Beyond the Screen: Gestural Perspective-Taking with a Biochemistry Simulation

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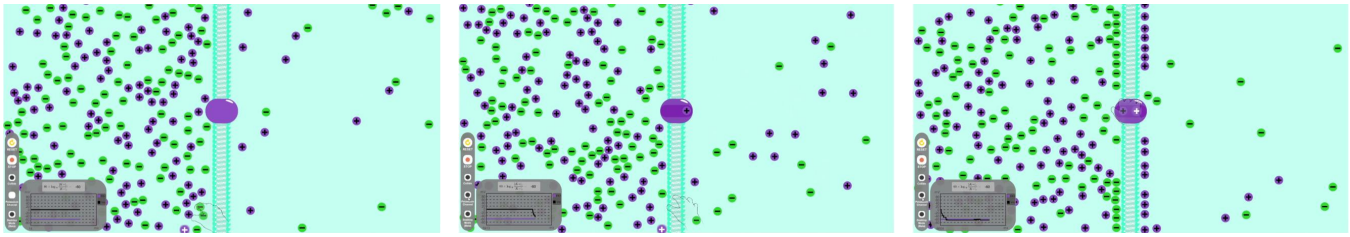

Figure 1: Gesture based dynamic equilibrium simulation; left when the channel is not opened, middle the channel is opened, and right when equilibrium is achieved.

ABSTRACT

Significant research has been conducted on how students' gestures aid in learning scientific concepts, yet there remains a gap in understanding the impact of gesture-based interactions between students and simulations on their interpretation of visualized scientific phenomena. Addressing this, our paper presents a usability test conducted on a dynamic equilibrium visualization simulation developed for introductory college courses. Through a user study involving 40 participants, we conducted a qualitative evaluation to determine how students interpret gesture-controlled simulations. The findings confirm that students generally interpret visualized scientific concepts effectively and that interacting through gestures enhances their interpretation of the simulations. Additionally, this paper discusses the limitations of the current study and suggests directions for future research.

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CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in visualization**.

KEYWORDS

Gesture-controlled simulation, User testing, Science interpretation, Dynamic equilibrium

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1 INTRODUCTION

There is a steadily growing body of research suggesting that student achievement in science is generally supported by direct access to multimodal representations [4]. It was found that visualization not only aids students' memory but also sparks interest and maintains concentration [12]. Scholars have been actively researching the methods and effectiveness of visualizing abstract concepts, with

various studies demonstrating their efficacy [9, 16, 22]. Visual representations in educational materials are particularly crucial for bridging the gap between abstract scientific theories and tangible understanding, especially in subjects like biochemistry, where concepts are often microscopic and not directly observable [24].

However, the visualization of complex scientific concepts can vary in effectiveness depending on students' prior knowledge and visuospatial abilities, and it does not always guarantee improved learning outcomes [13, 25]. The interpretation of visualizations can differ among students, potentially leading to non-canonical understandings of the concepts [20]. This variability poses a particular challenge in formal education settings, where instructors may find it difficult to gauge in real time how multiple students are interpreting visualized concepts [7]. Consequently, it is crucial to meticulously design visual simulations that minimize potential confusion in students' interpretation of complex scientific concepts. Essential to this process is conducting user testing, which can allow designers to understand how learners are interpreting various interface elements, and what meanings they are potentially making as they engage with them.

Designing visual simulations for more embodied interaction is a promising approach to facilitate student learning and "ground" their understanding of abstract concepts in learner's own body movements [3]. With the advancement of technologies such as the Leap Motion and Kinect, students can interact with simulations using natural physical movements, as opposed to traditional methods such as keyboards or mouse clicks. Research has demonstrated that users interact more efficiently with simulations through gesture-based controls [15, 18]. Nonetheless, most of these studies focused primarily on the efficiency of the interaction between the user and the simulation, with less attention paid to how gesture-based interactions might facilitate interpretation and meaning-making with the simulations. In the learning sciences field, while there is significant research on how students' gestures assist in learning scientific concepts [2, 10, 17], there remains a gap in understanding the impact of gesture-based interactions on students' interpretation and meaning-making of these simulations.

In response, this paper presents a usability study conducted on a visualization simulation of dynamic equilibrium developed for use in introductory college biochemistry courses, analyzing how students interact and interpret with visualized models. The main aim of this usability study is not to measure how well students achieve high learning outcomes through the simulation but to analyze how well a diverse group of students, even those not majoring in biochemistry, are able to interpret the complex interrelated concepts and interface related to dynamic equilibrium in a gesture-controlled simulation. Thus, the research questions are as follows: (1) To what extent do participants using a gesture-controlled biochemistry simulation effectively interpret the interface components? (2) To what extent do participants using a gesture-controlled biochemistry simulation identify with the target particle, and how does that identification seem to impact their interactions?

2 RELATED WORK

Previous research suggests that prompting students to create representational gestures of scientific phenomena are beneficial for learning [5, 14, 23]. Representational gestures are gestures that illustrate an aspect of an object or some process [19], such as rotating one's hands to show that a scientific object has a shape of a sphere, or using one's fingers to show the trajectory of projectile. Representational gestures can be especially useful in explaining scientific phenomena that are not visible or occur at a scale of space or time such they are not visible (e.g., molecular interactions, magnetic forces). Much research has examined the impact of spontaneous gestures on learning, but there is also emerging interest in how gestures can be guided such that the meaning that a person makes between their gesture and what it represents is emergent [17, 21]. One way that gestures can be guided is through digital interfaces that track and respond to gestures. Depending on the feedback that the person making the gestures is getting from the interface, and the meanings that the person is making from how the interface responds to the gestures, a person may be led to change their gestures in some way or explore a different path.

Gesture-controlled simulations are starting to be employed in educational contexts. For example, Chinthammit [6] describes an organic chemistry simulation where learners use hand gestures to rotate and explore different molecular structures. In this case, gestures were essentially used to engage with digital manipulatives (the molecules) projected on screen. Likewise, Matulic and Vogel [18], users could interact with a terrain modeling simulation by using mid-air hand gestures that served the purpose of "sculpting" digital terrain. In most examples of gesture-controlled simulations and educational technology, gestures are used to simulate physical interaction with digital objects. For the biochemistry simulation described in this paper, gestures are used to represent the movement of the objects themselves, with the digital objects essentially becoming avatars of the users' hands. This presents a novel paradigm for gesture-based engagement with educational simulations.

3 SIMULATION DESIGN

We designed the simulation to teach the concept of dynamic equilibrium (Figure 2). After interacting with the simulation, students are expected to understand the factors influencing the movements of charged particles across a semi-permeable cell membrane and how this movement eventually leads to dynamic equilibrium. Concentration differences between the separated chambers and electrical potential dictate this movement. In a real cell, such movement is happening for millions of particles across the entirety of the cell membrane. Visualizing this type of scientific process accurately is not only computationally challenging but also does not lead to a useful learning tool due to the visual clutter [8]. Therefore, several pedagogical simplifications are made in the simulation design to enhance the simulation's teaching efficacy.

The simulation is built in Unity3D because it includes a robust physics and graphics engine along with its flexibility to interact with gesture-based interface hardware such as the Leap Motion controller. The simulation visualizes a zoomed in section of a cell membrane which separates the intracellular and extracellular fluid. On each side, there are small green and purple dots representing negatively charged chloride (Cl^-) and positively charged potassium (K^+) ions. We intentionally used green and purple representations

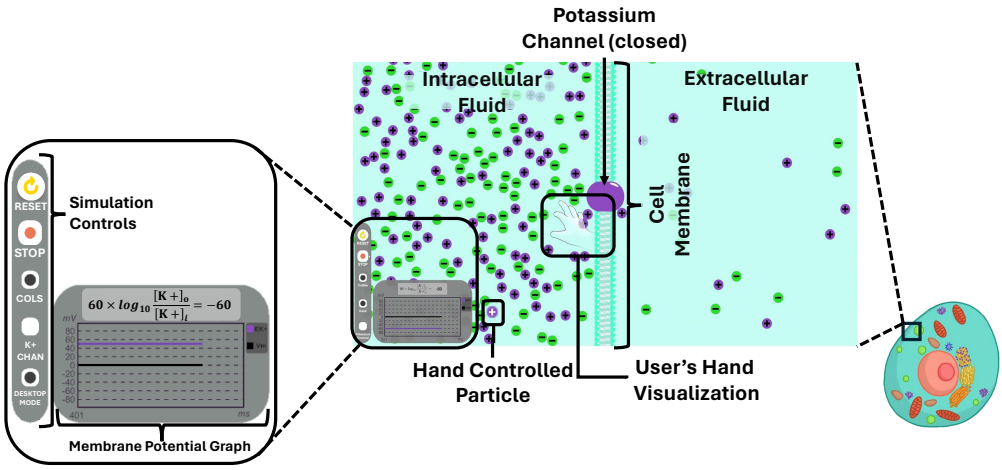

Figure 2: Visualization design with key aspects annotated.

because these colors are considered optimal for visualizing contrasts between two objects [11]. Once the simulation begins, the particles experience a random force vector. This random movement leads to inter-particle collisions and collisions with the border of the visualization. These collisions are handled by Unity's physics engine. A purple channel is embedded in the cell membrane that allows only K^+ to pass through if the channel is in the open state. At the start of the simulation, the K^+ channel is closed and therefore no particles can move between the intracellular and extracellular fluids. A radio button was included in the simulation controls to open and close the channel. Other simulation controls allow for resetting and pausing the simulation, toggling inter-ionic collisions, and toggling the visibility of the ghost hand (discussed in Section 4).

At the start of the simulation, the equilibrium potential (E_o) is computed using the Nernst equation. Once the K^+ channel is opened and K^+ is exchanged, the simulation begins to track the intra- and extracellular K^+ concentration levels to compute the membrane potential (V_o). In the simulation, when K^+ moves across the channel, V_o is computed as $\hat{V}_o - \alpha * ([K^+]_{i,i} - [K^+]_{e,i})$ where $\hat{V}_o$ is the membrane potential in the last frame, $[K^+]_{i,i}$ and $[K^+]_{e,i}$ are the initial K^+ concentrations inside and outside the cell, and $\alpha \in (0, 1]$ is a scaling factor set by the facilitator. If a K^+ ion collides with the K^+ channel and if $V_o \neq E_o$, the K^+ is allowed to move across the channel. The changes in V_o and E_o are visualized in the graph on the bottom left of the interface where the purple line depicts E_o and remains constant during the simulation and the black line depicts V_o, updating in real-time as the simulation runs. It is important that membrane potential updates in real-time because it will eventually converge to the black line. When $V_o = E_o$, the cell is in dynamic equilibrium and there should be no net flux in ion concentration across the cell. Therefore, the movement of K^+ across the channels is dictated by two factors:

(1) **Chemical Driving Force**: Random diffusion which occurs if a K^+ ion gets close to the potassium channel.
(2) **Electrical Driving Force**: The difference between the membrane potential and the equilibrium potential.

Chemical driving force is usually well understood by students because they can easily visualize the intra- and extracellular K^+ concentration gradient. Focusing on only one channel with a limited number of ions should lead to increasing the visual saliency of this concentration difference. However, electrical driving force is a more challenging concept to deliver because of how quickly particles diffuse at the beginning of the simulation which leads to V_o approaching E_o quickly. To overcome the second challenge, the simulation includes the α term when computing the membrane potential every frame. This can scale the value of K^+ moving across the channel. If α is close to 0, more K^+ has to move across to reach equilibrium and the student would have more time to see how the membrane potential approaches dynamic equilibrium in the graph.

Another important concept visualized in the simulation is the phenomenon of K^+ and Cl^- attracting each other across the membrane. Although this attraction is present all the time, it is most important to observe this across the membrane to remind the students that the ions are also influenced by the electrical driving force and not just the chemical driving force. To implement this, if a K^+ and Cl^- align (within some threshold) across the membrane and both ions are close to the membrane (within some threshold), a force vector pulling the ions towards each other is activated. Figure 1c shows the ions aligned in the simulation.

4 HAND TRACKING DESIGN

The most important feature of the simulation is allowing the learner to embody a designated K^+ with their hand ($K^{+,*}$). Hand tracking is accomplished with the Leap Motion controller which is placed on a desk facing upward below the learner's hand (Figure 3). By default, the simulation tracks the right hand, although the handedness can be changed before starting the simulation. The (x, y, z) position of the palm is transmitted to Unity3D and is used to localize $K^{+,*}$. Specifically, gesturing left and right modulates the x-coordinate of $K^{+,*}$ and gesturing up and down modulates the y-coordinate of $K^{+,*}$. Moving the hand forward and backward does not change $K^{+,*}$'s position creating a gesture plane. The intended display for the simulation is a large monitor. To ensure comfortable gesturing,

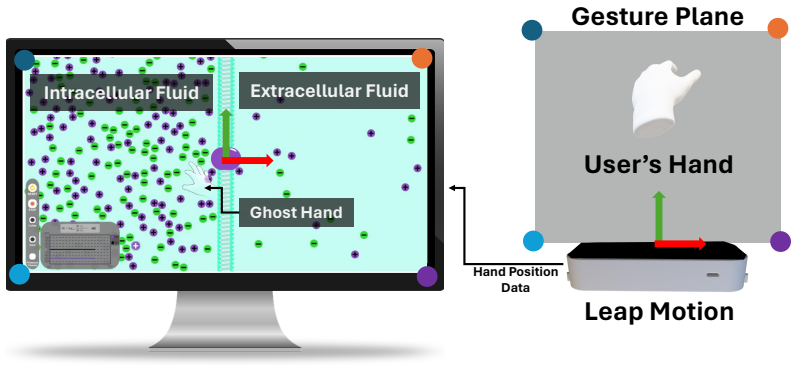

Figure 3: Hand tracking setup. The colored circles depict how the hand position in the gesture plane is mapped to the $K^{+,*}$ position on the monitor.

the width and height of the gesture plane can be specified and the corners of the gesture plane correspond to corners of the monitor allowing the $K^{+,*}$ to reach all parts of the simulation window without the learner having to gesture across large distances. To increase the visual saliency of $K^{+,*}$, it is shaded with a lighter hue of purple and the positive symbol is colored white (as opposed to black). Additionally, a hand model is visualized on top of the simulation to give the user an additional visual cue on how to orient their hand gestures. It is also important to note that if the learner attempts to move $K^{+,*}$ across the channel when $V_o = E_o$, $K^{+,*}$ will not move but the hand visualization will track the learner's gesture to indicate to the learner that the hand tracking is functioning properly even though the ion stopped following their hand. It is important for the leaner to distinguish that the ion cannot pass through the cell membrane freely and there is another force (electrical driving force) that can prevent the transmission. If the user's hand moves outside of the gesture plane, the ghost hand visualization disappears but $K^{+,*}$ continues to move as if it were a regular particle. Once the hand re-enters the gesture plane, the hand tracking behavior as described above reconvenes.

5 USER STUDY

A qualitative user evaluation was conducted to assess the usability and interpretability of our gesture-controlled simulation.

5.1 Participants

Forty undergraduate students, none of whom were majoring in biochemistry, participated in a survey and interview about the simulation. Their average age was 18.95 (SD=0.93). None of these participants had prior experience with Leap Motion-based hand gesture-controlled simulation, and only one had previously encountered a Kinect-based gesture-controlled simulation in a museum.

5.2 Procedure

The study began with collecting consent forms. We then adjusted the student's position for optimal use of the Leap Motion device. We explained that the purpose of this research was not to evaluate their learning performance but rather to gauge the ease and intuitiveness of their interaction with the system, as well as their interpretation of the simulation. The researcher introduced the basic components of the visualization, such as using purple dots to represent potassium ions, green dots for chloride ions, and a central structure to depict the cell membrane. This clarification was particularly necessary, as all the students were from disciplines outside of biochemistry. After the brief introduction, students interacted with the simulation while its channel was closed, and they were asked to share their observations. Next, they were prompted to predict the outcomes of opening the channel. Following their predictions, we opened the channel and let students interact with their designated ion as much as they wanted. We then sought their interpretations of the phenomena they observed. The participants were also questioned about their ability to understand the relationship between the graph and ion movements while manipulating the designated ion and their overall experience with gesture-based ion control. We ensured that the students had sufficient time to express their thoughts, advancing to the next phase only after they had finished speaking. The session concluded with a survey administered to all participants.

6 RESULTS

6.1 Survey Analysis

We conducted a survey to assess the ease of use, perceived usefulness, and level of immersion of the simulation. The survey items were adapted from those used in [1], tailored to fit our study's objectives. The survey items and results are summarized in Table 1. Overall, students rated the ease of use of the simulation highly, giving it a score of 4.19 out of 5. This indicates that the gesture control simulation was not difficult for students to use. Notably, 39 out of 40 participants had no prior experience with gesture-controlled simulations of any scale, further underscoring its user-friendliness. However, students did encounter some difficulty in interpreting the relationship between graphs and ion movements, with an average score of 3.17 out of 5 in this aspect. This challenge was somewhat anticipated, considering their lack of disciplinary knowledge [25]. Regarding the perceived usefulness of the simulation, students rated it as highly effective for learning, with a score of 4.6 out of 5. They also believed that the simulation could possibly enhance their understanding of both electrical and chemical potentials. Lastly, the immersion aspect received a positive response, scoring 4.28 out of

Table 1: Survey Results

Category	Items	Mean (SD)
Ease of use	It was easy to learn to use the gesture-controlled simulation.	4.35 (0.69)
	I would like to continue working with the simulation.	3.8 (0.96)
	The graph information in the lower left was easy to understand.	3.17 (1.15)
	The text information presented on the screen was easy to read and understand.	4.62 (0.66)
	I found it easy to know what was happening at each stage of the simulation.	4.12 (0.88)
	I didn't have any technical problems using the simulation.	4.42 (0.95)
	The visual quality of the simulation was good.	4.82 (0.38)
	I had no difficulty using gestures to move the ions in the direction I wanted.	3.87 (0.96)
	The overall simulation was easy to use.	4.55 (0.63)
Usefulness	I think the simulation will help students learn biochemistry concepts.	4.7 (0.54)
	I think the simulation could help me develop my understanding of biochemistry concepts if I had more time to interact with it.	4.65 (0.57)
	I think the simulation could improve my knowledge of chemical potential if I had more time to interact with it.	4.52 (0.75)
	I think the simulation could improve my knowledge of electrical potential if I had more time to interact with it.	4.47 (0.75)
Immersion	I was fully immersed when using the simulation.	4.4 (0.77)
	I felt like I was part of the simulation while controlling the ions through gestures.	4.17 (0.95)

5, indicating that most students were deeply engaged while using the gesture control simulation.

6.2 Interview Analysis

During the interviews, all 40 students reported high satisfaction with the clarity of the simulation interface and its visualizations. They had no trouble interpreting various elements such as potassium ions, chloride ions, cell membranes, a potassium ion channel, and simulation control buttons. This response is consistent with the survey results, where the visual quality was rated at 4.82 out of 5.

We asked students about their expectations for what would happen upon opening the K^+ channel. Thirty-eight students anticipated that ions would move from areas of higher ion density (intracellular fluid) to areas of lower ion density (extracellular fluid) until a similar ion distribution was achieved in both fluids. This reflected their understanding of chemical potential, though they did not consider the electrical potential. Two students, drawing on their high school AP (Advanced Placement) biology lessons about dynamic equilibrium, predicted that ions would not distribute evenly, with a higher concentration remaining in the intracellular fluid. This response suggests they recognized the existence of electrical potential, even though they did not specifically use biochemistry terminology.

After opening the K^+ channel, we allowed the students to freely interact with the simulation and asked them how they interpreted it. All the students noticed that ions were not equally distributed between the fluids, with a higher concentration remaining in the intracellular fluid. Eleven students interpreted that this was likely due to the electrical charge of ions, observing the accumulation of ions with opposite electrical charges near the cell membrane.

Next, we asked the students how they interpreted the graphs. Sixteen students figured out that the movement of K^+ ions between the fluids affected the black line on the graph. They achieved this understanding by continuously moving a designated ion between the two fluids using hand gestures. The students deduced that ions couldn't pass through the cell membrane, as evidenced by a 'ghost hand' that could pass through the membrane (confirming that the hand tracking was functioning properly), while the ion itself could not. However, when the designated ion was placed near the K^+ channel and failed to move to the other fluid, many students ascribed this either to their own control errors or to a bug in the simulation, rather than contemplating why their designated ion did not pass through the K^+ channel.

7 DISCUSSION

During user testing, no student reported difficulty in controlling the simulation through gestures. This was significant since none of the students had prior experience with using hand gestures to interact with simulations. In addition, a high average score of 4.17 in response to a survey question about feeling part of the simulation through gestures suggested that embodying gestures played a role in the students' meaning-making processes.

The interpretation of visualized scientific concepts, facilitated by gesture-based interactions, was also received positively. Before opening the K^+ channel, students were able to make educated guesses about chemical potential by observing the concentration gradient of the ions. Upon opening the channel, they endeavored to understand what factors, beyond chemical potential, could influence ion movement, facilitated by their manipulation of a designated ion through gestures. It is encouraging that, despite most participants having limited prior knowledge of dynamic equilibrium, 11 students correctly surmised that electrical charge might be influential. Notably, the majority of students reported feeling deeply engaged with the learning content while interacting with the simulation. This suggests that gesture-based control could enhance engagement and a sense of embodiment.

However, the usability test revealed several areas for improvement. We had deliberately engineered only a slight change in the graph when a K^+ ion transits between fluids, aiming for students to witness the dynamic equilibrium process after we open the K^+ channel. This approach allowed students to see how the graph changes during dynamic equilibrium. However, the subtle changes in the graph's response to the ion's movement post-equilibrium made it difficult for them to interpret the correlation between the graph and the ion's movement. One student proposed the addition of a recording feature in the simulation, allowing for the capture and subsequent analysis of the ion's movement between the fluids over time, which could aid in better understanding their relationship.

Finally, the design choice to prevent the designated ion from traversing the K^+ channel under specific conditions (when $V_o = E_o$, $K^{+,*}$) caused confusion among many students. In future versions, it will be crucial to visually clarify that this phenomenon is not due to a control issue or a simulation bug, but is rooted in scientific principles. For instance, varying the hue of the K^+ channel to indicate its passability could engage students in reflecting upon the reasons behind the change in the channel's hue.

8 LIMITATION AND FUTURE DIRECTION

This study primarily explores how students from diverse backgrounds, possessing relatively limited prior knowledge of dynamic equilibrium, interpret scientific concepts through gesture-based simulation interactions. Since prior knowledge plays a significant role in understanding scientific concepts [25], it is essential for future research to investigate the learning outcomes specifically among biochemistry students. Furthermore, our findings indicate that while students could readily interpret the chemical potential in the gesture-controlled simulation, a more evident indicator is needed for the inferential concept of electrical potential. In response to this, we are in the process of developing haptic gloves to provide students with physical feedback as they maneuver a designated ion, enabling them to feel sensations such as collisions with surrounding ions and the attraction to opposite electrical charges. We anticipate that the addition of haptic feedback will not only deepen the immersion in the learning experience but also offer an additional layer of reasoning for students when interpreting scientific concepts.

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