

## ORIGINAL RESEARCH ARTICLE

# Enhancing conceptual understanding and retention in thermodynamics through haptic-enhanced immersive simulations: a quasi-experimental study

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*Received: 16 June 2025; Revised: 25 July 2025; Accepted: 27 July 2025; Published: 30 October 2025*

Immersive technologies are increasingly used in science education, yet the role of embodied interaction – particularly haptic feedback – in promoting conceptual understanding remains underexplored. This study investigated the effectiveness of Haptic + Visual Immersive Simulations (H+VISs) compared to Visual-only Immersive Simulations (VOISs) in teaching thermodynamics. A quasi-experimental design was employed with 130 secondary students, who completed pre-, immediate post-, and delayed post-tests using a validated Thermodynamics Concept Test. Results showed that the HVIS group significantly outperformed the VIS group in both post-tests, indicating improved learning gains and retention. The HVIS group also scored higher on the Embodied Thermodynamics Scale and reported lower cognitive load, as measured by the Paas scale. Repeated measures analysis of variance revealed significant main effects for time and group, as well as a significant interaction, favoring the HVIS condition. National Aeronautics and Space Administration (NASA-TLX) ratings indicated that the HVIS group experienced higher perceived performance and lower effort and frustration. Path analysis further revealed that embodied learning partially mediated the effect of instructional modality on retention. These findings support the integration of haptic feedback in immersive Science and Technology, Engineering and Mathematics (STEM) instruction, emphasizing the role of multisensory engagement in fostering deeper learning and reducing cognitive effort in abstract domains such as thermodynamics.

**Keywords:** haptic feedback; immersive learning; thermodynamics; embodied cognition; cognitive load

## Introduction

Thermodynamics is a critical yet conceptually challenging topic in the secondary and post-secondary science curricula globally, including the Philippine senior high school and undergraduate STEM programs. Concepts such as heat flow, entropy, and energy transformations are foundational not only in physics but also in chemistry, biology, environmental science, and engineering. Internationally, thermodynamics is a core component of curricula such as the U.S. Next Generation Science Standards (NGSS), the UK's A-Level Physics, and the International Baccalaureate (IB), reflecting its

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essential role in preparing students for STEM-related academic and professional pathways (Brown & Bybee, 2023; Bybee, 2013; Talbot & Tabison, 2023).

However, thermodynamics concepts are often abstract and counterintuitive, presenting persistent learning difficulties. These challenges are compounded in rural and resource-constrained settings, such as many public schools in the Philippines, where laboratory access and opportunities for hands-on experimentation are limited or absent (Linn & Songer, 1991; Mercado, 2020; Orleans, 2007). Students across multiple contexts commonly struggle with misconceptions about energy conservation, heat transfer, and entropy (Loverude, 2015; Smith et al., 2015), particularly when instruction relies heavily on static visuals and teacher-centered lectures. These limitations can lead to cognitive overload, conceptual misunderstandings, and poor retention (Dejene & Chen, 2019; Paas & Sweller, 2012).

In recent years, immersive learning technologies – particularly virtual and augmented simulations – have emerged as promising solutions to address these instructional deficits. These tools enable students to interact with dynamic systems in multi-sensory, three-dimensional environments, offering new possibilities for active, experiential learning (Bhowmik, 2024). However, most educational simulations remain predominantly visual and auditory, with limited engagement of the tactile (haptic) modality, which plays a critical role in how humans perceive and reason about thermal processes. Integrating haptic feedback – such as temperature variation, vibration, or resistance – into immersive thermodynamics simulations offers the potential to foster embodied cognition, enhance physical intuition, and reduce extraneous cognitive load, thereby supporting deeper conceptual understanding and long-term retention (Huang et al., 2022; Lee et al., 2020; Peiris et al., 2017; Sun et al., 2022).

This study is anchored on Embodied Cognition Theory, which posits that meaningful learning emerges from bodily interactions with the environment (Shapiro, 2019a), and Cognitive Load Theory (CLT), which emphasizes the importance of managing working memory resources by distributing processing across multiple modalities (Paas et al., 2004; Paas & Sweller, 2012). When applied to haptic-augmented immersive environments, these frameworks suggest that physically grounded experiences can scaffold abstract reasoning, particularly in conceptually demanding areas such as thermodynamics.

Despite growing international interest in immersive and haptic technologies, empirical research investigating their educational impact remains limited, particularly in developing countries and rural school settings. To date, no study has systematically examined the comparative effects of haptic-enhanced versus visual-only immersive learning on thermodynamics understanding, cognitive load, embodiment, and retention in the Philippine context. Filling this gap is essential not only for national curriculum enhancement but also for aligning with global trends in equitable and inclusive digital education.

## **Literature review**

### ***Challenges in thermodynamics learning in secondary and tertiary education***

Thermodynamics is widely recognized as one of the most difficult domains in science education due to its abstract, non-intuitive nature and reliance on microscopic reasoning (Smith et al., 2015; Sokrat et al., 2014). Students often struggle with concepts such as entropy, heat flow, and energy conservation, which are not directly

observable and are typically presented in highly symbolic language (Brundage et al., 2024; Smith et al., 2015). In the Philippines, particularly in rural and marginalized areas, this challenge is exacerbated by limited access to laboratory equipment, lack of digital infrastructure, and a reliance on passive instructional methods such as printed media or lectures (Latchem & Jung, 2009; Trelease, 2016). These conditions often result in rote memorization, low engagement, and persistent misconceptions (Lapitan, 2021).

### ***Embodied cognition and the role of multisensory learning***

Embodied cognition theory posits that knowledge is grounded in physical experience, and learning is enhanced when multiple sensory modalities are engaged (Ignatow, 2007; Shapiro & Spaulding, 2014). In science education, embodied learning has been shown to help students form intuitive understandings of abstract phenomena through bodily interaction and sensorimotor feedback (Johnson-Glenberg et al., 2014). Haptic feedback – referring to tactile information such as pressure, resistance, or temperature – has the potential to provide learners with embodied representations of thermodynamic processes that are otherwise invisible or symbolic in nature (Jones et al., 2005; MacLean, 2000; Lécuyer, 2009). For example, simulation environments that incorporate heat-like sensations can help learners grasp the flow of thermal energy, making the learning experience more meaningful and memorable.

### ***Cognitive load theory and immersive simulation environments***

According to the CLT, learning is optimized when instructional design reduces extraneous cognitive load and supports germane processing (van Merriënboer & Sweller, 2005). Immersive simulations have been shown to increase learner engagement and facilitate understanding by allowing learners to visualize and manipulate dynamic systems (Lindgren et al., 2016). When designed effectively, such environments can decrease the working memory demands imposed by abstract concepts. Recent studies have demonstrated that the addition of haptic feedback in immersive systems can further reduce cognitive load by distributing information across sensory modalities, thus freeing cognitive resources for deeper processing (Makransky et al., 2019; Wenk et al., 2021).

### ***Educational applications of haptic feedback in STEM domains***

The use of haptics in STEM education has gained increasing attention for its capacity to improve learning outcomes in fields such as engineering, biology, and medicine (Pellas et al., 2020). In surgical training, for instance, haptic-enhanced Virtual Reality (VR) has been shown to accelerate skill acquisition, improve precision, and reduce error rates (Perry et al., 2015). In physics education, however, the integration of haptic feedback remains underexplored, particularly in topics such as thermodynamics where tactile sensations could reinforce conceptual learning. A few experimental studies outside the Philippines suggest that haptic cues improve students' understanding of forces, pressure, and fluid dynamics (Minogue & Borland, 2015), but the extension of these findings to entropy and heat flow remains a research gap.

### ***Immersive learning and equity in Philippine rural education***

While immersive technologies are often perceived as expensive and urban-centric, recent research demonstrates their feasibility and potential benefits in rural Philippine schools when implemented using low-cost headsets and offline content delivery systems (Reyes et al., 2024). Integrating immersive simulations into rural classrooms can democratize access to high-quality science education, especially in settings where physical laboratories are absent. However, there is a lack of localized studies examining how these tools function in real classroom conditions, and how they affect cognitive and affective outcomes among rural learners. This gap is particularly pressing in the Philippine context, where policy frameworks now emphasize digital transformation and technology integration in public education under the MATATAG curriculum (Demate et al., 2025).

#### **Research aim**

The researcher aimed to determine the impact of haptic feedback in immersive thermodynamic simulations on embodied conceptual learning. Specifically, this aims to:

- Evaluate the effectiveness of haptic feedback in simulating heat flow and entropy through immersive thermodynamic simulations using ThermoVR-PH
- Assess the extent to which haptic-enhanced immersive instruction promotes embodied learning and strengthens physical intuition in abstract thermal systems
- Compare the impact of haptic + visual immersive simulation (HVIS) and visual-only immersive simulation (VOIS) on students' cognitive load, subjective workload (NASA-TLX), and thermodynamic conceptual retention over time
- Determine whether embodied learning mediates the relationship between instructional modality (HVIS vs. VIS) and long-term conceptual retention in thermodynamics

#### **Research methodology**

##### ***Research design***

This study employed a quasi-experimental pretest–posttest non-equivalent groups design to examine the impact of haptic feedback in immersive thermodynamic simulations on conceptual understanding and embodied learning (Creswell & Creswell, 2023). Two matched Grade 12 STEM classes from Nueva Vizcaya General Comprehensive High School, Bayombong, Nueva Vizcaya, Philippines, were assigned to either a Haptic + Visual Immersive Simulation (HVIS) group or a Visual-Only Immersive Simulation (VOIS) group. Both groups received the same VR-based thermodynamics instruction, with only the HVIS group experiencing haptic cues. Quantitative data were collected at three time points – pretest, immediate posttest, and delayed posttest – using validated instruments. This design enabled the analysis of learning gains, retention, cognitive load, and physical intuition in an ecologically valid rural school context.

### ***Study context and participants***

The investigation was carried out at Nueva Vizcaya General Comprehensive High School, Bayombong, Nueva Vizcaya, a rural public secondary school selected for its stable computer laboratory. The accessible population comprised 130 Grade 12 STEM students enrolled in two intact physics sections. A priori power analysis ( $\alpha = 0.05$ , power = 0.80,  $d = 0.50$ ) indicated a minimum of 64 students per group (Faul et al., 2009); the final sample consisted of 65 students in the haptic + visual immersive simulation (HVIS) condition and 65 in the visual-only immersive simulation (VOIS) condition. Sections were first matched on mean physics grades from the previous term and then randomly assigned to conditions. Written informed consent was obtained from students and guardians in accordance with the Research Ethics Committee of the Schools Division Office of Nueva Vizcaya.

### ***Data collection***

Four instruments captured the principal outcome variables. Conceptual understanding of thermodynamics was measured with a 20-item Thermodynamics Concept Test that was Rasch-validated for local use (KR-20 = 0.86). Embodied learning and physical intuition were assessed using a 12-item Embodied Thermodynamics Scale adapted from Johnson-Glenberg et al. (2016) ( $\alpha = 0.88$ ). Cognitive load was gauged with the 9-point Paas Mental-Effort Rating Scale (Paas, 1992), and subjective workload was recorded via the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). All instruments were forward- and back-translated into Filipino, pilot-tested with 30 non-participant students, and demonstrated acceptable reliability ( $\alpha \geq .80$ ).

### ***Instructional design and implementation***

The thermodynamics lessons were co-designed by licensed physics educators and validated by curriculum experts to ensure alignment with the Department of Education's senior high school curriculum. Lessons were adapted into three delivery modes matching the treatment groups. Each mode covered the same learning objectives, content, and assessment criteria.

The immersive simulations were developed using Unity 3D, with the HVIS group incorporating low-cost haptic feedback via improvised haptic devices. The VIS group accessed the same simulations without haptic components. All groups were given equal instructional time across 3 weeks.

### ***Intervention procedure***

The intervention involved two experimental groups: the Haptic-Enhanced Visual Immersive Simulation (HEVIS) group and the Visual Immersive Simulation (VIS) group. Both groups studied the same thermodynamics content over a period of 3 weeks, specifically focusing on the first and second laws of thermodynamics, thermal equilibrium, heat transfer, and applications in real-life scenarios. The primary distinction between the two groups was the sensory modality integrated into the simulation experience.

### *HVIS group*

Participants in the HVIS group engaged with custom-designed, low-cost haptic-enhanced immersive simulations developed using Unity 3D. The simulations were accessed through laptops or mobile devices with VR cardboard viewers. Haptic feedback was delivered using improvised, recycled vibration motors attached to handheld controllers. These motors were triggered in synchronization with simulation events (e.g. vibration feedback when thermal energy was transferred or when equilibrium was reached).

The haptic devices were assembled using affordable components such as coin vibration motors, microcontrollers (e.g. Arduino Nano), and recycled plastic casings. Each student was guided using the device during the orientation session. The integration of tactile feedback aimed to enhance students' sensory immersion and embodiment of physical concepts. Students interacted with the simulations in a structured classroom environment for 40 min per session, three times per week, under the supervision of the same physics teacher throughout the study.

### *VIS group*

The VIS group used the same visual simulations created in Unity 3D, delivered via VR cardboard and mobile phones or laptops, but without the haptic feedback mechanism. Students received the same visual content, interactive controls, and narration as the HVIS group, allowing for comparable visual immersion. The difference lay solely in the absence of tactile cues.

Both groups underwent a brief orientation prior to the first session to ensure familiarity with the simulation controls and virtual interface. Instruction was delivered synchronously by the same teacher to both groups to ensure consistency of pedagogical approach and content coverage.

### *Data analysis*

Data were analyzed using IBM SPSS (Version 29). Missing values ( $\leq 5\%$ ) were estimated using expectation-maximization after confirming that data were missing at random. Normality (Shapiro–Wilk) and homogeneity (Levene) assumptions were satisfied. An analysis of covariance (ANCOVA) compared post-test conceptual scores across conditions while controlling for pre-test performance. Independent-samples *t* tests assessed differences in cognitive-load and embodied-learning scores, whereas NASA-TLX subscales were examined using multivariate analysis of variance (MANOVA). Retention was evaluated with a  $2 \times 2$  repeated-measures analysis of variance (ANOVA) (time  $\times$  group). Finally, path analysis tested whether embodied-learning scores mediated the relationship between instructional modality and retention (Han & Black, 2011). Effect sizes were reported as partial  $\eta^2$  for ANCOVA, Cohen's *d* for *t* tests, and standardized  $\beta$  coefficients for mediation paths. All statistical decisions used a two-tailed  $\alpha$  of .05.

### *Ethical considerations*

This study adhered to established ethical protocols in line with international standards for research involving human participants. Ethical clearance was obtained from

the Research Ethics Committee of the Schools Division Office of Nueva Vizcaya, which is accredited to oversee research activities within public secondary schools in the region. The committee ensures that research conducted under its jurisdiction upholds the principles of voluntary participation, informed consent, confidentiality, and non-maleficence.

Prior to data collection, all participants and their guardians were provided with informed consent forms that clearly outlined the purpose of the study, the nature of their involvement, data protection measures, and their right to withdraw at any time without penalty. Consent was obtained in writing from both students and parents. Participants were not offered any monetary or material incentives; however, they were assured that their participation would contribute to innovations in teaching methods within their school system and that no academic advantage or disadvantage would result from participation or non-participation.

To address potential inequities – particularly the concern of disadvantaging students without access to haptic devices – the instructional design incorporated equal access to core thermodynamic content through both haptic-enhanced visual immersive simulations (HVIS) and standard visual immersive simulations (VIS). All students received instruction aligned with the same learning competencies, and assessments were designed to measure understanding independent of modality. Students in the VIS group were not penalized in any way and were offered opportunities to engage with the haptic technology after the intervention phase to ensure fairness and inclusive exposure to the innovation.

The study was also designed to minimize risk and cognitive overload, with protocols for debriefing, wellbeing monitoring, and teacher supervision during all immersive sessions. Data collected were anonymized, securely stored, and used solely for academic and developmental purposes. These measures ensured that the study was conducted with the highest standards of ethical integrity, transparency, and participant protection.

## Results

Table 1 presents the mean scores and standard deviations on the Thermodynamics Concept Test administered at three time points – pre-test, immediate post-test, and delayed post-test – for the HVIS (Haptic + Visual Immersive Simulation) and VOIS (Visual-only Immersive Simulation) groups. At baseline, both groups demonstrated comparable pre-test scores ( $M = 49.8$  for HVIS;  $M = 49.5$  for VIS), indicating initial equivalence. However, at the immediate and delayed post-tests, the HVIS group significantly outperformed the VIS group, suggesting superior conceptual gains and retention in the haptic-enhanced immersive condition.

To explore the impact of instructional modality on embodied understanding and perceived mental effort, independent samples  $t$ -tests were conducted. Table 2 summarizes the results. The HVIS group scored significantly higher on the Embodied Thermodynamics Scale ( $M = 48.3$ ,  $SD = 4.9$ ) compared to the VIS group ( $M = 40.1$ ,  $SD = 5.6$ ),  $t(128) = 9.10$ ,  $p < 0.001$ . Meanwhile, participants in the HVIS condition reported significantly lower mental effort on the Paas scale ( $M = 4.6$ ) than those in the VIS group ( $M = 5.4$ ),  $t(128) = -3.71$ ,  $p < 0.001$ .

Table 3 presents the NASA Task Load Index (NASA-TLX) subscale ratings. While both groups reported similar mental, physical, and temporal demands, the HVIS group rated their performance higher and reported lower effort and frustration

Table 1. Pre-test and post-test scores on thermodynamics concept test by instructional group ( $N = 130$ ).

Test time	Group	<i>M</i>	SD
Pre-test	HVIS	49.8	8.3
	VIS	49.5	8.1
Immediate post-test	HVIS	75.4	9.1
	VIS	68.2	9.4
Delayed post-test	HVIS	70.1	8.7
	VIS	62.3	8.9

HVIS: Haptic + Visual Immersive Simulations; VOIS: Visual-Only Immersive Simulation.

Table 2. Embodied thermodynamics and cognitive load scores by instructional group.

Measure	HVIS		VIS		<i>t</i> (128)	<i>p</i>
	<i>M</i>	SD	<i>M</i>	SD		
Embodied thermodynamics scale	48.3	4.9	40.1	5.6	9.10	< 0.001
Paas mental-effort rating	4.6	1.2	5.4	1.3	-3.71	< 0.001

HVIS: Haptic + Visual Immersive Simulations; VOIS: Visual-Only Immersive Simulation.

Table 3. NASA task load index (NASA-TLX) subscale scores by instructional group.

Subscale	HVIS		VIS	
	<i>M</i>	SD	<i>M</i>	SD
Mental demand	52	14	55	15
Physical demand	38	13	34	12
Temporal demand	44	15	48	17
Performance	70	11	62	12
Effort	46	12	55	13
Frustration	33	14	40	15

HVIS: Haptic + Visual Immersive Simulations; VOIS: Visual-Only Immersive Simulation.

compared to the VIS group. These findings indicate a more favorable user experience under the multimodal immersive condition.

A repeated measures ANOVA (see Table 4) was conducted to examine the effects of instructional group and time on concept retention. Significant main effects were found for Time,  $F(1, 128) = 87.41, p < 0.001$ , partial  $\eta^2 = 0.41$ , and Group,  $F(1, 128) = 22.40, p < 0.001$ , partial  $\eta^2 = 0.15$ . A significant Time  $\times$  Group interaction,  $F(1, 128) = 12.65, p < 0.001$ , partial  $\eta^2 = 0.09$ , indicated that the HVIS group retained their learning significantly better over time.

To determine whether embodied learning mediated the effect of instructional modality on retention, a path analysis was conducted. As shown in Table 5, instructional modality significantly predicted embodied learning ( $\beta = 0.78, p < 0.001$ ), which in turn significantly predicted retention ( $\beta = 0.23, p = 0.003$ ). The direct effect of instructional modality on retention remained significant ( $\beta = 0.42, p < 0.001$ ). The indirect effect was also significant ( $\beta = 0.18, 95\% \text{ CI } [0.07, 0.35]$ ), indicating partial mediation.

Table 4. Repeated measures ANOVA on retention scores by group and time.

Effect	<i>F</i> (1,128)	<i>P</i>	Partial $\eta^2$
Time	87.41**	< 0.01	0.41
Group	22.40**	< 0.01	0.15
Time×Group	12.65**	< 0.01	0.09

ANOVA: analysis of variance. \*\**p* < 0.01.

Table 5. Path analysis: mediation of instructional modality on retention via embodied learning.

Path	Standardized $\beta$	SE	95% CI	<i>p</i>
Instructional modality → Embodied learning	0.78	0.06	[0.65, 0.89]	< 0.001
Embodied learning → Retention	0.23	0.07	[0.08, 0.41]	0.003
Instructional modality → Retention (direct)	0.42	0.08	[0.26, 0.58]	< 0.001
Instructional Modality → Embodied Learning → Retention (Indirect)	0.18	0.06	[0.07,0.35]	< 0.001

## Discussion

The results demonstrate that learners exposed to Haptic + Visual Immersive Simulations (HVISs) significantly outperformed those in the Visual-only Immersive Simulation (VOIS) group on both immediate and delayed post-tests, despite equivalent baseline scores. This indicates that the addition of haptic feedback facilitated greater conceptual understanding and retention of thermodynamic principles. These findings align with prior studies suggesting that multisensory environments can enhance science learning by reducing cognitive overload and promoting active engagement with abstract content (Lindgren et al., 2016; Makransky et al., 2019).

Higher scores on the Embodied Thermodynamics Scale further support the role of sensorimotor engagement in fostering conceptual gains, consistent with Embodied Cognition Theory, which posits that learning is grounded in physical experience (Johnson-Glenberg et al., 2014; Shapiro & Spaulding, 2014). Simultaneously, the HVIS group reported significantly lower cognitive load as measured by the Paas scale, suggesting that distributing cognitive processing across visual and tactile modalities alleviated working memory demands – an outcome anticipated by CLT (Sweller, 2011; van Merriënboer & Sweller, 2005).

In addition to cognitive outcomes, participants in the HVIS condition also reported a more favorable user experience across the NASA-TLX dimensions of performance, effort, and frustration. These affective indicators suggest that haptic-enhanced simulations not only support cognitive processing but also reduce the psychological barriers often associated with complex scientific content (Wenk et al., 2021).

Moreover, path analysis revealed the fact that embodied learning partially mediated the relationship between instructional modality and delayed retention, underscoring the importance of bodily interaction in promoting long-term conceptual integration. This mediating effect reinforces recent claims that haptic cues in immersive environments can deepen students’ physical intuition and support lasting learning in conceptually challenging domains such as thermodynamics (Huang et al., 2022; Peiris et al., 2017; Sun et al., 2022).

## **Conclusions and implications**

This study provides robust evidence that haptic-enhanced visual immersive simulations (HVIS) significantly improve high school students' acquisition and retention of thermodynamic concepts compared to visual-only immersive simulations (VOISs). The integration of tactile interaction with immersive visual learning environments enhances not only cognitive performance but also students' engagement and perceived learning experience. These findings contribute to the growing body of research on embodied cognition, particularly within the context of abstract scientific domains in secondary education.

The field of thermodynamics, with its reliance on non-visible, abstract constructs such as heat transfer, entropy, and internal energy, is especially well-suited to haptic enhancement. Unlike physics concepts that are primarily visual (e.g. motion, optics) or mathematical (e.g. vectors, force diagrams), thermodynamic phenomena cannot be directly observed, making them more cognitively demanding for novice learners. The application of haptic feedback offers a sensory proxy for these invisible phenomena, enabling learners to engage in experiential representations that would otherwise be inaccessible in traditional classroom settings. This suggests that the pedagogical benefits of haptic integration may be content-specific, with higher impact in areas where abstract, non-observable mechanisms are central to conceptual understanding.

The implications of these findings are particularly relevant for secondary schools in the Philippines, where disparities in access to advanced educational technologies persist. While high-end haptic devices may be financially prohibitive for many public schools, the study highlights the promise of low-cost, improvised, or modular haptic interfaces that can be locally developed and deployed. Educational stakeholders are encouraged to explore context-responsive strategies – such as community-based fabrication of haptic tools, collaborative resource sharing, and integration into science laboratories – to ensure that technological innovation supports equity rather than deepens existing gaps.

Policymakers, curriculum designers, and teacher education institutions should consider incorporating immersive and haptic-based pedagogies into national STEM education strategies. Targeted investments, supported by evidence-based implementation models, can enable schools to prioritize high-impact areas such as thermodynamics, where traditional didactic methods remain insufficient. Further research is recommended to investigate the generalizability of haptic-enhanced learning across other scientific domains, the long-term cost–benefit ratio of different haptic modalities, and the professional development needs of teachers tasked with implementing these technologies.

In summary, this study confirms the pedagogical potential of haptic-enhanced immersive instruction as a transformative tool in science education. By aligning technological design with the cognitive demands of specific physics topics, and by considering local resource constraints, educational systems can harness embodied learning to promote deeper, more accessible, and more equitable scientific understanding.

## **Limitations**

Despite the promising outcomes of this study on the effectiveness of haptic-enhanced visual immersive simulations (HVIS) for thermodynamics instruction, several limitations should be acknowledged. First, the research was conducted in a limited number

of public secondary school within Nueva Vizcaya, Philippines, which may restrict the generalizability of findings to other regions or educational contexts with different technological infrastructure, teacher training levels, or student demographics. Second, due to resource constraints, only a small-scale implementation of the haptic devices was feasible, and not all students had simultaneous access to the technology during the intervention. Although post-intervention access was granted to VIS-group participants, this staggered exposure may have influenced students' motivation or perception. Third, the study focused exclusively on thermodynamic concepts, which inherently involve abstract ideas such as entropy, heat transfer, and molecular interaction – domains potentially well-suited to tactile visualization. The results may not extend to other physics topics that are more concrete or less interactive. Fourth, while the assessment tools were carefully validated, the measurement of conceptual understanding and retention relied primarily on cognitive tests and self-reported experiences, which could be influenced by factors such as novelty effects, test anxiety, or individual learning styles. Finally, the study did not capture long-term academic outcomes or track whether the conceptual gains translated into improved performance in other STEM areas. Future research should consider longitudinal designs, broader participant samples, and cross-disciplinary applications to enhance the external validity and scalability of immersive haptic instruction in secondary education.

### **Research ethics**

#### **Informed consent statement**

Informed consent was obtained from all research participants.

#### **Data availability statement**

Data are unavailable due to privacy or ethical restrictions.

### **Acknowledgements**

This is the section to thank all collaborators, donators etc.

### **Conflicts of interest**

The authors declare no conflicts of interest.

### **References**

- Bhowmik, A. K. (2024). Virtual and augmented reality: Human sensory-perceptual requirements and trends for immersive spatial computing experiences. *Journal of the Society for Information Display*, 32(8), 605–646. <https://doi.org/10.1002/jsid.2001>
- Brown, P. L., & Bybee, R. W. (2023). Promoting sensemaking through an impactful instructional sequence. *The Science Teacher*, 90(6), 22–27. <https://doi.org/10.1080/00368555.2023.12315951>
- Brundage, M. J., Meltzer, D. E., & Singh, C. (2024). Investigating introductory and advanced students' difficulties with entropy and the second law of thermodynamics using a validated

- instrument. *Physical Review Physics Education Research*, 20(2), 020110. <https://doi.org/10.1103/physrevphyseducres.20.020110>
- Bybee, R. W. (2013). *Next generation science standards: By states, for states. Volume 1, the standards – Arranged by disciplinary core ideas and by topics*. The National Academics Press.
- Creswell, J. W., & Creswell, J. D. (2023). *Research design: Qualitative, quantitative & mixed methods approaches* (6th ed.). Sage.
- Dejene, W., & Chen, D. (2019). The practice of modularized curriculum in higher education institution: Active learning and continuous assessment in focus. *Cogent Education*, 6(1), 1–16. <https://doi.org/10.1080/2331186x.2019.1611052>
- Demate, R. B. et al. (2025). Teacher perspectives on MATATAG curriculum: Challenges and collaborative solutions. *Multidisciplinary Reviews*, 8(11), 2025351–2025351. <https://doi.org/10.31893/multirev.2025351>
- Faul, F. et al. (2009). Statistical Power Analyses Using G\*Power 3.1: Tests for Correlation and Regression Analyses. *Behavior Research Methods*, 41(4), 1149–1160. <https://doi.org/10.3758/brm.41.4.1149>
- Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education*, 57(4), 2281–2290. <https://doi.org/10.1016/j.compedu.2011.06.012>
- Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (task load index): Results of empirical and theoretical research. *Advances in Psychology*, 52, 139–183. [https://doi.org/10.1016/s0166-4115\(08\)62386-9](https://doi.org/10.1016/s0166-4115(08)62386-9)
- Huang, Y. et al. (2022). Recent advances in multi-mode haptic feedback technologies towards wearable interfaces. *Materials Today Physics*, 22, 100602. <https://doi.org/10.1016/j.mtphys.2021.100602>
- Ignatow, G. (2007). Theories of embodied knowledge: New directions for cultural and cognitive sociology? *Journal for the Theory of Social Behaviour*, 37(2), 115–135. <https://doi.org/10.1111/j.1468-5914.2007.00328.x>
- Johnson-Glenberg, M. C. et al. (2014). Collaborative embodied learning in mixed reality motion-capture environments: Two science studies. *Journal of Educational Psychology*, 106(1), 86–104. <https://doi.org/10.1037/a0034008>
- Jones, M. G. et al. (2005). Haptic augmentation of science instruction: Does touch matter? *Science Education*, 90(1), 111–123. <https://doi.org/10.1002/sce.20086>
- Lapitan, L. (2021). An effective blended online teaching and learning strategy during the COVID-19 pandemic. *Education for Chemical Engineers*, 35(35), 116–131. <https://doi.org/10.1016/j.ece.2021.01.012>
- Latchem, C., & Jung, I. (2009). *Distance and blended learning in Asia*. Routledge eBooks. Informa. <https://doi.org/10.4324/9780203878774>
- Lécuyer, A. (2009). Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback. *Presence: Teleoperators and Virtual Environments*, 18(1), 39–53. <https://doi.org/10.1162/pres.18.1.39>
- Lee, J. et al. (2020). Thermo-haptic materials and devices for wearable virtual and augmented reality. *Advanced Functional Materials*, 31(39), 2007376. <https://doi.org/10.1002/adfm.202007376>
- Lindgren, R. et al. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers & Education*, 95, 174–187. <https://doi.org/10.1016/j.compedu.2016.01.001>
- Linn, M. C., & Songer, N. B. (1991). Teaching thermodynamics to middle school students: What are appropriate cognitive demands? *Journal of Research in Science Teaching*, 28(10), 885–918. <https://doi.org/10.1002/tea.3660281003>
- Loverude, M. (2015). Identifying student resources in reasoning about entropy and the approach to thermal equilibrium. *Physical Review Special Topics – Physics Education Research*, 11(2), 020118. <https://doi.org/10.1103/physrevstper.11.020118>
- MacLean, K.E. (2000, April 1). Designing with haptic feedback. In, IEEE Xplore. IEEE. <https://doi.org/10.1109/ROBOT.2000.844146>

- Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction, 60*, 225–236. <https://doi.org/10.1016/j.learninstruc.2017.12.007>
- Mercado, J. C. (2020). Development of laboratory manual in physics for engineers. *Online Submission, 9*(10), 200–210.
- Minogue, J., & Borland, D. (2015). Investigating students' ideas about buoyancy and the influence of haptic feedback. *Journal of Science Education and Technology, 25*(2), 187–202. <https://doi.org/10.1007/s10956-015-9585-1>
- Orleans, A. V. (2007). The condition of secondary school physics education in the Philippines: Recent developments and remaining challenges for substantive improvements. *The Australian Educational Researcher, 34*(1), 33–54. <https://doi.org/10.1007/bf03216849>
- Paas, F., Renkl, A., & Sweller, J. (2004). Cognitive load theory: Instructional implications of the interaction between information structures and cognitive architecture. *Instructional Science, 32*(1), 1–8. <https://doi.org/10.10023/B:TRUC.0000021806.17516.d0>
- Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review, 24*(1), 27–45. <https://doi.org/10.1007/s10648-011-9179-2>
- Paas, F. G. (1992). Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach. *Journal of Educational Psychology, 84*(4), 429–434. <https://doi.org/10.1037/0022-0663.84.4.429>
- Peiris, R. L. et al. (2017). ThermoVR. In, *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2 May 2017 pp. 5452–5456. Association for Computing Machinery. <https://doi.org/10.1145/3025453.3025824>
- Pellas, N., Dengel, A., & Christopoulos, A. (2020). A scoping review of immersive virtual reality in STEM education. *IEEE Transactions on Learning Technologies, 13*(4), 1. <https://doi.org/10.1109/tlt.2020.3019405>
- Perry, S., Bridges, S. M., & Burrow, M. F. (2015). A review of the use of simulation in dental education. *Simulation in Healthcare: Journal of the Society for Simulation in Healthcare, 10*(1), 31–37. <https://doi.org/10.1097/sih.0000000000000059>
- Reyes, R. L. et al. (2024). Enhancing experiential science learning with virtual labs: A narrative account of merits, challenges, and implementation strategies. *Journal of Computer Assisted Learning, 40*(6), 3167–3186. <https://doi.org/10.1111/jcal.13061>
- Shapiro, L. (2019a). *Embodied cognition*. Routledge. <https://doi.org/10.4324/9781315180380>
- Shapiro, L., & Spaulding, S. (Eds.). (2014). *The Routledge handbook of embodied cognition*. Routledge. <https://doi.org/10.4324/9781315775845>
- Shapiro, L. A. (2019b). *Embodied cognition*. Routledge.
- Smith, T. I. et al. (2015). Identifying student difficulties with entropy, heat engines, and the Carnot cycle. *Physical Review Special Topics – Physics Education Research, 11*(2), 020116. <https://doi.org/10.1103/physrevstper.11.020116>
- Sokrat, H. et al. (2014). Difficulties of students from the faculty of science with regard to understanding the concepts of chemical thermodynamics. *Procedia – Social and Behavioral Sciences, 116*, 368–372. <https://doi.org/10.1016/j.sbspro.2014.01.223>
- Sun, Z. et al. (2022). Augmented tactile-perception and haptic-feedback rings as human-machine interfaces aiming for immersive interactions. *Nature Communications, 13*(1), 5224. <https://doi.org/10.1038/s41467-022-32745-8>
- Sweller, J. (2011, January 1). Cognitive load theory. In, Mestre, J. P., & Ross, B. H. (Eds.). ScienceDirect, Academic Press. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780123876911000028>
- Talbot, C., & Davison, C. (2023). *Chemistry for the IB diploma*. 3rd ed. Hodder Education.
- Trelease, R. B. (2016). From chalkboard, slides, and paper to e-learning: How computing technologies have transformed anatomical sciences education. *Anatomical Sciences Education, 9*(6), 583–602. <https://doi.org/10.1002/ase.1620>

- van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, *17*(2), 147–177. <https://doi.org/10.1007/s10648-005-3951-0>
- Wenk, N. et al. (2021). Effect of immersive visualization technologies on cognitive load, motivation, usability, and embodiment. *Virtual Reality*, *27*(1), 307–331. <https://doi.org/10.1007/s10055-021-00565-8>