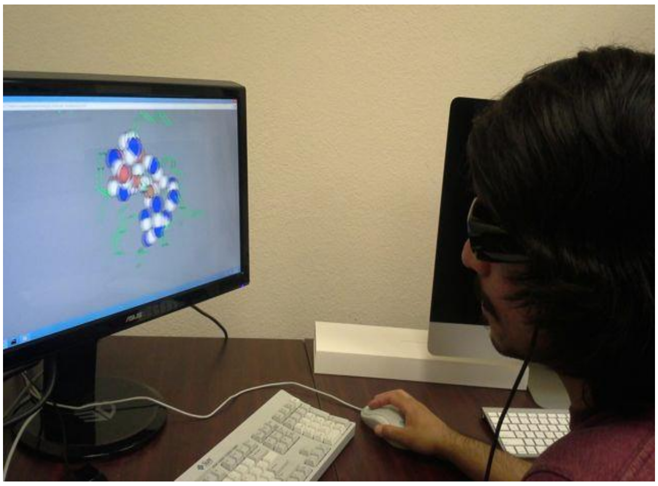


Figure 5. A user was exploring data using stereoscopic visualization.

B. *Stereoscopic Visualization Using NVIDIA 3D Vision*

For users with a 3D capable monitor, a PC with a NVIDIA 3D capable graphics card, and an NVIDIA 3D Vision kit, our system provides stereoscopic visualization implemented using NVIDIA 3D Vision. Users can toggle the stereoscopic visualization on and off with the "*s*" key.

Aggregate structures are rendered from two cameras that are slightly offset from each other. When the user updates the scene, a new frame is rendered. The images captured from two cameras are placed side-by-side in a single PNG image and saved on the server. Figure 4 shows an example frame. The saved frame is then loaded by the NVIDIA 3D Vision embedded web element.

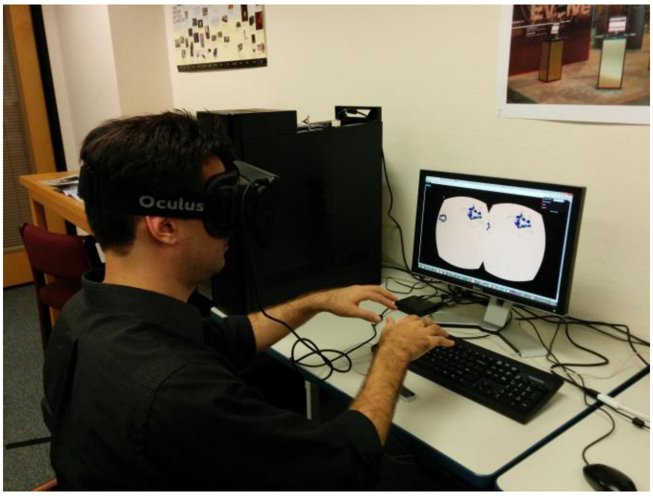


Figure 6. A user was using Oculus Rift for nucleation data visualization.

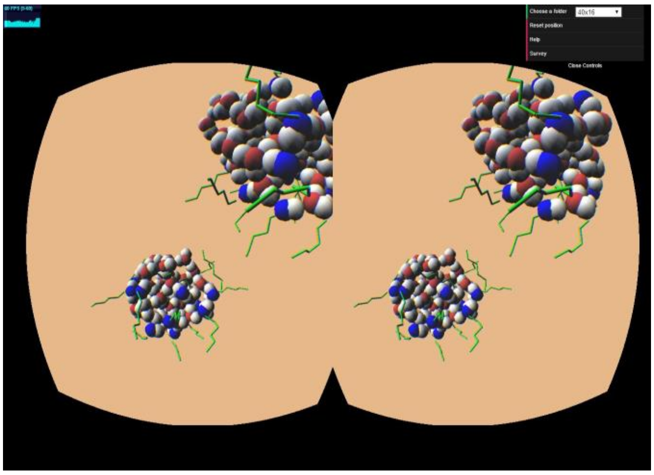


Figure 7. A screenshot of the Oculus-Leap Visualization.

This process of rendering frames suffers from some latency. Rendering from two cameras and encoding the PNG image does not introduce any significant performance decrease. However, saving the PNG image on the server, downloading the saved image from the server, and loading the image into the NVIDIA 3D Vision embedded web element all take time. Because the frame is being sent to the server and then retrieved from the server, the primary performance bottleneck is the network connecting the client and server. As a result, users with slower network connections might experience some delay.

Because of the brief load time associated with rendering and loading each new frame, frames are not continuously rendered while the view is being manipulated. While the user rotates or zooms the view, the stereoscopic display is momentarily disabled. When the manipulation is complete, the new frame is rendered and displayed. If the client has a slow network connection, while the client waits for the frame to be saved on the server, the standard visualization will continue be displayed to the user.

Users can rotate and zoom the camera view using the same controls offered by the anaglyph solution. Additionally, users can use the “*l*” and “*k*” keys to increase and decrease the separation of the cameras in the scene, for better viewing comfort and clarity. Figure 5 shows a user was exploring data using stereoscopic visualization.

While there are many websites that use NVIDIA 3D Vision to display static images or video, the authors of this paper are not aware of any interactive web applications currently using NVIDIA 3D Vision. Existing projects using NVIDIA 3D Vision can be found at https://www.3dvisionlive.com/.

C. Visualization Using Oculus Rift

For users with an Oculus Rift and a Leap Motion Controller, the Oculus-Leap Visualization provides a greater feeling of immersion than a traditional keyboard and mouse setup. It allows for a more natural way for the user to explore and visualize data. Figure 6 shows a user using Oculus Rift for nucleation data visualization and Figure 7 shows one screenshot.

This option requires software installation on the user side. The Oculus-Bridge executable needs to be extracted and run. During visualization, it is important to keep the Oculus-Bridge software running. Users also need to download and install the latest software for the Leap Motion Controller. Since the Oculus-Leap Visualization does not provide any information on the data itself, users should already have had some experience with the data being visualized.

Implemented with the Three.js library, the application delivers excellent performance on many machines. The majority of computations done by the server entail sending a pre-written JSON file to the client. If the file does not exist, it is created and sent to the user, with a copy permanently saved on the server for faster access in the future. The majority of visualization is done on the client’s machine and there is only a slight delay when the client requests a new aggregate structure to be displayed.

Under the “Oculus VR” mode, the GUI was designed in a way that the software could assist the user with basic tasks without numerous and complex controls. Through the GUI, the user can select different groups of aggregate structures, reset the position of the structures, check the help page for the requirements and setup, and take the survey used in the user study. Three main controls, that is, translation, zoom, and rotation, are currently supported. Translation can be done using any finger and the index finger is recommended. Zoom needs 3 fingers and the thumb, middle and index fingers are recommended. Rotation can be done using any number of fingers except 1 or 3 fingers. Keeping an open hand with all 5 fingers erect is recommended. The user can also compare two aggregate structures while the left hand controls one aggregate structure and the right hand controls the other. To switch to a different structure, users can simply zoom the aggregate structure away until it disappears and a new one appears. Note that the palm of the hands should always be above the Leap motion sensor and the fingers should be straight. It is more difficult for the motion sensor to detect bent or curved fingers. This may cause faulty results.

Since Oculus VR technology is quite new, there are only few existing tools that use it. One of which is the Oculus Rift Tuscany Demo that allows the user to interact with objects inside a modeled house with the Oculus Rift and the Razer Hydra, a device that allows for user input in three dimensions [27]. Another similar demo is “Shark Punch” which incorporates the Leap Motion controller physically attached to the Oculus Rift.

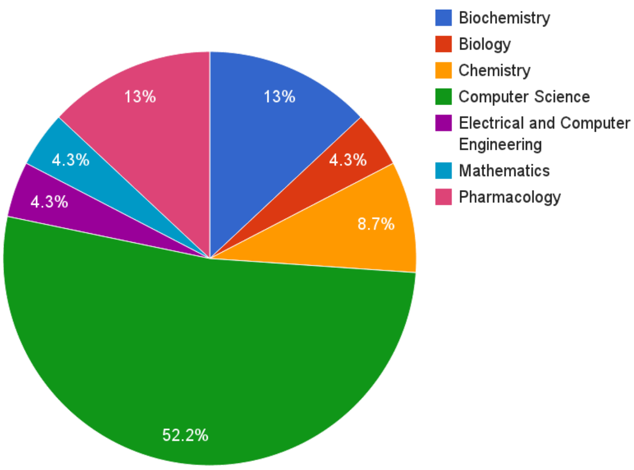


Figure 8. User Profile.

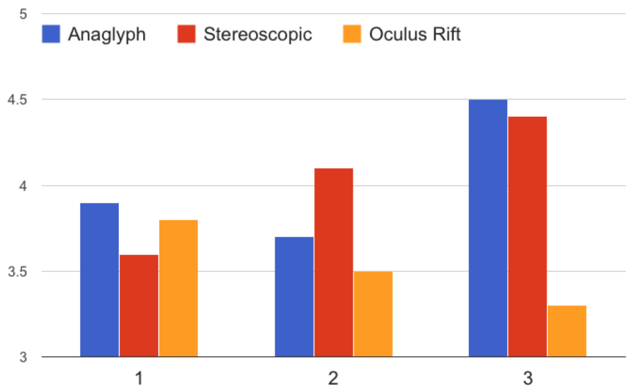


Figure 9. Average user ratings for Question 1-3.

IV. User Study

To gain a better understanding of how users feel about these different solutions, we conducted a user study that involved 23 people from 7 disciplines at our university, as shown in Figure 8. Among 23 users, 10 users are CS or ECE majors and 13 users are domain experts.

Each user was asked to answer the following 11 questions after using one of the Stereoscopic VR techniques to explore the dataset.

1) How helpful was the visualization in general? (Rate 1-5)
2) How clear was the image in the visualization? (Rate 1-5)
3) How easy was it to use the web site? (Rate 1-5)
4) Did the visualization cause any discomfort? If yes, please describe it.
5) Did you find this form of visualization helpful? Why or why not?
6) Would you recommend this form of visualization to others? Why or why not?
7) What was the easiest feature to use?
8) What feature did you like the most? Why?
9) What feature did you dislike the most? Why?
10) How enjoyable was your overall experience? (Rate 1-5)
11) What improvements can make this site better?

The first three survey questions were designed to measure overall user satisfaction toward three virtual reality enhanced visualization schemes we have developed. Figure 9 shows the average user ratings (1 being poorest, 5 being best). We can see that the majority of those surveyed felt that visualization was helpful.

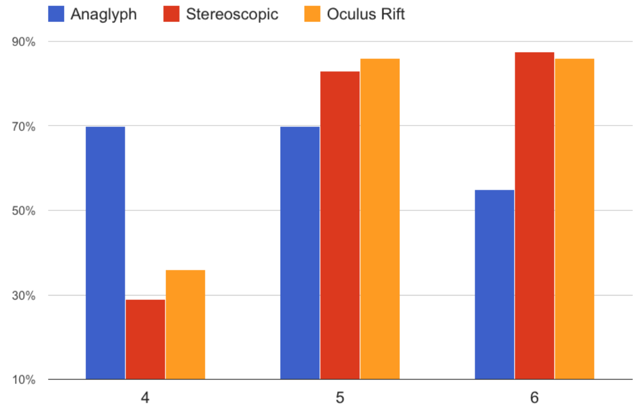


Figure 10. Percentages of users who gave positive answers to Question 4-6.

Figure 10 shows the percentage of users who gave positive answers to Question 4-6. The Oculus Rift and stereoscopic visualizations seem preferable to the anaglyph visualization.

Among all user interaction features, 98% of users said rotation and zooming are easiest to use. Viewing molecular structures in 3D and gesture control are the features the majority of our users liked most. The following are some exemplary answers to Question 8:

- "I can see great potential for this kind of molecule manipulation, like doing 3D molecular building." (From a Pharmaceutical student on gesture control)
- "It was cool to see the molecule in different point of views." (From a biochemistry student on 3D visualization)
- "It showed a much clearer image of the molecule. It's good for chemistry students. They can use this to observe 3D models." (From a Chemistry student on 3D visualization)
- "The molecule rotations felt like something out of a sci-fi movie. Visually, it functioned exactly like I imagined it would." (From a Computer Science student on 3D visualization)
- "It is so unusual and novel. It is also quite fun to do." (From a Biology student on gesture control)

While many subjects found the anaglyph visualization helpful, 70% of users said they experienced discomfort including headaches, dizziness, and eyestrain. In contrast, the Oculus Rift and stereoscopic visualizations caused discomfort for 36% and 29% of those surveyed respectively. Most complaints on the Oculus Rift and stereoscopic visualizations are connected to user interaction. As a result, test subjects were more likely to recommend the Oculus Rift and stereoscopic solutions than the anaglyph solution. The following are some comments in response to Question 9:

- "My eyes had a rough start adjusting to the glasses when I put them on and made my vision funny in terms of coloration for a few minutes after taking them off." (From a Engineering student on anaglyph glasses)
- "I wear glasses so it was uncomfortable." (From a biochemistry student on glasses)
- "It was very difficult to rotate the molecule due to the limited amount of space. After I learned how to properly rotate the molecule, it was counter intuitive and did not work how I expected." (From a Chemistry student on rotation supported by Oculus Rift VR)
- "Zooming in and out required an additional click to have the image on the bottom update." (From a Computer Science student on the NVIDIA 3D Vision mode)
- "Perhaps my eyes, but it didn't quite seem in focus. I wanted a crisp distinction between the different types of atoms, but it's not clear other than color." (From a Biology student on anaglyph)

Figure 11 shows the percentages of CS and non-CS major users who gave positive answers to survey question 5. We noticed that the biologists, chemists, and pharmacologists found the anaglyph and Oculus Rift solutions helpful more often than computer scientists. The CS major users seem to have higher expectations on the 3D effects and usability as many of them have taken courses such as Software Engineering, Virtual Reality, and Human Computer Interaction. The stereoscopic implementation was the most consistent in popularity between students with different majors.

In this user study, we received some valuable suggestions for improvement. For example, users would have preferred a more intense 3D feeling from the stereoscopic visualization and they would like the Oculus Rift solution to include better ways for users to learn the control scheme. We also noticed that users with corrective lenses often expressed frustration with visualization techniques that required removing prescription glasses or wearing visualization glasses over prescription lenses.

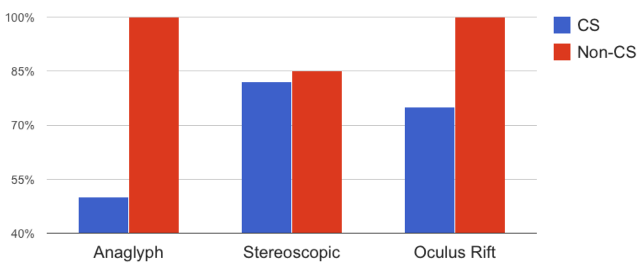


Figure 11. Percentages of CS and non-CS major users who gave positive answers to Question 5.

V. Conclusion and Future Work

In this paper, we describe the design and implementation of a web-based system that incorporates stereoscopic VR enhanced data visualization for collaborative atmospheric nucleation research and online education. Four different schemes were developed for users with different levels of hardware and software support. The findings from our user study demonstrate that stereoscopic virtual reality enhanced visualization has a great potential to enhance data understanding in data-intensive computing research and education.

In the future, we would like to further improve user interaction based on user feedback. We will extend our user study to researchers and students at other universities and institutions to gain more insight.

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