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Research article

Enhancing pre-service teachers' understanding of density through the CAVE virtual reality experience

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Abstract: The concept of density is difficult for students to understand because it cannot be directly observed. To gain a deeper understanding of this concept, students need to learn about density at the microscopic and macroscopic levels. Virtual Reality (VR) provides an opportunity for students to experience the phenomena at both levels. A density exploration simulation was used in a Cave Automatic Virtual Environment (CAVE) to investigate the impact of the CAVE on preservice teachers' understanding of density. Three preservice teachers were interviewed before and after their CAVE experience on the concept of density. The data collected consisted of participants' recorded audio responses, written texts, and drawings made during the interviews. Thematic analysis was used to examine the raw data, and three major themes emerged regarding participants' understanding of the concept of density. The experience helped participants visualize water and oil molecules, recognize differences in molecular structures, explore the role of intermolecular forces in determining water density, and observe that air does not affect ice density at the microscopic scale. The study suggests that students can benefit from VR experiences such as those in the CAVE to explore density at macroscopic and microscopic levels.

Keywords: density, pre-service teacher education, virtual reality (VR), cave automatic virtual environment (CAVE), conceptual understanding, misconceptions

1. Introduction

Knowledge about density is common among most people, including young learners. Even at the age of four, children begin to develop ideas about "heavy" and "light" materials and often believe that larger objects are heavier [1]. Density, as a physical quantity, plays a critical role in many areas and is fundamental in fields of Science, Technology, Engineering, and Math (STEM). Many students view density solely as the result of dividing mass by volume, rendering it an abstract calculation. This view can prevent them from recognizing, for example, that compressing an object increases its density. They often miss the core idea that density describes how tightly mass is packed into a given space [2]. It is therefore essential that students have a thorough and clear understanding of the concept of density, rather than merely memorizing the formula and definition [2,3].

As a concept, even high school students often misunderstand the concept of density. Many believe they understand it simply because they can apply the formula D = M/V to solve problems [4]. However, reciting the formula or performing calculations does not equate to a deep conceptual understanding. While some students who are comfortable with ratios may grasp the mathematical relationship, most fail to connect it to the idea of density as the measure of how tightly mass is packed in each space. To move beyond surface-level knowledge, students need to confront their naive conceptions of density [1]. They must also explore the molecular-level factors that affect density, such as molecular mass, structure, intermolecular forces, and temperature. As Xu and Clarke [5] emphasize, understanding density requires engagement at the macroscopic (what can be seen and measured) and microscopic (what happens at the particle level) levels.

Since the term density is quite common outside the classroom, as used informally, teachers often assume that students can distinguish the informal and formal uses of the term. It is not uncommon for students to use the words density, weight, and denseness synonymously, indicating that the concept of density is not well understood and is often associated with misconceptions [5]. One of the reasons many students find this concept difficult is that, unlike other quantities such as mass, weight, length, and time, density cannot be measured or observed directly; it must be computed from other quantities. Moreover, density is typically taught as a macroscopic property of matter, along with its formula and definition [6]. Thus, students struggle to relate the concept microscopically to the nature of matter. As a result, students often view density as an isolated property of matter, lacking deeper conceptual significance [7]. Even after relevant instruction involving laboratory experiments or the use of computer simulations, some students may struggle to grasp the concept [1,8]. This ongoing difficulty highlights the need for new tools to be introduced in the teaching of density, enabling students to explore macroscopic and microscopic aspects of density [5].

While teaching approaches and instructional models have been explored, there is limited research on how immersive technologies, such as the Cave Automatic Virtual Environment (CAVE), can support students in developing a deeper understanding of density at the microscopic scale. Researchers have primarily focused on learners' comprehension of density at the macroscopic level, emphasizing the application of the density formula and definition from a quantitative perspective. However, there is a gap in research regarding how learners develop their understanding of density at the microscopic level through the Density CAVE experience. One potential solution for providing students with microscopic-scale experiences is virtual reality, and a 3D CAVE experience has the potential to impact students’ understanding of density at the microscopic level.

Therefore, a CAVE density simulation was adapted to explore the potential impacts and drawbacks of using VR technologies for learning about micro-scale phenomena such as density. Specifically, we investigate how CAVE technology can help students explore the concept of density at the microscopic scale and identify major themes arising from the analysis of the collected data. The National Research Council [9] recommends that students should understand the concepts of density rather than just memorizing the formula and definition. Understanding basic concepts such as density is crucial for students' future learning success [2]. Additionally, we examine conceptual changes in participants' comprehension of density at the microscopic level before and after experiencing the Density CAVE. Unlike two-dimensional computer technologies, the CAVE enables users to actively engage in the learning process. Users manipulate simulations of molecules, such as oil and water molecules, using their eyes, ears, and muscles, along with their cognitive abilities, leading to full immersion in the learning process.

2. Theoretical perspectives and review of relevant literature

In this study, we examined the construction of knowledge through conceptual change. The process of conceptual change is based on the theory of constructivism. In the 1990s and 2000s, conceptual change became one of the most crucial areas of research in science education. The conceptual change model proposed by Posner et al. [10] is widely cited and serves as a theoretical framework for numerous studies on conceptual change and students’ learning.

2.1. The conceptual change process

The process of conceptual change can be a lengthy and complex endeavor because learners have constructed their conceptions over long periods. Therefore, it can be quite challenging for learners to accept that their ideas require adjustment and/or replacement, even when these ideas lack evidence to support them: “Changes can be strenuous and potentially threatening, particularly when the individual is firmly committed to prior assumptions” [10, p. 223]. Some learners will go to extreme lengths to defend these ideas. On the other hand, some preconceptions can be revised through instruction [9,11,12]. Regardless of the tenacity of the beliefs, learners will resist making a change “…unless they are dissatisfied with their current concepts and find an intelligible and plausible alternative that appears fruitful for further inquiry” [10, p. 223]. The conceptual change model is widely accepted by science educators.

Although there are differing perspectives on how conceptual change occurs, there is broad agreement that it does occur and is fundamental to science learning [3,13], making it a central concern in science education research. The conceptual change learning model views learning as an interaction between a learner’s knowledge and new instructional content. It is not a matter of simply replacing incorrect ideas but involves complex cognitive engagement, where learners often retain multiple conceptions while developing new ones with greater explanatory power. Nadelson et al. [3] emphasize that conceptual change is driven not only by cognitive conflict but also by a dynamic interplay of factors, including motivation, epistemological beliefs, and cultural context. Crucially, the process requires more than the passive reception of information; learners must actively process, engage with, and integrate new ideas. This model also acknowledges that misconceptions may persist or re-emerge when triggered by contextual cues, reinforcing the need for sustained instructional support and iterative opportunities for students to refine and reconstruct their understanding [14].

2.2. Teaching for conceptual change

Teaching for conceptual change is a good instructional approach to addressing and correcting students' misconceptions by helping them replace inaccurate ideas with scientifically accurate understandings [15]. To do this successfully, teachers must first understand students' existing preconceptions and misconceptions [16,17]. Since misconceptions are rarely expressed aloud or in writing, science teachers face the persistent challenge of identifying and addressing these misunderstandings, which often go undetected in the classroom [18]. These misconceptions, if uncorrected, hinder conceptual understanding and affect students' future learning [16]. To overcome this, instructional scaffolding has emerged as a powerful tool in science classrooms. Haidar et al. [19] demonstrated that integrating scaffolding into inquiry-based learning significantly reduced science misconceptions in elementary students by 23.3% in the experimental group compared to 12.6% in the control group. The study reinforces the importance of scaffolding as a targeted intervention, particularly when aligned with inquiry practices, to help learners reconstruct scientific concepts through guided investigation and peer or teacher support.

2.3. Teaching density

In practice, especially in lower grades, density is commonly taught through simplistic notions such as floating, sinking, or heaviness. Little attention is given to comparing equal masses and different volumes, an approach that limits conceptual depth and overlooks foundational understandings that do not require calculation [8]. At the higher grade levels, the intuitive aspects are often ignored, and the focus is on two factors: Memorizing the definition and solving problems using the formula D = M/V. Stephen and Mkpanang [4] observed that many physics teachers rely on teaching methods that prioritize rote memorization of definitions and procedures, which students often do not fully understand and cannot transfer to new contexts. This approach results in poor conceptual understanding and undermines the ability to apply scientific knowledge in meaningful ways.

Although students may recall definitions and formulas for density, and teachers often interpret this as understanding, density remains an abstract concept that many learners struggle to apply in meaningful contexts and have several misconceptions about [20,21]. When teachers fail to connect the hands-on, experience-based understandings formed in elementary school with the mathematical relationships introduced in later grades, they risk creating a cognitive disconnect that hinders students from developing a deep and comprehensive understanding of complex concepts like density [22,23].

2.4. Students' misconceptions about density

Smolleck & Hershberger [16] found that young learners use their prior knowledge and experiences with sinking and floating to inform their conceptions about sinking and floating. Common misconceptions were that "glass sinks" (age 5), "heavy metal sinks" (ages 7, 6, 4), "plastic floats" (ages 6, 5), "all wood floats" (ages 8, 7, 6), and "objects with air inside them float" (age 8). They claim that while these conceptions are sometimes true, they are not always true, and thus again illustrate how incomplete conceptions can lead to misconceptions [24].

Xu & Clarke [5] identified four dominant views on density displayed in Figure 1. The first two conceptualizations of density are constructed at the microscopic level, while the third and fourth ones describe density at the macroscopic scale. At the macroscopic scale, density is described in terms of measurable quantities and observable phenomena. Xu and Clarke [5] argue that within each scale, there are differences. For instance, on the microscopic side, the density concept is concerned with the number of particles, whereas the second view of the concept highlights the distance between particles. At the macroscopic end, density is presented as a mass-to-volume ratio on the one hand, and the buoyancy of an object in the water on the other hand. Xu and Clarke [5] contend that a complete understanding of the concept of density requires the integration of the four ideas rather than simply a combination of these four separate ideas. That way, students will be able to see the macroscopic and the microscopic levels of the same phenomenon as a coherent explanatory framework.

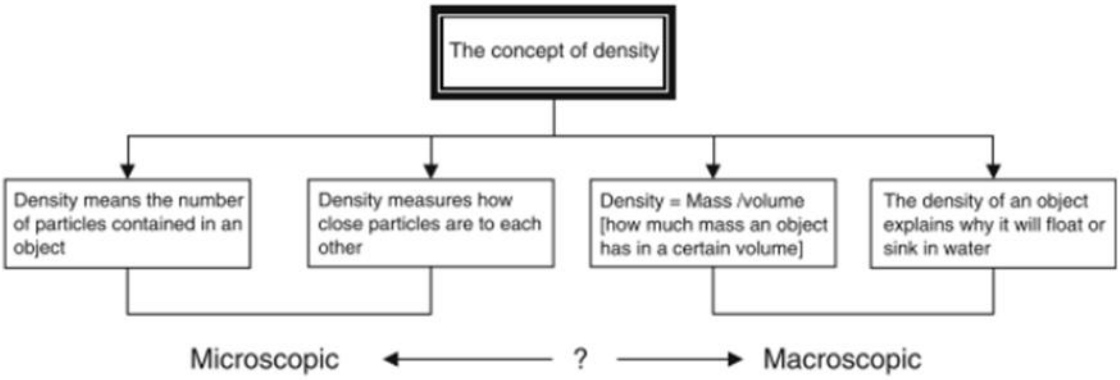


Figure 1. Schematic diagram of the four views of density. Xu & Clarke, [5].

2.5. Virtual Reality and learning

Virtual Reality (VR) refers to a field of computing that focuses on creating immersive virtual environments, which users can enter, experience, and interact with using specialized hardware. These technologies simulate environments and provide sensory feedback to make the experience feel as real as possible [25,26]. VR may be applied to any area where computers are involved, with the most common fields being the military, entertainment, and education [27,28]. Research indicates that virtual worlds may be more appealing and engaging than traditional learning methods [29,30]. According to Yamamoto and Altun [28], virtual reality is widely used in military training through simulations, and its future promises even greater effectiveness as advancements in AI and immersive technologies enhance interactivity, safety, and learning outcomes in combat preparation.

In the context of science education, VR has been utilized to help students visualize and comprehend abstract scientific concepts that are challenging to represent in two-dimensional or traditional classroom settings. Researchers have explored its use in teaching topics such as molecular structures, chemical bonding, physics phenomena, and biological systems [31,32]. For instance, VR has enabled learners to explore atomic interactions in chemistry, observe the structure of cells in biology, and experience complex physical principles such as electromagnetic fields and motion in a highly interactive environment. These applications have been shown to enhance spatial understanding, conceptual reasoning, and learner engagement.

Another well-known VR application with an educational focus is Science Space. The application contains NewtonWorld, MaxwellWorld, and PaulingWorld. The application uses mainly Head-Mounted Displays that display stereoscopic images and a magnetic position tracking system for heads and hands. NewtonWorld focuses on teaching physics, mainly the Laws of Motion. In MaxwellWorld, students investigate electrostatic forces and fields. Finally, PaulingWorld enables students to visualize molecules through representations and view details about their structures and atoms [25].

2.6. Development of the CAVE

The Cave Automatic Virtual Environment (CAVE) is a large-scale, high-resolution three-dimensional virtual reality theater that utilizes rear-projected graphics on its walls and floor to deliver an immersive and interactive experience. It provides an engaging display environment for applications in science, engineering, and art. The CAVE was researched and developed by the Electronic Visualization Laboratory at the University of Illinois at Chicago as a tool for scientific visualization [33].

The CAVE is composed of three 10-foot-square vertical walls and a 10-foot-square floor that act as projection screens for the images (see Figure 2). Projection cameras and speakers are mounted on the ceiling of the room. The hand wand is used to control the interaction between the user and the virtual environment (see Figure 3). An audio system provides sound feedback to the user. The Head-Mounted Displays (HMDs) (see Figure 3) feature motion trackers to provide the user with enhanced three-dimensional images. Head-Mounted Displays (HMDs) and the CAVE are examples of fully immersive systems. Fully immersive systems enable the user to view images in three Dimensions (3D). Figure 4 shows a user interacting with water molecules in a fully immersive system.

Figure 2. The CAVE has three vertical walls and a floor that acts as a projection screen.

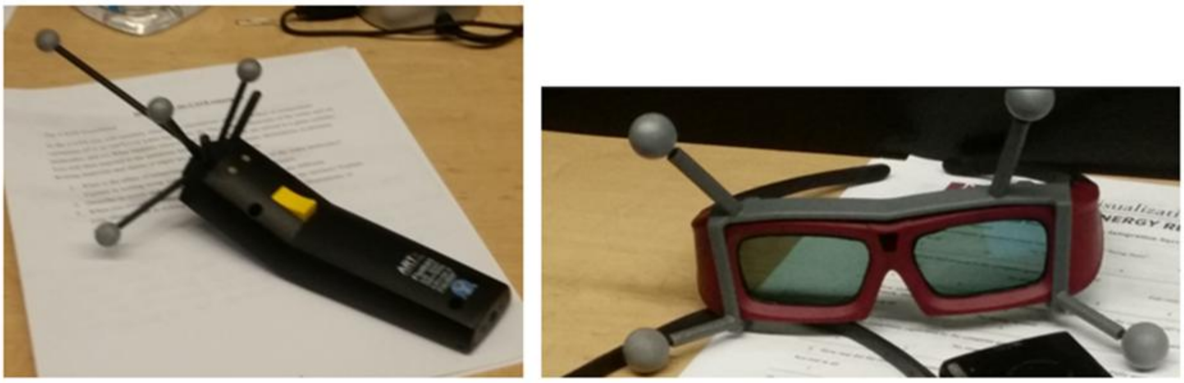


Figure 3. Hand Wand and HMD unit with Infra-Red motion trackers attached.

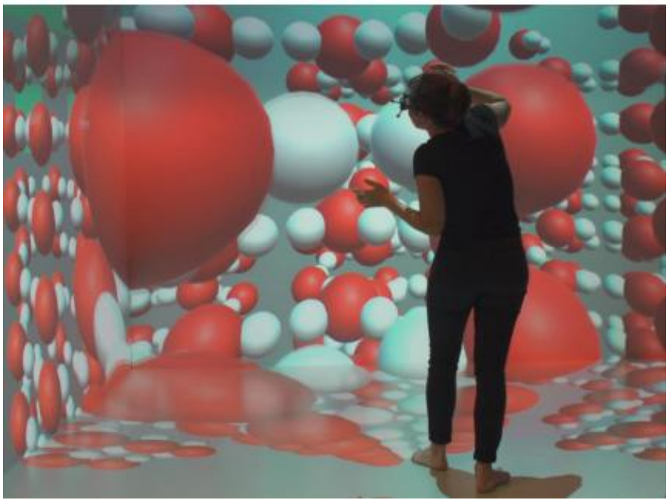


Figure 4. A user interacting with water molecules in the CAVE.

Cruz-Neira et al. [34] concluded that the CAVE is an effective and convincing virtual reality paradigm that enhances the applicability and quality of the virtual experience. The CAVE supports a multi-person (teacher/student) presentation format and enables some use of successive refinement. Moreover, the flatness of projection screens and the quality of geometric corrections available in projectors enable the presentation of 3D stereo images with very low distortion. This is in comparison to monitor-based and head-mounted display virtual reality systems. Because the projection plane does not rotate with the viewer, the CAVE has dramatically minimized error sensitivity due to rotational tracking noise and latency associated with head rotation. They argue that the CAVE is a valuable tool for scientific visualization that provides scientific insight, discovery, and communication. Cruz-Neira et al. [34] recommend that further research efforts should tie the CAVE into high-speed networks and supercomputers. In addition, motion-control platforms and other highly tactile devices should be incorporated in the CAVE, as well as hardening and simplifying the CAVE's design for the nation's science museums, schools, and shopping malls.

3. Methodology

The Pre-service teachers have the daunting task of teaching the concept of density to young learners. Learners may have misconceptions that need addressing and concepts that need refining or revising. Exploring the conceptual changes that take place in learners helps teachers find a way to address their misconceptions. In this study, we investigated pre-service teachers' understanding of the concept of density through the CAVE VR experience using the conceptual change model. The study offers pre-service teachers an opportunity to understand how learners test, experience, and revise their conceptual models. Rather than focusing on generalizations or averages, qualitative inquiry emphasizes the exploration of specific experiences, enabling rich insights into participants' conceptual development [35,36]. This approach is particularly well-suited for uncovering the subtle shifts in understanding and misconceptions that may not be revealed through quantitative methods [37]. To get an in-depth knowledge of the participants' misconceptions about the density concept, we examined three participants' responses.

This enabled us to build themes, concepts, and possible theoretical insights from the detailed data collected [38]. As Creswell [39] noted, qualitative research begins with interpretive frameworks that guide the study of complex problems, in this case, the challenges pre-service teachers face in grasping the abstract nature of density. By analyzing participants' responses, reflections, and interactions within the VR environment, we sought to capture how immersive technology supports or hinders conceptual change related to density. To improve the reliability and validity of the study, three sets of raw data were collected from the three participants, and each set of data was analyzed separately. In addition, participants' interviews, written responses, and drawings were used to collect data. This gave participants more than one way to express their responses.

3.1. Participants and context

Three preservice elementary school teachers were the participants for this study because they were non-science majors who had a basic understanding of the concept of density from their high school education. All participants had similar academic backgrounds and preparedness. We excluded any students who had completed an introductory physics course. The introductory course addresses the concept of density, a requirement for all elementary education majors at a university in the Midwestern Rocky Mountain region. The participants were recruited using convenience sampling [40], and these three preservice elementary school teachers volunteered to provide in-depth data for analysis. Convenience sampling was employed due to the availability of elementary pre-service teachers and their proximity to the CAVE facility's location.

The pseudonyms for the participants were Emma, Olivia, and Sophia, who were interviewed for the study. Emma took biology in her freshman year, chemistry in her sophomore year, physics in her junior year, and AP environmental science in her senior year of high school. Olivia studied physics and chemistry in high school and was taking an online Introduction to Physics and Astronomy course at the college level. Sophia took physical science in her sophomore year of high school, AP environmental science and chemistry in her junior year, and introductory courses in astronomy and chemistry at the college level.

We emphasized respect and transparency in its interactions with the participants. They were fully informed about the time commitments for the study and that their participation was voluntary, with no penalty for withdrawal at any time. Furthermore, the participants were assured that their names and personal information would not be used in the study's analysis, research papers, or presentations. Instead, pseudonyms would be used to protect their privacy. This study was approved by the University IRB.

3.2. Data collection

The pre- and post-CAVE interviews were structured to assess the participants’ basic knowledge before and after the CAVE experiences. The follow-up interviews aimed to seek clarification on the responses from the previous interviews and to provide participants with an opportunity to express any information they may have omitted. The follow-up interviews were structured according to the participants’ responses in the pre and post-CAVE interviews. The pre and post-CAVE interviews for each participant were conducted a week apart. The post-CAVE interviews were conducted immediately after the CAVE experience.

The participants responded to the questions through verbal responses, drawings, or written responses on blank sheets of paper provided. To assist participants in understanding interview questions better, the interviewer used visual aids. For the pre-CAVE interview, the following visuals were displayed: Transparent containers with ice cubes floating on water and oil floating on water. In addition, a container with salad dressing was displayed (see Figure 15). For the post-CAVE interview, the following visuals were displayed: A photo of an ice cube and a cruise ship floating on water (see Figure 16). There were also photos of a razor blade floating on water and a water strider walking on water (see Figure 17).

The verbal responses were recorded and transcribed, and written responses and drawings were scanned and saved for analysis. The three formats of responses provided participants with multiple ways to express their knowledge about the density concept. Some gaps in the verbal responses were filled in by the writings and drawings. This made it easier for us to observe the conceptual change process before and after the CAVE experience. The participants’ responses were used to explore the conceptual change in their understanding of density before and after their VE at the macro and micro levels before and after the CAVE experience.

The data were collected through recorded interviews, written responses, and drawings. Face-to-face interviews were used because they offered more flexibility in terms of question content, were more appropriate for long interviews with complex questions, and permitted visual aids in presenting questions and responses [41]. The interviews were transcribed immediately after the recordings, and any unclear parts were filled in from written notes. To identify areas that required follow-up, we reviewed their notes shortly after the interviews, listened to the audio recordings, and took notes on follow-up questions for further exploration. All drawings and writings were scanned and electronically stored. The lead author conducted all the interviews with the participants. The follow-up interviews aimed to gain deeper insight, detail, and clarification of concepts and themes, and to give participants an opportunity to add information that they may have previously omitted. The first interview used Guided Questions (See Appendix A), and participants were provided with plain paper, a pencil, and a pen. For each participant, two pre-CAVE Density experience and two post-CAVE Density experience interviews were conducted. During the interviews, verbal, written, and drawing methods were used to collect data.

For the pre-CAVE interview, Question 1(a) assessed participants' basic understanding and prior knowledge of density at the microscopic level, using visuals of ice cubes floating on water. Question 1(b) asked participants to explain the effect of heat on water molecules, while Question 2 required an explanation of why oil floats on water with drawings of oil and water molecules. Question 3 explored the participants' understanding of the density concept at the microscopic level. In subsequent interviews, participants were not corrected if they gave incorrect answers so that their responses did not influence later ones. The questions for the follow-up interview of the Pre-CAVE Density experience interview were individualized according to the responses given in the initial interview (see Appendix B for the follow-up questions of the pre-CAVE interview).

The Density CAVE experience included three virtual rooms (see Figure 5). The first room demonstrated how the behavior of water molecules changes from freezing temperature to the boiling point. The wand controls had an option to vary the temperature of water in the CAVE. The second virtual room enabled comparisons of the structures of water and oil molecules, and the third room simulated a mixture of oil and water poured into a virtual cylinder. Each room featured relevant sound effects, including the bubbling of boiling water and the sound of the water-oil mixture.

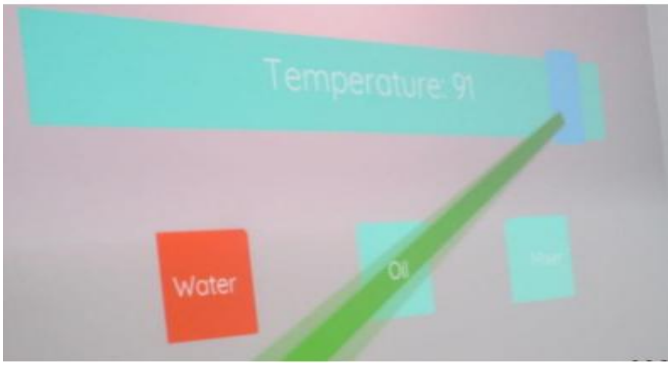


Figure 5. A graphic display of the functions of the CAVE room for water at 42 ℃.

The maximum time that each participant could manipulate the CAVE simulations was 30 minutes. The participants manipulated the three simulations as many times as they felt necessary. Before creating the simulations, the computer technician instructed participants on the use of the hand wand and HMDs to create 3-dimensional simulations. In the CAVE room, participants observed the simulations of (a) the effect of temperature variations on the behavior of water molecules, (b) the chemical structures of water and oil molecules, and (c) a mixture of oil and water molecules poured into a virtual glass cylinder. Participants responded to questions about the density-related simulations they conducted in the CAVE (See Appendix B). Figure 6 displays images of water molecules at temperatures of 0 ℃, 58 ℃, 99 ℃, and 100 ℃.

Figure 6. Water molecules at temperatures 0 ℃, 58 ℃, 99 ℃, and 100 ℃.

For the second task, participants observed images of oil and water molecules and then described the differences between the oil and water molecules (see Figure 7). The third task required the participants to fill a virtual cylinder with a mixture of oil and water and then describe their observations (see Figure 7).

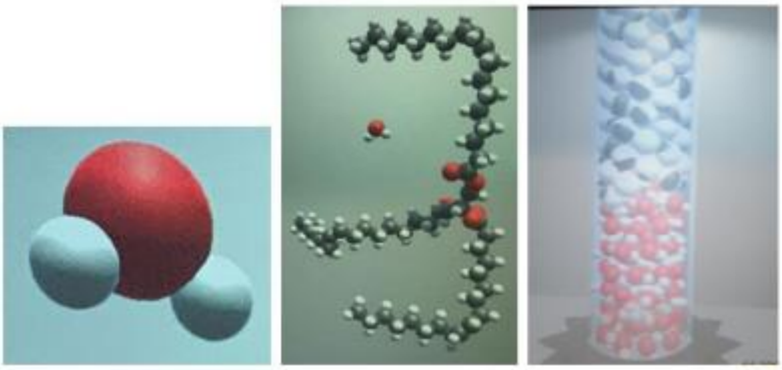


Figure 7. A water molecule, water and oil molecules, and oil floating on water in a virtual cylinder.

3.3. The post-CAVE experience interview

As part of the data collection process, a post-CAVE experience interview was conducted to investigate the impact of the Density CAVE simulation on participants' understanding of density at the microscopic level. The interview questions explored how participants conceptualized molecular differences between ice and water, and how these differences relate to observable phenomena such as floating and sinking. Questions also examined participants' understanding of factors influencing density beyond molecular structure, as well as their explanations of everyday scenarios involving fluids of different densities. One week later, a follow-up interview was conducted to clarify earlier responses and further probe participants' grasp of density-related phenomena, including the flotation of objects such as icebergs, cruise ships, and razor blades, as well as the role of surface tension. These interviews provided insights into participants' evolving mental models and conceptual frameworks regarding density following their immersive VR experience (see Appendices C and D).

3.4. Data analysis

To analyze how the participants conceptualized density through the CAVE VR experience, three types of qualitative data were collected: semi-structured interviews, participants' written responses, and their drawings. Interview recordings were transcribed, while written work and drawings were scanned and organized into individual data files for each participant. Digital and printed formats were used throughout the analysis. Each participant's dataset was examined to identify patterns or recurring trends related to their understanding of density. Latent-content and manifest-content analyses were used because there was no hypothesis to consider [42,43].

Thematic analysis was used to identify themes and recurring patterns in the data. We adopted a "Big Q" qualitative approach, which aligned with an interpretivist paradigm and acknowledged the researcher's active role in constructing meaning from the data, as opposed to a positivist or "small q" perspective. Small "q" qualitative research uses qualitative data collection techniques within a quantitative research framework to answer a pre-defined, or a hypothesis-driven, question, similar to a quantitative study. The data analysis involved looking for pre-existing themes. Replication or consistency was not the main goal. The Big "Q" approach to thematic analysis further supports the view that researcher subjectivity enriches, rather than detracts from, the interpretive depth of qualitative inquiry [42,44,45].

Thematic analysis (See Table 1) in this study followed the four stages outlined by Boyatzis [42], offering a structured yet flexible approach to interpreting participants' understanding of density. First, in the sensing themes stage, codable moments, instances in the data that reflected meaningful insight or conceptual shifts, were identified through close, repeated readings of interview transcripts, written responses, and visual artifacts. Second, for the "doing it reliably stage", these moments were consistently recognized and coded across all data sources to ensure analytical reliability. Third, the process of developing codes involved grouping similar responses and visual elements into preliminary categories, which were refined and validated through iterative comparisons across participants.

Finally, in the interpreting themes stage, these patterns were analyzed in light of conceptual change theory and the role of immersive learning environments, with the goal of understanding how pre-service teachers constructed or reconstructed their knowledge of density. This layered analysis enabled us to generate nuanced insights into how the CAVE experience influenced conceptual development and contributed to the broader discourse on science education and virtual reality-based learning.

Table 1. Example of thematic coding of data segments.

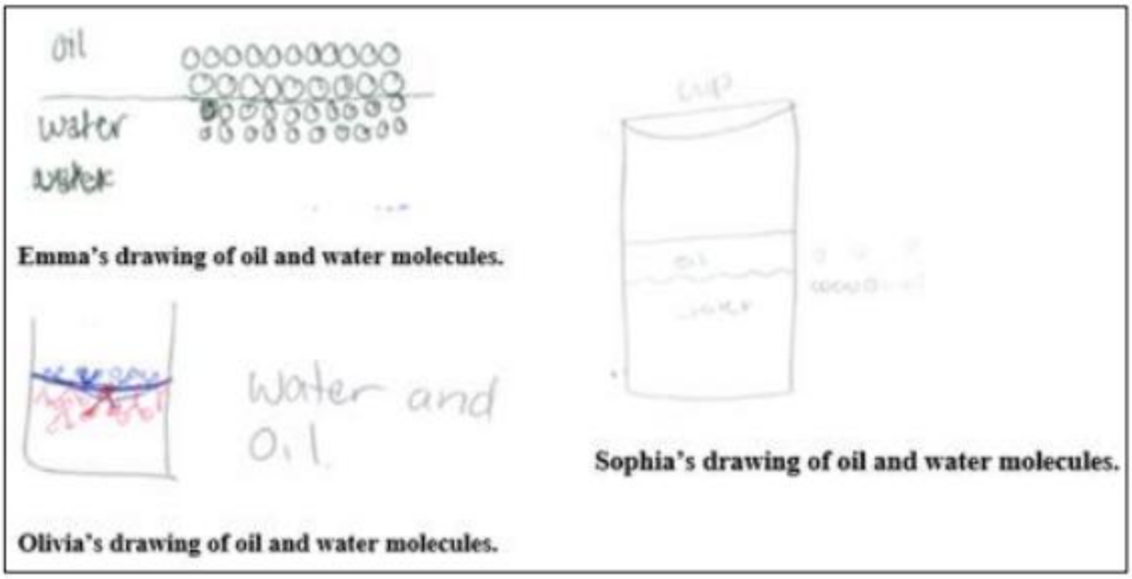
Pre-CAVE Interview Data Segments	Code	Theme	Remarks
Emma segment 1: it's a different, like state of like being a solid, like it's solid and so the water molecules [in ice] are like closer together and more organized.	Floatation of ice on water	Molecular Spacing and Density	1. It builds on the concept that molecules in solids are more compactly packed than in liquids, but there is a conceptual gap that needs addressing
Emma segment 2: Emma The molecules are closer together [in ice] than in water, but I don't know why that would make ice float,			2. Misconception that water molecules are less compact than ice molecules, so ice should sink, but it doesn't so there is a conceptual gap
Olivia: Segment 1: ice is more dense than water because the molecules are more compacted so you would think that the ice should be at the bottom, but it's at the top.	Floatation of ice on water	Molecular Spacing and Density	1. Misconception that ice is more dense than water because ice molecules are more compact
Olivia: Segment 2: But since the water is more flexible and can fill whatever container, it fills the container first and then the ice goes on top.			2. Fills in the knowledge gap of more dense ice floating on water with own thinking/idea

4. Results

The thematic analysis of participants’ responses before and after the Density CAVE experience revealed three key themes that illustrate shifts in their conceptual understanding of density: (1) differences in molecular properties, (2) molecular spacing and density, and (3) the overlooked role of molecular mass. These themes are explored in detail below, highlighting participants’ evolving reasoning as supported by their drawings and interview responses. The first theme explores how participants explained the immiscibility of oil and water through their perceptions of molecular composition and structure. The second theme focuses on participants’ evolving understanding of how the arrangement and spacing of molecules, particularly in ice and water, affect density and related phenomena, such as flotation. The third theme highlights persistent gaps in participants’ understanding, despite gains in other areas, emphasizing the need for further instructional focus. Each theme is discussed in turn, supported by participants’ drawings, interview excerpts, and reflections that illustrate their conceptual development throughout the study.

4.1. Differences in molecular properties

From the analysis of participants’ artifacts and their interviews, it was revealed that they consistently attributed the flotation of oil on water to differences in molecular properties, before and after the Density CAVE experience. Before the VR session, participants believed that oil and water do not mix because of the contrasting nature of their molecules. For example, Emma suggested that molecular size differences prevented mixing, while Olivia described oil and water molecules as being “*completely different*” and unable to “*get along*.” Sophia added that the compact arrangement of water molecules acted as a barrier to the more loosely arranged oil molecules. Figure 8 shows the illustrations from participants before the CAVE experience.



Emma’s drawing of oil and water molecules.

Sophia’s drawing of oil and water molecules.

Olivia’s drawing of oil and water molecules.

Figure 8. Participants’ drawing of oil and water molecules.

There was a conceptual change after the Density Cave experience as participants deepened their explanations by incorporating more specific molecular reasoning. Emma emphasized that hydrogen atoms in water molecules bond more easily with each other, making water denser and pushing less dense oil molecules to the surface. Olivia extended her reasoning by highlighting chemical structure incompatibilities, explaining that oil, composed of hydrogen, oxygen, and carbon, cannot mix with water because the molecules "*don't fit together as well*." Sophia reiterated the idea that water's tightly packed molecules created a physical and chemical barrier to the larger, more spread-out oil molecules.

Figure 9 shows how participants illustrated oil and water molecules after the Density CAVE experience, reflecting a more detailed and scientifically grounded understanding of molecular differences. Overall, the immersive visualization reinforced and expanded participants' conceptual understanding by helping them articulate density and molecular interactions with greater clarity. This aligns with the conceptual change framework, as the experience supported the refinement and elaboration of their pre-existing ideas through active engagement and visual exploration.

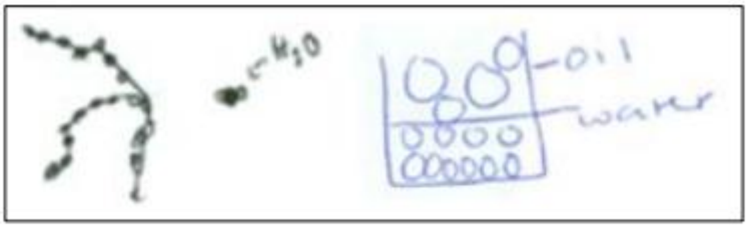
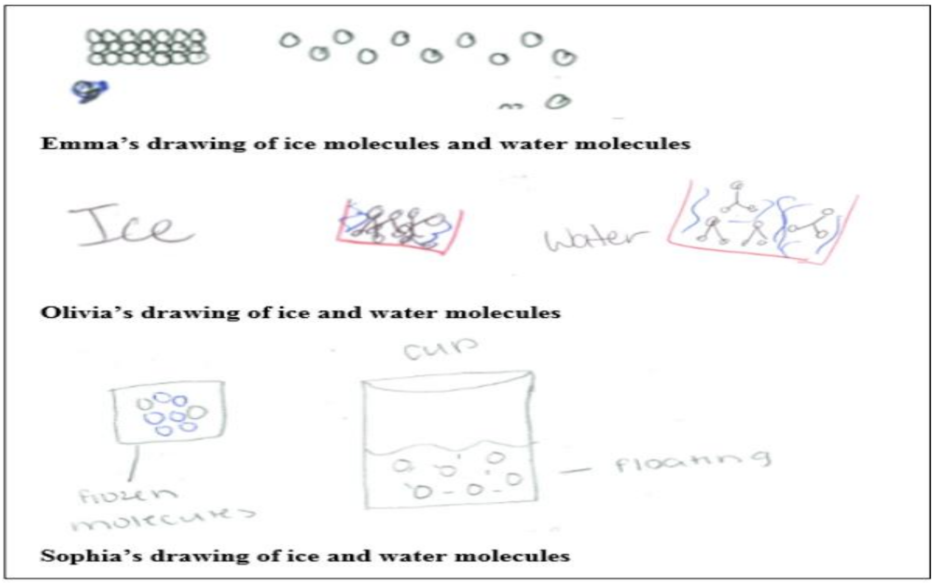


Figure 9. Emma and Sophia's drawing of oil and water molecules.

4.2. Molecular spacing and density

The analysis revealed that the Density CAVE experience had a significant influence on participants' understanding of the relationship between molecular spacing and density. Before engaging with the simulation, all participants exhibited the common misconception that molecules in ice, due to its solid form, are more closely packed than in water. For instance, Emma stated that, "*... the water molecules in ice are closer together and more organized,*" while Olivia described ice molecules as "*very compact and have some structure to them.*" Participants' initial drawings, as shown in Figure 10 below, supported these views, depicting ice as denser than water.

After the CAVE experience, there was a change in the participants' conceptual perspective. They began to understand that although ice is a solid, its molecular structure includes more space between molecules due to the formation of a crystalline lattice. Olivia, reflecting this change, explained that in the solid state "*they freeze and form crystalline structures… there is a lot of space between them,*" while Sophia mentioned that "*ice molecules formed octagons, the same shape as the stop sign, and they weren't moving.*" This revised understanding was reflected in their updated drawings, which depicted water as having more densely packed molecules than ice.



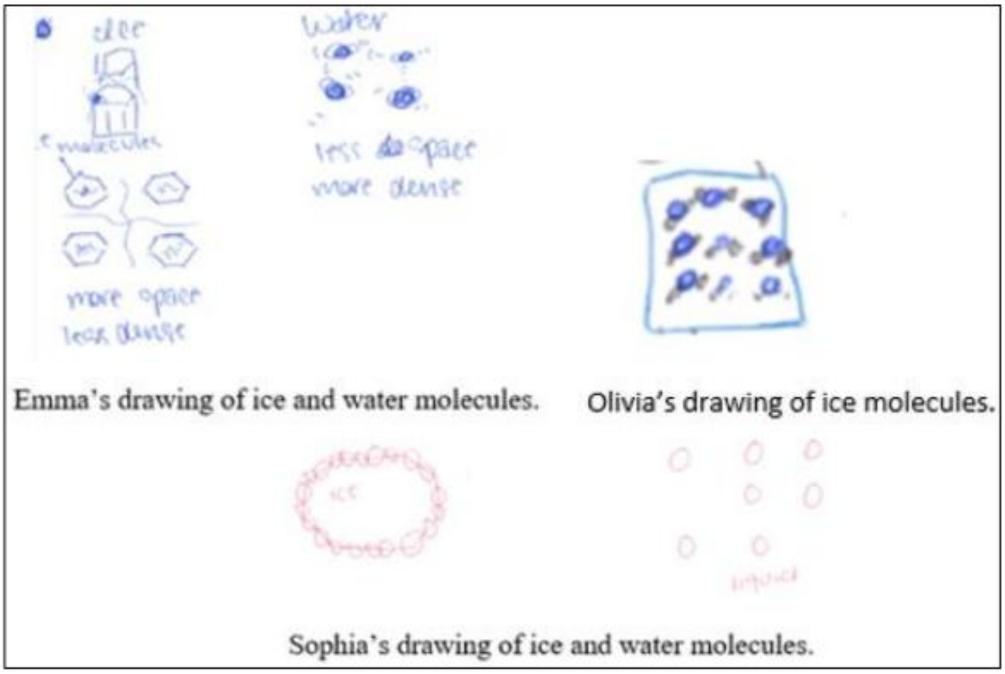
Emma's drawing of ice molecules and water molecules

Olivia's drawing of ice and water molecules

Sophia's drawing of ice and water molecules

Figure 10. Participants' drawings of ice molecules (left) and water molecules (right).

Figure 11 illustrates the participants' understanding of ice and water molecules following the Density CAVE experience and how their conceptualization changed. Unlike their previous thinking, they now viewed ice molecules as having more space between them than water molecules.



Emma's drawing of ice and water molecules.

Olivia's drawing of ice molecules.

Sophia's drawing of ice and water molecules.

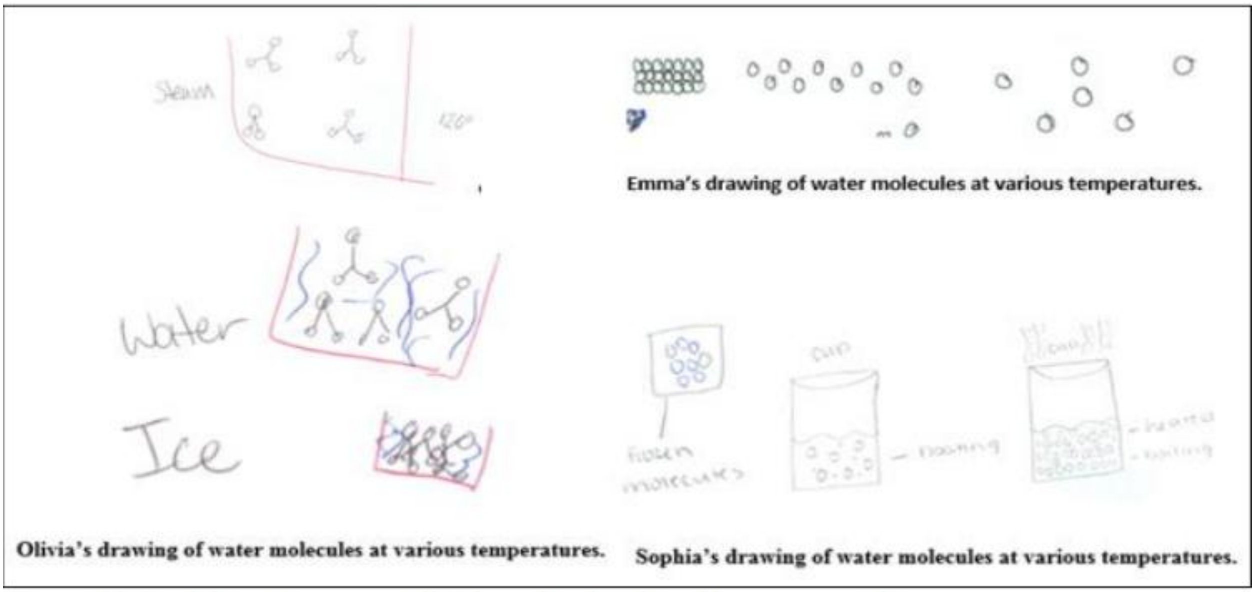
Figure 11. Participants' conceptualization of ice and water molecules.

Another important shift in participants' understanding of density was in their conceptualization and explanation of why ice floats on water. Before the Density CAVE experience, participants provided explanations grounded in everyday reasoning rather than scientific understanding. Some attributed the flotation of ice to the presence of air trapped inside the ice; for example, Emma speculated that "*there might be air inside of the ice that's causing it to float*." Others, like Olivia, believed air had less weight, or that water simply displaced the ice due to being more flexible; she stated that “*water is more able to fill a container more easily than ice.”* These explanations lacked reference to molecular structure or density and reflected a limited conceptual grasp of the phenomenon.

After the Density CAVE experience, participants’ explanations became more aligned with scientific reasoning. They began to describe flotation in terms of molecular arrangement and density differences. It became evident that they now recognized that ice, despite being a solid, has a structured molecular lattice that creates more space between molecules, reducing its density compared to liquid water. One participant noted that water molecules in ice are organized into fixed structures with more space between them, while in liquid water, the molecules move more freely and are more closely packed. Sofia, for example, argued that “*less molecules and the molecules aren’t moving in the fixed shape that’s what makes it less dense to float on water.*” This shift in reasoning marks a significant conceptual development, as participants transitioned from superficial and incorrect explanations to scientifically grounded interpretations that directly linked molecular structure to the phenomenon of density.

The final aspect of this conceptual shift involved how participants understood the effect of temperature on molecular spacing. Before the Density CAVE experience, the participants had a limited/inaccurate understanding of how molecular spacing is impacted by temperature.

For example, Emma believed that “*when you heat the molecules, they might move a little bit but then… go back to being as they were before*,” suggesting a limited understanding of kinetic behavior at different temperatures. Olivia thought that heating simply caused “*more space between” unchanged molecules, while Sophia described water vapor inaccurately as “a bunch of little droplets in the air,*” indicating confusion between physical states and particulate behavior. The participants’ conceptualization of molecules of ice, water, and steam before the Density CAVE experience is shown in Figure 12.



Emma’s drawing of water molecules at various temperatures.

Olivia’s drawing of water molecules at various temperatures.

Sophia’s drawing of water molecules at various temperatures.

Figure 12. Participants’ conceptualization of molecules of ice, water, and steam.

After the Density CAVE experience, participants demonstrated a more coherent and scientifically accurate understanding of how temperature affects molecular behavior. They were able to describe changes in molecular motion and spacing across the solid, liquid, and gaseous states of water with improved precision. Unlike their earlier fragmented explanations, participants now recognized the dynamic nature of molecular interactions driven by thermal energy. Emma, for instance, described steam as composed of "*water molecules that are full of kinetic energy and fly around in all directions*," contrasting this with ice, where molecules are "o*rganized with hydrogen bonds… expanded to become towers of molecules*." Olivia echoed this refined understanding, noting that molecular spacing varies with temperature as molecules "*speed up or slow down*" in response to heat. She accurately observed that in boiling water, "the molecules are buzzing all about," while in freezing conditions, "*they form octagons and do not move*." Sophia also showed conceptual growth by differentiating the three states of water at the molecular level. She described liquid water as having molecules that "*flow and don't have much space between them,*" whereas in the frozen state, the molecules "f*orm crystalline structures with a lot of space between them.*" Furthermore, she no longer equated water vapor with physical droplets, instead recognizing that at temperatures above 100°C, molecules "*bounce around in the container*" with increased spacing.

These improved explanations indicate that the CAVE experience enabled participants to visualize and internalize the connection between temperature, molecular movement, and density. By engaging directly with simulations of phase changes and molecular arrangements, participants moved beyond surface-level misconceptions and developed a more integrated understanding of matter at the microscopic scale.

Emma's drawing of ice molecules forming towers and steam molecules.

Sofia's drawing of molecules of ice, boiling water, and steam.

Figure 13. Drawings show the influence of temperature on water molecules.

4.3. Overlooked role of molecular mass

While the Density CAVE experience led to significant improvements in participants' understanding of molecular spacing, temperature effects, and the relationship between phase changes and density, it did not appear to influence their conceptualization of molecular mass as a factor in determining density. Before the experience, participants consistently described density as the result of how tightly molecules are packed in a given space, without referencing molecular weight. Emma, for example, stated that a substance is "*dense because there are many molecules in the allotted* *space,*” and that “*the less molecules that exist, the less dense something is.*” Similarly, Olivia explained density differences across states of water based on molecular compactness, saying, “*the more dense are going to be very compact, very close together,*” while Sophia defined density simply as “*the amount of stuff in a given subject.*” Their drawings (Figures 14–16) also reflected these ideas, emphasizing molecular spacing but omitting any representation of mass differences.

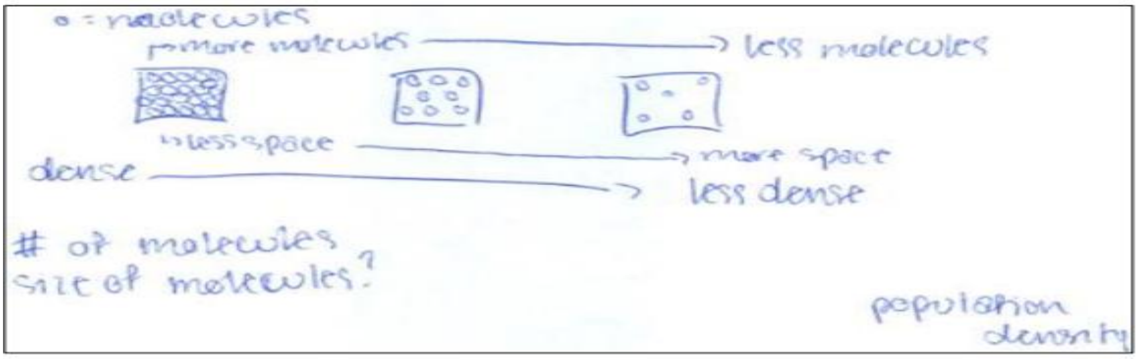


Figure 14. Emma’s drawing illustrates the definition of density.

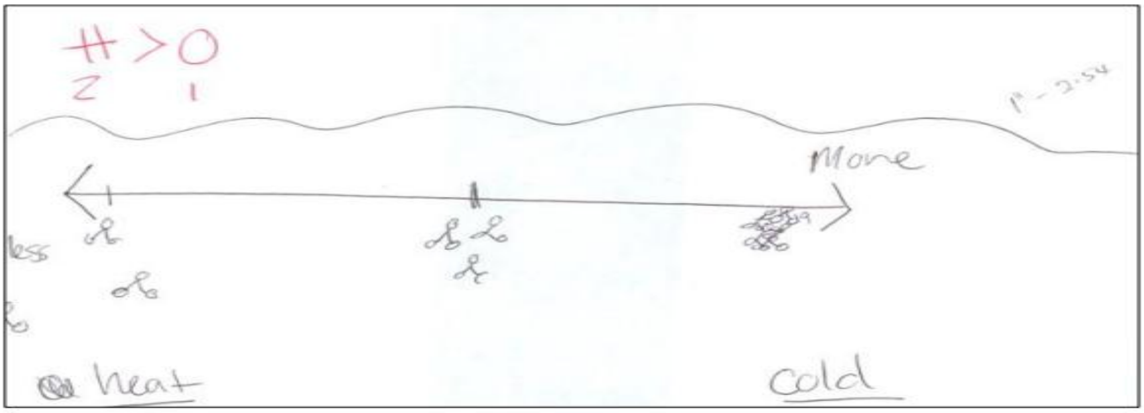


Figure 15. Olivia’s drawing showing how density varies with temperature.

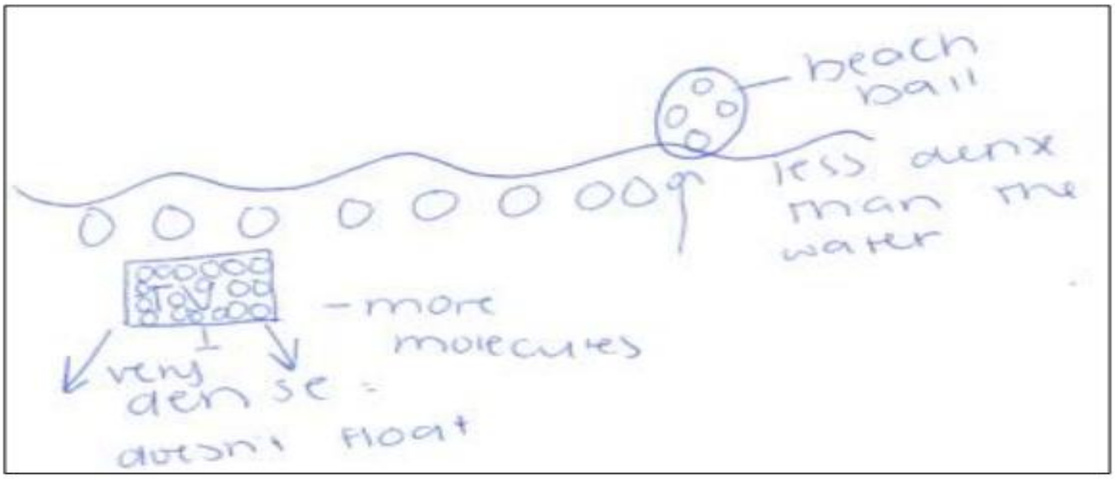


Figure 16. Sophia’s drawing to show the relative densities of a beach ball, water, and a TV.

After the Density CAVE experience, this pattern persisted. Participants' improved explanations still focused on molecular arrangement and spacing, with no mention of the masses of the individual molecules. For instance, Olivia remarked that "density is determined by how closely compacted the molecules are," and Sophia explained that oil floats on water because "water molecules are more packed closer together," despite acknowledging that "oil molecules are bigger." These statements suggest that while the CAVE successfully reinforced structural and spatial aspects of molecular behavior, it did not lead participants to incorporate molecular mass into their understanding of density. This finding reveals a persistent conceptual gap and points to the need for targeted instructional strategies that explicitly address the role of molecular mass in scientific explanations of density.

Based on our findings, it is clear that the Density CAVE experience influenced the participants' understanding of the density concept at the microscopic level in four distinct ways. Participants were able to (a) visualize water and oil molecules and recognize the differences in their molecular structures, (b) observe that water molecules can have different spacing arrangements determined by the temperature, (c) grasp the role of intermolecular forces in determining the density of water, and (d) understand that at the microscopic scale, air does not affect the density of ice. However, there is no evidence that the Density CAVE experience had any impact on the participants' understanding of the role of molecular mass in determining density.

5. Discussion, implications, and future research

5.1. Discussion

Our findings of this study confirm longstanding challenges in density instruction, echoing research that characterizes density as an abstract, conceptually demanding topic [1,7,8,21,46,47]. Consistent with these studies, participants in this study demonstrated a range of misconceptions at macroscopic and microscopic levels. For instance, many believe that ice molecules are more compact than those in water, or that ice floats due to trapped air, ideas that align with common misunderstandings about density being influenced solely by visible attributes such as size, state, or buoyancy. This aligns with Panagou et al.'s [47] conclusion that misconceptions about density persist even among high-achieving students and are not easily corrected through traditional instruction.

As demonstrated in this study, participants initially relied heavily on macro-scale experiences to explain phenomena such as ice floating or oil not mixing with water, often attributing these to the presence of air or visible traits like "heaviness" and "compactness." This aligns with Lee and Kwok's [46] observation that students' everyday encounters with floating objects, such as beach balls or oil, can reinforce superficial understandings of density. The Density CAVE experience provided visualizations of molecular structures and interactions, yet misconceptions rooted in macro-scale reasoning persisted in several participants' explanations. This reinforces the argument that while immersive technologies can support learning, conceptual change is not automatic. Thus, bridging macro and micro perspectives requires intentional instructional scaffolding that helps learners reconcile everyday observations with scientifically accurate molecular models.

Moreover, the study highlights that even when students correctly associate density with molecular spacing or arrangement, a clear step toward a more accurate understanding, they continue to overlook the role of molecular mass, which is equally essential in understanding the concept of density. This pattern aligns with Panagou et al. [47], who found that students frequently interpret density as an extensive property dependent solely on visible quantity or arrangement rather than as an intensive property shaped by mass and volume. The persistence of this gap in participants' reasoning, even after immersive engagement, suggests that students may require more than visualization to internalize the multifaceted nature of density. These findings emphasize the importance of designing instructional experiences that not only engage students in exploring molecular phenomena but also prompt them to consider less intuitive factors, such as molecular mass, and reconcile these with prior knowledge and observable outcomes.

Our findings of this study confirm that conceptual change in density understanding is complex and shaped by students' prior experiences. As Pritchard [48] explains, learners actively construct knowledge by integrating new information with existing beliefs. In this study, participants' explanations remained grounded in macro-scale experiences, such as associating flotation with the presence of air, even after engaging with the Density CAVE simulation. While some conceptual gains were observed, especially in understanding molecular arrangement, the brief exposure (under 30 minutes) limited deeper integration of new ideas, particularly regarding the role of molecular mass. The results underscore the importance of instruction that explicitly connects macro- and microscopic perspectives, rather than relying solely on visualization tools, to address persistent misconceptions and deepen learners' scientific comprehension within the study's limited sample and scope.

The lack of concrete evidence that the Density CAVE experience improved understanding of the role of molecular mass could be attributed to several factors: The CAVE experience may have focused more on the visual or experiential elements of density (such as the behavior of objects in water) instead of connecting molecular mass with density; the duration of the activity might not have been sufficient for participants to grasp the more abstract relationships; and visual representations could have inaccurately or ambiguously depicted particles or molecules, causing participants to concentrate on superficial characteristics rather than explanations at the molecular level. While immersive environments can be exciting, they can also be overwhelming; excessive sensory input might hinder deeper understanding of concepts. Additionally, if participants perceived the experience as entertainment rather than an educational opportunity, they may not have engaged cognitively with the scientific principles involved.

5.2. Implications for teaching density through the density CAVE experience

This study reinforces the persistent challenges students face when transitioning from macro-scale to micro-scale understandings of density. While the Density CAVE experience offers powerful visualizations of molecular behavior, its effectiveness in promoting conceptual change depends heavily on instructional support and the alignment of prior knowledge with new representations. In this study, the Density CAVE helped students visualize molecular spacing in water, ice, and oil, fostering a clearer understanding of phenomena like ice floating or oil separation based on molecular arrangement and intermolecular forces. This aligns with Dalgarno and Lee [49], who highlight how immersive simulations enhance spatial understanding of molecules and their interactions. However, for this study, it did not significantly enhance the participants' understanding of molecular mass in relation to density.

When teaching density, the Density CAVE provides an effective visual and interactive tool for helping students explore molecular behavior at the microscopic level. It enables learners to observe how temperature affects molecular spacing and structure in substances like water and oil, bridging abstract concepts with immersive representations. However, as Xu and Clarke [5] emphasize, multi-scale reasoning is critical. Students must connect macro-level experiences with microscopic explanations to form accurate scientific understandings. While the CAVE supported multiple visualizations, students did not use it to explicitly represent molecular mass, a key component of density. Therefore, teachers must scaffold the experience through pre- and post-lesson activities that clarify how mass and volume influence density. With strategic instructional support, the Density CAVE can serve as a valuable complement to traditional methods, helping students overcome persistent misconceptions and fostering a more integrated understanding of density at macro and micro levels.

5.3. Recommendations for future research

Given the limited research on students' misconceptions about density at the middle and high school levels, further studies exploring this topic in various ways are desired. Specifically, researchers should explore how teachers can better support students' use of scientific language when discussing density, as inconsistencies in terminology can hinder teaching and learning. Additionally, to more precisely evaluate the educational value of the CAVE simulation system, researchers could implement controlled experimental designs comparing outcomes between students who use the CAVE simulation and those who receive traditional instruction. This would help isolate the unique contribution of immersive visualization to students' conceptual understanding of density at the molecular level.

In conclusion, this study highlights the potential of the Density CAVE as an instructional tool that supports pre-service teachers in developing a more nuanced understanding of density at the microscopic level. Thematic analysis revealed differences in understanding molecular properties and molecular spacing, indicating that the role of molecular mass as a central area of conceptual development was not fully explored by us. Participants demonstrated conceptual gains in visualizing molecular interactions, such as the spacing in ice versus water and the incompatibility of oil and water molecules, which helped correct common misconceptions about these phenomena. However, the CAVE experience fell short in promoting understanding of molecular mass, a critical component of density [46,49].

These results align with the broader literature, which suggests that density remains an abstract concept for learners, even when immersive tools are employed [5,8,47]. Future studies on the concept of density involving the CAVE simulation should incorporate representations of molecular mass and dynamic movement. When integrated into a comprehensive pedagogical framework, the CAVE simulation setup can play a valuable role in fostering deeper, scientifically accurate understandings of density.

Author contributions

Godfrey Walwema designed the study, conducted the participant interviews, and collected all the data. Johannes Addido and Samuel Katende contributed to the literature review, discussion, and interpretation of the findings. Johannes Addido and Samuel Katende assisted in revising the manuscript, with a particular focus on the implications of the results for science education. All authors contributed to the editing and final review of the manuscript. All authors have read and approved the revised and published version of the article.

Use of Generative-AI tools declaration

The authors declare that no generative artificial intelligence (Gen-AI) tools were used in the creation of this article. Also, no Gen-AI tools were used to slice and print the 3D models used in the study. However, Grammarly was used for the initial language editing of the paper.

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Conflict of interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics declaration

This study was approved by the University of Wyoming IRB.

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Appendix

Appendix A. The pre-CAVE experience follow-up interview

1 (a). Interviewer shows the participant a transparent container with ice cubes and water (see Figure 17) and then asks the following questions:

i. What do you see? What is the ice doing? Why is the ice floating? What is ice made of? ii. If they are both water, why then does ice float on top of the water? iii. Imagine if you could zoom in and see water molecules in the ice and water. What would it look like? Draw and label a diagram on the paper that you think you would see. Please explain your diagram. (b). If you heated water molecules, what would it look like? Again, explain your drawing.

2. Interviewer shows the participant a transparent container with water and vegetable oil (shown in Figure 17) and then asks the following questions: i. What do you see? What is the oil doing? Why is the oil floating? What makes oil float on water? ii. Imagine being able to zoom in and see oil molecules floating on top of water molecules. What would it look like? Draw and label a diagram of

what you think you would see. Please explain your drawing.

3. Interviewer shows the participant a transparent container with vinaigrette salad dressing (see Figure 17) and then asks the participant the following questions: i. What do you see in the container? Explain what you see in the container. ii. Imagine if you could zoom in and see the molecules in the container. What would it look like? Draw and label a diagram on the paper that you think you would see. Please explain your drawing.

Figure 17. Ice cubes floating on water, oil floating on water, and particles suspended in the salad dressing.

Appendix B. The pre-CAVE experience follow-up interview

They then responded to the questions below in writing, diagrams, and drawings.

1. What is the effect of temperature on the molecular spacing of the water molecules? Explain in writing using words, diagrams, illustrations, or pictures.
2. Describe in words and drawings how the water molecules behave when the temperature changes from 0 ℃ to 100 ℃, and then explain their observations. How are Oil and water molecules different?
3. When you pour a mixture of water and oil molecules, what happens to the mixture? Explain your observations in writing using words in addition to drawings.

Appendix C. The post-CAVE experience interview

The post-CAVE experience interview guide questions are given below:

1. From your observations in the CAVE room, explain the difference between water and ice molecules. How does this difference account for the fact that ice floats on water?
2. What factors in terms of molecular structure make one substance float on top of the other?
3. Apart from the molecular structure of the substance, what other factors might affect the density of the substance?
4. What would you expect to happen when a red-colored ice cube is placed in a container half-filled

with warm water? (The interviewer explains that it could have been any
other color instead of red.) Explain in words and drawings.
5. How do molecules rearrange themselves when:
   a. water is added to a container with water.
   b. vegetable oil is added to a container with water.
6. A container has 50 ml of water, and an equal amount of 50 ml of saltwater is added to the container. What can you say about the resulting volume of the mixture? Why would that be the case? How would the density of the resulting mixture compare with the density of the water? They then responded to the questions below in writing, diagrams, and drawings.

Appendix D. The post-CAVE experience follow-up interview

The following is the Post-CAVE experience follow-up interview Guide:

1. The interviewer shows the participant two photographs: the first photo of an iceberg floating on water and the second photo of a ship floating on water (see Figure 18). They then ask the following questions: What do you see in the photo? What do you see in this photo? What does an ice cube and a ship have in common that makes them float on water? Please feel free to draw as you explain.

Figure 18. An iceberg and a cruise ship floating on water.

2. The interviewer shows the participant a photo of a razor blade floating on water (see Figure 19). They then ask the following questions. What is the razor blade made of? Is steel denser than water or not? What could be the reason this is possible? Again, feel free to draw.
3. Interviewer shows the participant a photo of a water strider walking on water (see Figure 19). Some insects like water strider /pond skater, spiders can walk on water. How is that possible, or what makes it possible? Again, feel free to draw.

Figure 19. A razor blade floating on water and a water strider walking on water.

4. Finally, I would like to know more about your science background. What science classes did you attend at school (Middle School and High School)? How long ago was that? Did you take any physics, chemistry or physical science class at high school? Have you attended any science courses at the university?

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