Does Virtual Reality Design Matter for Learning? A Study of Fluid Dynamics

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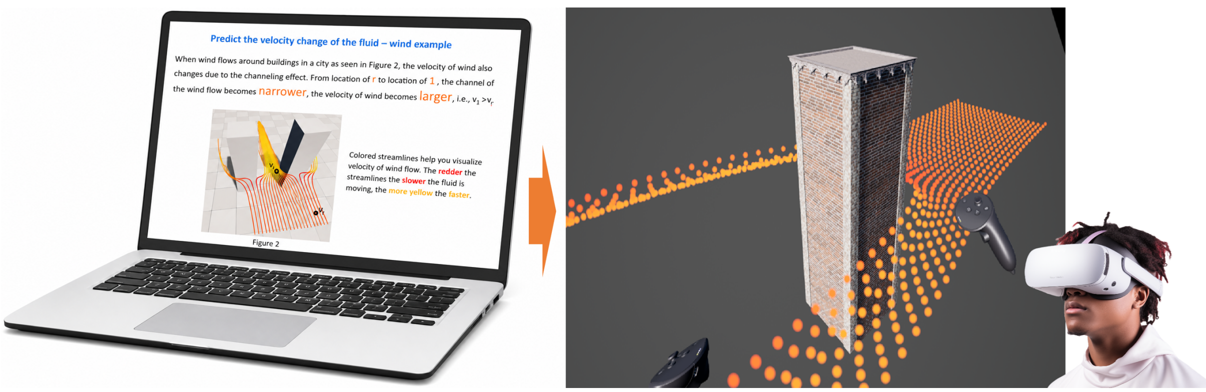

Figure 1: Two instructional approaches for teaching wind-flow behavior around buildings. Left) Slide-based instruction explaining changes in wind velocity. Right) An immersive VR environment that allows learners to interactively visualize wind-flow patterns around a building.

Abstract

Developing a deep conceptual understanding of physical phenomena is essential for engineering students to transfer their knowledge across different domains. However, teaching abstract and invisible concepts, such as fluid dynamics, that cannot be directly observed in the physical world, remains challenging. Virtual Reality (VR) offers new opportunities to support learning by enabling interactive visualizations that make invisible physical processes observable. Despite this potential, the use of VR in STEM education remains relatively limited due to the high cost and technical expertise required for development. Consequently, it remains unclear whether the benefits of incorporating VR into instruction justify these costs, highlighting the need to evaluate whether VR can improve conceptual understanding.

This study investigates the effectiveness of VR as a supplementary tool for teaching fluid dynamics, a complex and non-intuitive physics phenomenon that is difficult to observe directly. To evaluate this, we conducted a between-subjects study with 31 participants comparing two instructional conditions: traditional slide-based instruction and slides supplemented with a VR experience. Participants' conceptual understanding was assessed using a comprehension quiz. Our findings revealed that participants who experienced only traditional teaching content outperformed those who experienced the additional VR-based learning module.

Index Terms: VR teaching modules, conceptual understanding, invisible physics.

1 Introduction

In today's rapidly changing field of engineering, it is important for engineering students to have a strong conceptual understanding of the physical processes that drive the world. Students' comprehension should extend beyond routine computations, enabling them to apply their knowledge intuitively across diverse contexts, guided by conceptual understanding. Conceptual knowledge is a unit of information that connects logical meanings [19] and later extends as problematizing real-world physics, predicting system interaction, determining quantities, and solving problems [8]. Conceptual knowledge of underlying processes is critical for engineering students to develop. However, educators struggle to instill this deep level of comprehension within their students [2]. Research has also indicated that students are often able to pass their courses solely through mathematical procedures. Students may be able to answer questions though calculation while still being unable to answer deep conceptual questions pertaining to the topic [20, 37]. Having a strong ability to calculate as well as apply a deep conceptual understanding of fluid concepts is critical for physics and engineering students.

STEM educators face many challenges in helping students develop a conceptual understanding of complex topics. Lectures and mathematical derivations are essential for introducing foundational knowledge; however, research has indicated that students

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may struggle to deepen their understanding unless traditional approach is complemented by hands-on learning experiences [11, 20]. Many of these experiences take place in physical laboratory settings, yet students may still find it difficult to understand phenomena that are not visible or cannot be directly observed [33]. This is where extended reality (XR) simulations can play a major role in developing student comprehension, allowing educators to make the invisible phenomena visible and interactive in real time [5]. XR can enhance education by visualizing abstract concepts, enabling learners to explore different physical scales, and providing interactive simulations when laboratories are unavailable, costly, or unsafe [14, 16, 5, 10].

Although research in learning science has indicated VR as a promising tool for improving STEM education [13], developing an effective educational VR application is not a simple process. The level of technical knowledge required is high, and development can be costly in terms of both time and financial resources [28, 4]. Additionally, there are many aspects of application design that must be considered during development, such as usability, interaction methods, and the structure of the educational content [25, 24, 39, 7]. Moreover, learning science research has indicated that VR could impede learning due to extraneous cognitive load imposed by VR hardware and software [17]. Although there is strong interest in the use of VR in STEM education, there is currently no handbook of "best practices" to accompany it, leaving educators and developers in the dark about which design principles to follow when developing such applications [24]. VR has an important role in STEM education, and it is likely to become more widely adopted over time. However, there are still many barriers that need to be overcome in order to fully take advantage of its many benefits.

This study investigates whether supplementing traditional instruction with an interactive VR wind-simulation application can improve students' conceptual understanding of fluid dynamics. Unlike prior works that have focused on using VR applications as the sole source of educational content [4, 28], this study examined how VR can be utilized as an interactive addition to traditional learning content rather than a replacement for it. For this study, a traditional learning module consisting of a set of informative slides was first created, along with a quiz to evaluate students' conceptual understanding of the content. A VR application was then developed based on the traditional module to serve as an additional interactive lab component. Finally, a user study was conducted to compare the two teaching methods. To explore if VR can help students' conceptual understanding of fluid dynamics, we address the following research question: *Does learning through an interactive VR lead to higher overall conceptual understanding of fluid dynamics compared to traditional slide-based learning alone?*

To answer this research question, our user study compared two instructional methods: VR application and traditional slides. Results revealed:

- Participants in the traditional teaching content had a significantly deeper level of comprehension than participants in the VR group.

- This pattern was consistent across overall performance, questions equally exposed to both groups (FairProp), and questions requiring knowledge transfer to new scenarios (NewProp).

Our work provides empirical evidence that VR alone does not inherently improve learning outcomes. In our study, traditional slide-based learning, iteratively refined by engineering instructors and learning scientists, outperformed a VR condition that prioritized accurate 3D visualization of otherwise inaccessible real-world data but was developed by a VR specialist without equivalent instructional design iteration. These results reaffirm that the medium is not the message: pedagogical quality, rather than display modality, drives learning gains. We frame this as a call to action for the VR education community. VR remains a promising platform for learning, but only when grounded in learning science principles. Without deliberate instructional design, even compelling 3D visualizations of authentic data may fail to outperform well-designed traditional materials. The field must move beyond technology-first development toward design-first approaches that integrate learning scientists into the VR content creation pipeline.

2 Related Work

Research in both physics [11, 12] and engineering [20, 32] have shown that students are often able to pass courses by applying mathematical procedures while lacking a conceptual understanding of the underlying principles. Although procedural proficiency enables students to solve familiar problem types, it does not necessarily translate into the ability to reason about physical systems beyond equation-based contexts. Conceptual knowledge enables reasoning about real-world physics, such as predicting system interaction, determining quantities, and solving problems [8, 19]. This type of understanding extends beyond memorization or following established computational procedures [37] and is the source of "engineering judgment" that allows engineers to make intuitive decisions without or before computation [33].

It has been found that lecture content alone may be insufficient for helping students to grasp these topics; hands-on and interactive experiences can also play an important role in reinforcing comprehension [33]. Although many of these hands-on experiences can be conducted in an physical laboratory, invisible phenomena often require virtual representations. These phenomena can be rendered in 2D to assist student comprehension [1], while others used XR applications to develop more immersive experiences [4]. Fluid dynamics have proven to be especially difficult for students to comprehend, with many common pitfalls and misunderstandings. The most common being a misunderstanding of the inversely-proportional relationship between pressure and velocity [9]. Wind tunnels and computational fluid dynamics (CFD) software can be employed to help visualize. However, both approaches introduce practical barriers: wind tunnels are expensive and unavailable at many institutions [1], and CFD software requires high technical knowledge to use [3, 27]. In response, several prior works have tried to improve teaching methods using simpler solvers, computing languages, or visualization tools to replace expensive commercial CFD solvers [3, 21, 27, 35], with the goal to bring the topic from the graduate level to undergraduate curricula. Enabling students to solve numerical problems without being familiar with the usual necessary background knowledge. However, CFD results are typically viewed on 2D displays and are often examined at a single time point, reducing inherently dynamic, three-dimensional flow data to static representations. [34].

Although there is substantial interest in the topic of VR in STEM, there is still a lack of foundational practices. A comprehensive review of prior literature has revealed that 68% of the studies using XR to teach STEM failed to mention the theoretical foundation behind the structure of their study, instead focusing more on technical development and usability [24]. Additionally, many prior studies were loosely controlled. Lawson and colleagues reported that many of the studies confounded the medium (VR) with the instructional method, such as interactive activities in VR that are totally absent in the control group [15]. It was found that 26% of reviewed studies were fully controlled, with time spent learning and the content structure being the most common confounding variables [15]. These metrics can be difficult to account for as many virtual reality experiences tend to be short, around 6 to 30 minutes, which may also not be long enough to measure true conceptual change or long-term retention [13]. Another major limitation of current research is the metrics used to measure learning; often, studies use metrics like self-reporting rather than more objective measurements like quiz scores [17, 36].

3 METHODOLOGY

The present study compared two instructional conditions for teaching introductory fluid dynamics concepts: a traditional slide-based learning approach and a VR-augmented approach combining the same slides with an interactive VR visualization. Both methods were designed using established learning science principles [26] to emphasize conceptual understanding of pressure, velocity, and airflow behavior rather than mathematical computation. The study was approved by Institutional Review Board (IRB).

Virtual Reality Application The primary goal of the VR visualization was used to support the instructional material, not replace it. The VR scene included a visualization of wind flow around a single high rise building approximately 24 stories tall. In order to generate the wind data for this application, a specialist in CFD software first created a simulation consisting of the aforementioned scene in ANSYS Fluent. The simulation was then run and a single time interval's velocity and pressure data was then sampled. This sampled data was then converted into an fluid grid ascii (FGA) format to be imported into Unreal Engine. This technique utilized Unreal Engine's vector fields and particle system, Cascade, to render the simulation. Using a technique similar to those described by Yudin et al. [38]. Within the VR environment, participants could move between predefined viewpoints, read short explanatory text, rotate the building, move the source of the airflow, and toggle between different types of smoke visualizations. These interactions allowed participants to explore how wind behavior changes around the structure and helped reinforce the concepts introduced in the instructional slides.

Teaching Modules The slide-based module consisted of an instructional sequence (11 slides) introducing fundamental fluid dynamics concepts, including pressure, pressure differences, Bernoulli's equation, and the relationship between fluid velocity and pressure. Participants were given 10 minutes to review the slides before completing the conceptual quiz. The educational content for the introductory module was developed based on existing fluid dynamics/wind engineering teaching materials [31]. In designing the slides, we established standard practices of multimedia learning [23] and cognitive load theory [22]. The content was carefully tailored to ensure that it could be understood by individuals with no prior knowledge of fluid dynamics. Foundational physics concepts were introduced before addressing fluid-specific topics, and concepts were illustrated using familiar real-world examples to support conceptual understanding.

4 USER STUDY

4.1 Experimental Design

The study employed a between-subjects experimental design with a single independent variable: instruction modality (traditional slide-based instruction versus a combination of traditional slides and a VR application). Participants were assigned to one of the two conditions randomly. In the traditional learning module, participants were tasked with reviewing 11 slides related to wind flow, pressure, and velocity, with an emphasis on qualitative understanding rather than mathematical computation. Learning objectives included recognizing relationships between pressure and velocity, interpreting flow behavior around obstacles, and reasoning about airflow patterns around buildings.

4.2 Apparatus

The study was conducted using a desktop computer for the traditional learning condition and a Meta Quest Pro for the experimental condition. The VR scene was implemented using Unreal Engine 5.2, selected for its optimized rendering pipeline, integrated visual effects support and extensive particle systems. Users were able to control the flow of informative slides within the application, allowing them to progress at their own pace. Along with this, participants were able to change their perspective by teleportation between a few set perspectives. Users were also able to change the type of smoke used for the velocity visualization; With the choice between streamlines and dots. Finally, once participants reached the final slide, they were given the ability to rotate the building, and change the height of the smoke, allowing them to explore different aspects of the wind simulation on their own.

4.3 Participants

We recruited 31 participants (15 female, 15 male, 1 non-binary; $M_{\text{age}} = 22.84$, $SD_{\text{age}} = 5.05$). Participants reported demographic information, including ethnicity (e.g., 74% Caucasian, 19% Asian or pacific islander, 3% Hispanic/Latino, 3% Black or African American), education level, ACT or SAT scores, and GPA. Participants had a mean education level of 14.83 years (STDEV = 1.86) and a mean GPA of 3.48 (STDEV = 0.446). Participants in the control group had a mean GPA of 3.56 (STDEV = 0.45), and Participants in the VR group had a mean GPA of 3.41 (STDEV = 0.46), indicating comparable academic performance across groups. Participants were required to have a high school level of education or higher before being evaluated. Participants were required to have normal or corrected vision and must be able to speak and read English.

4.4 Procedure

The experimental procedure followed these steps (see Fig 2):

1. Consent and demographic Questionnaire: Upon arrival, participants were assigned a unique participant ID and were allocated to either the VR or control condition based on whether the ID number was odd or even. Then, participants were asked to provide a verbal consent and complete a demographics questionnaire.

2. Traditional learning module: Both experimental and control groups participated in a learning module consisting of 11 slides introducing basic physics and fluids dynamics concepts, such as pressure and velocity as well as their inversely proportional relationship. This learning module lasted for 10 minutes, during which participants viewed approximately one slide per minute.

3.1 Distractor questions (control group): After completing the traditional learning module, participants in control group answered five distraction questions (e.g., list as many red fruits as you can) designed to temporarily shift their attention away from the instructional content. This step was included to reduce short-term memory effects and to create a short cognitive break before the next phase of the study (5 minutes).

3.2 VR tutorial (VR group): Before beginning the VR learning session, participants in the VR condition completed a short tutorial designed to familiarize them with the VR system and interaction techniques. During this tutorial, participants learned how to wear and adjust the headset, navigate the virtual environment, and use the controllers to interact with objects. The VR tutorial lasted approximately 5 minutes.

4.1. Slide-based review (control group): Participants assigned to the control group were given 10 minutes to review the instructional slides presented earlier in the learning module. During this time, participants were allowed to freely navigate and revisit the slides without any restrictions.

4.2. VR Application (VR group): Participants assigned to the VR condition proceeded to the VR learning phase, which lasted 10 minutes. In this phase, participants used a virtual reality application designed to visualize and interact with fluid dynamics concepts in an immersive environment. This interactive visualization was

Table 1: Descriptive statistics for learning outcomes by condition.

Metric	Condition	Mean	SD	SE
FairProp	Control	0.910	0.168	0.042
	VR	0.696	0.243	0.063
NewProp	Control	0.896	0.201	0.050
	VR	0.678	0.271	0.070
FinalProp	Control	0.829	0.165	0.041
	VR	0.684	0.172	0.044

designed to complement the concepts introduced in the traditional slide-based module.

5. Understanding evaluation: Finally, participants in both groups completed a quiz designed to assess their conceptual understanding of the material presented during the experiment.

6. Compensation: After completing the study, participants received compensation for their participation. Participants were given the option to choose between a 20 gift card or extra course credit.

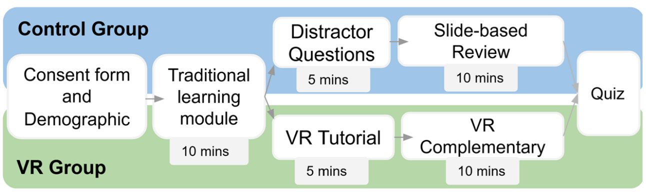

Figure 2: Experimental procedure for the control and VR groups.

4.5 Evaluation Metrics

Learning outcomes were assessed using a 15-question multiple-choice quiz designed to measure participants' conceptual understanding of fluid dynamics. Each question presented a visual diagram showing the flow of a fluid with two labeled points, and participants were asked to determine which point had a higher velocity or pressure. Participants were therefore required to rely on intuition and conceptual reasoning rather than performing calculations [32]. We computed three score-based metrics: Fair Question Score (FairProp), the proportion of correctly answered questions that were either shown to all participants or new to all participants; New Question Score (NewProp), the proportion of correctly answered questions that were new to all participants and had not been encountered during the learning phase; and Final Test Score (FinalProp), the overall proportion of correctly answered questions on the final test, computed as the number of correct answers divided by the total number of test questions. This metric was used to compare overall learning outcomes between the VR and control groups.

5 Results

We compared learning outcomes between the control condition and the VR condition using three derived metrics from the post-study quiz: *FinalProp*, *FairProp*, and *NewProp*. Figure 3 shows the comparison of conceptual understanding score for all three metrics across the two conditions.

Overall Learning Performance We first examined overall learning performance using the *FinalProp* metric, which represents the proportion of correctly answered questions across the entire quiz. As illustrated in table 1, participants in the control condition achieved higher scores ($M = 0.83$, $SD = 0.17$) compared to those in the VR condition ($M = 0.68$, $SD = 0.17$). An independent samples t-test revealed a statistically significant difference between

Table 2: Statistical comparisons for the three outcome measures. Effect sizes are Cohen's d for t-tests and rank-biserial correlations (r_{rb}) for Mann–Whitney tests.

Metric	**Test**	**Statistic**	p	**Effect**
FairProp	t-test	$t(29) = 2.86$	0.008	$d = 1.03$
	Mann–Whitney	$U = 187.50$	0.006	$r_{\text{rb}} = 0.56$
NewProp	t-test	$t(29) = 2.56$	0.016	$d = 0.92$
	Mann–Whitney	$U = 179.00$	0.014	$r_{\text{rb}} = 0.49$
FinalProp	t-test	$t(29) = 2.39$	0.023	$d = 0.86$
	Mann–Whitney	$U = 175.50$	0.029	$r_{\text{rb}} = 0.46$

conditions ($t(29) = 2.39$, $p = 0.023$) with a medium-to-large effect size ($d = 0.86$). Because the Shapiro-Wilk test indicated deviations from normality in the control group, we also conducted a Mann–Whitney test, which confirmed the same pattern of results ($U = 175.50$, $p = 0.029$, $r = 0.46$). Table 2 shows the statistical results. These results indicate that participants who received the traditional instructional format demonstrated significantly higher conceptual understanding than participants who engaged with the VR learning environment.

Performance on FairProp Questions To ensure that differences were not driven by unequal exposure to specific questions during learning, we analyzed performance on *FairProp*. The control group again achieved higher scores ($M = 0.91$, $SD = 0.17$) compared to the VR group ($M = 0.70$, $SD = 0.24$). This difference was statistically significant ($t(29) = 2.86$, $p = 0.008$) and associated with a large effect size ($d = 1.03$). The Mann–Whitney test confirmed this result ($U = 187.50$, $p = 0.006$, $r = 0.56$).

Performance on NewProp Questions Finally, we analyzed *NewProp*, which measures performance on questions that were not presented during the learning phase. Control participants again outperformed VR participants ($M = 0.90$, $SD = 0.20$ vs. $M = 0.68$, $SD = 0.27$). Statistical analysis revealed a significant difference between conditions ($t(29) = 2.56$, $p = 0.016$, $d = 0.92$). The Mann–Whitney test similarly showed a significant difference ($U = 179.00$, $p = 0.014$, $r = 0.49$). The user study showed that participants in the control condition ($M = 82.92$, $SE = 4.13$) answered a greater percentage of questions correctly than those in the VR condition ($M = 68.44$, $SE = 4.44$), $t(29) = 2.39$, $p = 0.023$, with the difference characterized by a medium to large effect size (Cohen's $d = 0.86$).

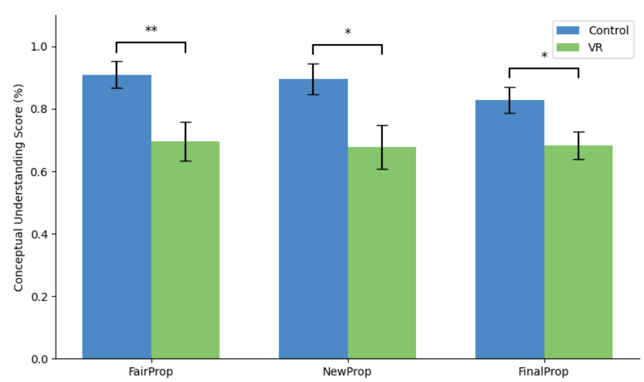

Figure 3: The percentage of conceptual accuracy across conditions. Error bars represent standard error and asterisks denote statistically significant differences (* $p < .05$ and ** $p < .01$).

6 DISCUSSION

This study investigated whether interactive VR can improve conceptual understanding of fluid dynamics compared to traditional slide-based instruction only. We discuss our findings with respect to our research question *RQ: Does learning through an interactive VR lead to higher overall conceptual understanding of fluid dynamics compared to traditional slide-based alone?* The results of the user study suggest that pairing traditional instructional content with an interactive VR module did not improve the overall students' conceptual understanding of fluid dynamics compared to a traditional slide-based only approach. One possible explanation relates to the additional cognitive demands introduced by immersive environments. Prior work has shown that VR can increase cognitive load due to the need to process spatial information, interact with the environment, and interpret dynamic visualizations simultaneously [18]. Another potential factor that may have influenced the results is participants' familiarity with VR interfaces. Although participants completed a brief five-minute VR tutorial before beginning the VR learning session, it is possible that some participants still required additional time to become fully comfortable with the virtual environment. Prior research suggests that unfamiliarity with immersive technologies can introduce additional cognitive demands [18].

Consistent with the overall comprehension scores, participants in the control condition also outperformed those in the VR condition on NewProp questions. This suggests that the VR-based learning experience did not provide advantages in applying conceptual knowledge to unfamiliar scenarios. One possible explanation is that new questions require learners to abstract general principles from the instructional material and apply them to new contexts. The slide-based materials explicitly presented the relationships between pressure and velocity using simplified diagrams and structured explanations, which may have helped participants form clearer conceptual rules. In contrast, the VR environment emphasized observing wind flow patterns around buildings through a dynamic visualization. While this visualization may support intuitive understanding of fluid behavior, which may have supported intuitive understanding but provided less guidance for extracting the abstract principles necessary for solving novel problems.

7 DESIGN RECOMMENDATIONS

For future educational applications it is critical to implement a foundational learning framework, 68% of existing studies involving VR education failed to mention the use of a theoretical foundation of learning sciences behind their application structure [24]. The use of these theoretical frameworks ensures that the design and structure of the application promote learning rather than prohibiting [26]. In addition, a set of "best practice" design principles should be kept in mind during development. Some studies have already taken steps towards evaluating the design principles that can mitigate these limitations [29, 39]. However, this is just scratching the surface of what design principles can be done to improve these learning applications. Interaction design is another important factor [6]. VR applications often require users to navigate the environment, manipulate objects, and interpret spatial information simultaneously [39]. Interaction techniques that are intuitive and require minimal effort—such as simple pointing, guided viewpoints, or automatic camera transitions- can reduce interaction overhead and allow learners to focus more on the educational content.

8 LIMITATIONS AND FUTURE WORK

A limitation of this work is due to the requirement to control for time spent on learning tasks. Although this control ensured that learning evaluations were more objective, it created limitations on how and if metrics could be collected, specifically surveys evaluating cognitive load and usability. There is a risk for memory deterioration, but these measurements could have been recorded in a post-evaluation survey. Another approach could be to have a preliminary study that focuses purely on the usability and design of the system, similar to Solmaz and collaborators' methods [29, 30].

Some of the quiz questions involved examples using water rather than wind. The traditional learning module did include examples using both water and wind. Since the control group viewed the traditional slides an additional time during their review session and the VR group only saw wind examples within the VR application, control participants may have had an unfair advantage on questions involving water. It is important to note that all the quiz questions involved only basic fluid concepts, both water and wind are fluids, and as far as the quiz questions were laid out, whether the figure used was wind or water would not change the specific answer; rather, the questions were intended to test students' intuitive understanding of fluid behavior.

9 CONCLUSION

This study investigated whether augmenting traditional experience with a VR experience improves conceptual understanding of fluid dynamics. Results showed that participants in traditional learning outperformed those in VR across overall, FairProp, and NewProp questions, indicating that VR did not enhance learning in this context. These findings suggest that while VR can be a powerful educational tool, it does not inherently lead to improved learning outcomes. Additional factors introduced by VR, such as increased cognitive and interaction demands, may hinder the development of a conceptual understanding despite its interactive nature. This was likely due to the design limitations, highlighting the importance for developers and educators to carefully consider these factors when using VR as an educational medium.

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REFERENCES

[1] K. Achuthan, L. S. Bose, S. Francis, K. S. Sreelatha, C. O. Sreekala, P. Nedungadi, and R. Raman. Improving perception of invisible phenomena in undergraduate physics education using ICT. In *2014 2nd International Conference on Information and Communication Technology (ICoICT)*, pp. 226–231, 2014. doi: 10.1109/ICoICT.2014.6914070 2

[2] M. Arnold and R. Millar. Learning the scientific "story": A case study in the teaching and learning of elementary thermodynamics. *Science Education*, 80(3):249–281, 1996. doi: 10.1002/(SICI)1098-237X(199606)80:3<249::AID-SCE1>3.0.CO;2-E 1

[3] N. A. Battista. Suite-CFD: An Array of Fluid Solvers Written in MATLAB and Python. *Fluids*, 5(1), 2020. doi: 10.3390/fluids5010028 2

[4] K. E. R. Boettcher and A. S. Behr. Using Virtual Reality for Teaching the Derivation of Conservation Laws in Fluid Mechanics. 11:42–57, 2021. 2

[5] Z. Borhani, F. Borhani, and F. R. Ortega. Experiencing gravitational red-shiftting in virtual reality. In *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 133–137, 2024. doi: 10.1109/VRW62533.2024.00028 2

[6] Z. Borhani, A. Ebrahimpour-Boroojeny, and F. R. Ortega. Small cues, big differences: Evaluating interaction and presentation for annotation retrieval in ar. *arXiv preprint arXiv:2509.11401*, 2025. 5

[7] Z. Borhani, P. Sharma, and F. R. Ortega. Survey of annotations in extended reality systems. *IEEE Transactions on Visualization and Computer Graphics*, 30(8):5074–5096, 2024. doi: 10.1109/TVCG.2023.3288869 2

[8] F. Bornasal, S. Brown, N. Perova-Mello, and K. Beddoes. Conceptual Growth in Engineering Practice. *Journal of Engineering Education*, 107(2):318–348, 2018. doi: 10.1002/JEE.20196 1, 2

[9] J. Clement. Students' preconceptions in introductory mechanics. *American Journal of Physics*, 50(1):66–71, 1982. doi: 10.1119/1.12989 2

[10] J. Franklin and A. Ryder. Electromagnetic field visualization in virtual reality. *American Journal of Physics*, 87(2):153–157, 2019. 2

[11] R. R. Hake. Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, 66(1), 1998. doi: 10.1119/1.18809 2

[12] I. A. Halloun and D. Hestenes. The initial knowledge state of college physics students. *American Journal of Physics*, 53(11), 1985. doi: 10.1119/1.14030 2

[13] D. Hamilton, J. McKechnie, E. Edgerton, and C. Wilson. Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design. *Journal of Computers in Education*, 8(1), 2021. doi: 10.1007/s40692-020-00169-2 2

[14] Y. Jiugen, Y. Jing, and X. Ruonan. Design research of physical virtual experiment based on virtual reality technology. In *2020 15th International Conference on Computer Science & Education (ICCSE)*, pp. 262–266. IEEE, 2020. 2

[15] A. P. Lawson, A. M. Martella, K. LaBonte, C. Y. Delgado, F. Zhao, J. A. Gluck, M. E. Munns, A. Wells LeRoy, and R. E. Mayer. Confounded or Controlled? A Systematic Review of Media Comparison Studies Involving Immersive Virtual Reality for STEM Education. *Educational Psychology Review*, 36(3):69, July 2024. doi: 10.1007/s10648-024-09908-8 2

[16] R. B. Loftin, M. Engleberg, and R. Benedetti. Applying virtual reality in education: A prototypical virtual physics laboratory. In *Proceedings of 1993 ieee research properties in virtual reality symposium*, pp. 67–74. IEEE, 1993. 2

[17] G. Makransky and G. B. Petersen. The Cognitive Affective Model of Immersive Learning (CAMIL): a Theoretical Research-Based Model of Learning in Immersive Virtual Reality, 2021. ISSN: 1573336X Number: 3 Volume: 33. doi: 10.1007/s10648-020-09586-2 2, 3

[18] R. E. Mayer, G. Makransky, and J. Parong. The Promise and Pitfalls of Learning in Immersive Virtual Reality. *International Journal of Human-Computer Interaction*, 39(11), 2023. doi: 10.1080/10447318.2022.2108563 5

[19] R. McCormick. Conceptual and Procedural Knowledge. *International Journal of Technology and Design Education*, 7(1–2):141–159, 1997. doi: 10.1023/A:1008819912213/METRICS 1, 2

[20] D. Montfort, S. Brown, and D. Pollock. An investigation of students' conceptual understanding In related sophomore to graduate-level engineering and mechanics courses. *Journal of Engineering Education*, 98(2), 2009. doi: 10.1002/j.2168-9830.2009.tb01011.x 1, 2

[21] R. G. Neves. Enhancing teaching and learning of fluid mechanics with interactive computational modelling. *Journal of Physics: Conference Series*, 1286(1):12047, 2019. doi: 10.1088/1742-6596/1286/1/012047 2

[22] F. Paas, T. van Gog, and J. Sweller. Cognitive load theory: New conceptualizations, specifications, and integrated research perspectives, 2010. ISSN: 1040726X Number: 2 Volume: 22. doi: 10.1007/s10648-010-9133-8 3

[23] R. Pal. Teaching Fluid Mechanics and Thermodynamics Simultaneously through Pipeline Flow Experiments. *Fluids 2019, Vol. 4, Page 103*, 4(2):103, 2019. doi: 10.3390/FLUIDS4020103 3

[24] J. Radianti, T. A. Majchrzak, J. Fromm, and I. Wohlgenannt. A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers and Education*, 147, 2020. doi: 10.1016/j.compedu.2019.103778 2, 5

[25] I. Radu and B. Schneider. How Augmented Reality (AR) Can Help and Hinder Collaborative Learning: A Study of AR in Electromagnetism Education. *IEEE Transactions on Visualization and Computer Graphics*, 29(9), 2023. doi: 10.1109/TVCG.2022.3169980 2

[26] M. G. Rhodes, A. M. Cleary, and E. L. DeLosh. *A guide to effective studying and learning: Practical strategies from the science of learning*. Oxford University Press, 2020. 3, 5

[27] C. Sert and G. Nakiboğlu. Use of Computational Fluid Dynamics (CFD) in teaching fluid mechanics. *ASEE Annual Conference and Exposition, Conference Proceedings*, Jan. 2007. 2

[28] M. Soliman, A. Pesyridis, D. Dalaymani-Zad, M. Gronfula, and M. Kourmpetis. The application of virtual reality in engineering education. *Applied Sciences (Switzerland)*, 11(6), 2021. doi: 10.3390/app11062879 2

[29] S. Solmaz, L. Kester, and T. Van Gerven. Preliminary investigation of a CFD-assisted virtual reality experience in engineering education. pp. 2207–2211. Universitat Politècnica de Catalunya, 2022. 5

[30] S. Solmaz, L. Kester, and T. Van Gerven. An immersive virtual reality learning environment with CFD simulations: Unveiling the Virtual Garage concept. *Education and Information Technologies*, 29(2):1455–1488, Feb. 2024. doi: 10.1007/s10639-023-11747-z 5

[31] T. Stathopoulos. Wind Effects on Structures Modern Structural Design for Wind by Emil Simiu and DongHun Yeo. *JOURNAL OF WIND ENGINEERING AND INDUSTRIAL AERODYNAMICS*, 212, May 2021. doi: 10.1016/j.jweia.2021.104635 3

[32] R. A. Streveler, S. Brown, G. L. Herman, and D. Montfort. Conceptual change and misconceptions in engineering education: Curriculum, measurement, and theory-focused approaches. In *Cambridge Handbook of Engineering Education Research*. 2015. doi: 10.1017/CBO9781139013451.008 2, 4

[33] R. A. Streveler, T. A. Litzinger, R. L. Miller, and P. S. Steif. Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions. *Journal of Engineering Education*, 97(3):279–294, 2008. doi: 10.1002/J.2168-9830.2008.TB00979.X 2

[34] J. Venn, C. E. Larkee, G. J. Garcia, V. L. Rayz, and J. F. LaDisa Jr. A workflow for viewing biomedical computational fluid dynamics results and corresponding data within virtual and augmented reality environments. *Frontiers in Medical Technology*, 5:1096289, 2023. 2

[35] R. S. Vianna, A. M. Cunha, R. B. V. Azeredo, R. Leiderman, and A. Pereira. Computing Effective Permeability of Porous Media with FEM and Micro-CT: An Educational Approach. *Fluids*, 5(1), 2020. doi: 10.3390/fluids5010016 2

[36] J. F. Villada Castillo, L. Bohorquez Santiago, and S. Martínez García. Optimization of Physics Learning Through Immersive Virtual Reality: A Study on the Efficacy of Serious Games. *Applied Sciences*, 15(6), 2025. doi: 10.3390/app15063405 3

[37] M. K. Watson, J. Pelkey, C. R. Noyes, and M. O. Rodgers. Assessing Conceptual Knowledge Using Three Concept Map Scoring Methods. *Journal of Engineering Education*, 105(1), 2016. doi: 10.1002/jee.20111 1, 2

[38] P. V. Yudin, M. I. Fedina, E. V. Strizh, O. V. Yudina, and K. V. Computational Hydrodynamics in Air Flows Modeling : Using the Unreal Engine based on the numerical solution of the Navier-Stokes equations. In *2019 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon)*, pp. 1–9, 2019. doi: 10.1109/FarEastCon.2019.8934325 3

[39] J. Zöllner, B. Preim, J.-W. Vahlbruch, V. Pottgießer, and P. Saalfeld. Exploration of interactive nuclide chart visualisations in virtual reality for physics education. *Computers & Graphics*, 130:104258, 2025. doi: 10.1016/j.cag.2025.104258 2, 5