

UNIVERSIDAD PANAMERICANA
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**“DISEÑO E IMPLEMENTACIÓN DE UN SIMULADOR
VISUO-HÁPTICO PARA EL APRENDIZAJE ACTIVO
DE LA LEY DE BOYLE EN EDUCACIÓN SUPERIOR”**

TESIS

QUE PARA OBTENER EL GRADO DE
MAESTRÍA EN INGENIERÍA

P R E S E N T A
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Abstract

En esta tesis se presenta el diseño, desarrollo y evaluación de un simulador visuo-háptico orientado a fortalecer el aprendizaje, mediante metodologías que se desprenden de la escuela activa, de la Ley de Boyle en educación superior. La enseñanza tradicional de la física suele enfrentar dificultades para motivar a los estudiantes y para vincular conceptos abstractos con experiencias significativas que faciliten su comprensión. Para atender este desafío, se desarrolló un simulador visuo-háptico en Unity, integrado mediante el framework HaDIU, que permite a los estudiantes manipular un sistema pistón-cilindro y experimentar en tiempo real una resistencia táctil proporcional a los cambios de presión del gas. En el sistema se materializan los principios de cognición corporizada al sincronizar retroalimentación visual, numérica y háptica, transformando la relación presión-volumen en una experiencia multisensorial e interactiva.

Se empleó un enfoque de métodos mixtos con la participación de 39 estudiantes de ingeniería. La evaluación combinó el instrumento End-User Computing Satisfaction (EUCS) con entrevistas semiestructuradas para analizar usabilidad, compromiso y valor educativo percibido. Los resultados cuantitativos mostraron altos niveles de satisfacción en precisión, facilidad de uso y capacidad de respuesta. El análisis cualitativo reveló una mayor motivación, una comprensión más intuitiva de la dinámica presión-volumen y un alto interés por extender el uso de simuladores visuo-hápticos a otros temas científicos. Los participantes describieron la experiencia táctil como un puente significativo entre la teoría y la práctica. Entre las mejoras sugeridas se identificó la necesidad de simplificar la interfaz y ofrecer mayor orientación conceptual.

Los hallazgos indican que los simuladores visuo-hápticos pueden fortalecer el compromiso estudiantil, enriquecer la comprensión percibida y apoyar el aprendizaje activo en cursos de física. Este trabajo amplía la aplicación de la simulación multisensorial a la termodinámica y resalta implicaciones pedagógicas para el uso de tecnologías interactivas en la educación STEM. Se recomienda seguir en esta línea de investigación para medir ganancias de aprendizaje (learning gains), ampliar la simulación a otras leyes de gases y establecer lineamientos de diseño para su implementación a escala en entornos educativos.

Introducción

En las últimas décadas, la educación superior ha transitado de modelos centrados en la clase magistral hacia enfoques que buscan involucrar de manera más activa al estudiante en su propio proceso de aprendizaje [1]. Este viraje responde tanto a cambios en las teorías pedagógicas como al impacto generalizado de las tecnologías digitales y a las nuevas expectativas de las generaciones de estudiantes. La literatura coincide en que el grado de compromiso de los alumnos con las actividades¹ de aprendizaje se vincula estrechamente con la calidad de sus resultados académicos, lo que ha impulsado la adopción de metodologías que privilegian la participación, el trabajo colaborativo y la resolución de problemas en contextos relevantes para su formación [2].

En este contexto, la enseñanza de la física representa un desafío particular. Muchos de sus contenidos se apoyan en definiciones matemáticas y conceptos altamente abstractos que, desde la perspectiva de los estudiantes, no siempre se conectan con situaciones de la vida cotidiana [3]. Temas como la termodinámica o las leyes de los gases suelen percibirse como distantes o difíciles, especialmente cuando se abordan casi exclusivamente por medio de clases expositivas, libros de texto y listas de ejercicios estándar [4]. Aunque estos recursos son fundamentales para transmitir conocimientos y desarrollar habilidades formales, no siempre resultan suficientes para alcanzar una comprensión conceptual sólida ni para mantener la motivación a lo largo del curso.

La complejidad de esta situación versa en la dificultad para proporcionar experiencias que ayuden al alumnado a vincular los modelos teóricos con fenómenos que puedan experimentar de manera directa [5]. Con una débil vinculación o inexistente, es frecuente que los estudiantes aprendan fórmulas, modelos y procedimientos sin llegar a interpretar o interiorizar lo que representan físicamente. En respuesta, han cobrado relevancia propuestas de aprendizaje activo que involucran a los sujetos de aprendizaje mediante exploración, manipulación e investigación de sistemas físicos, ya sea a través de laboratorios reales o de simulaciones interactivas. Estas aproximaciones reciben respaldo desde la investigación en ciencias cognitivas, que subraya el papel de la participación activa y de la interacción multimodal en la consolidación y transferencia del conocimiento [6].

La teoría de la cognición corporizada (en cierta literatura descrita como encarnada) aporta un marco conceptual especialmente útil para comprender por qué este tipo de experiencias son efectivas. Desde esta perspectiva, pensar y aprender no son procesos desvinculados del cuerpo, sino que se apoyan en las acciones y en la percepción del entorno físico [7]. Las experiencias sensoriales y motoras influyen en cómo se construyen y se organizan las representaciones mentales. Esta visión resulta coherente con el aprendizaje activo, al enfatizar que la

¹ A veces denominado como experiencias de aprendizaje

manipulación, la exploración y la interacción con objetos o entornos, físicos o virtuales, facilitan la construcción de significados más profundos [8]. En disciplinas STEM, donde muchos conceptos se expresan mediante relaciones abstractas, esta idea se vuelve sumamente relevante [9], [10].

Paralelamente, las generaciones actuales de estudiantes de educación superior han crecido rodeadas de dispositivos digitales, videojuegos y entornos interactivos, por lo que suelen esperar experiencias de aprendizaje que sean también dinámicas e interactivas [11]. Este escenario ha favorecido el desarrollo de diversas herramientas tecnológicas que integran simulaciones, visualizaciones y retroalimentación inmediata para apoyar la comprensión de contenidos complejos. Sin embargo, la mayoría de estas soluciones se centra en canales visuales y auditivos, mientras que la dimensión táctil o cinestésica permanece poco explorada, a pesar de su potencial para hacer más tangible lo que no se puede observar directamente en el laboratorio. En este sentido, los dispositivos hápticos ofrecen una oportunidad única, al permitir que los usuarios perciban fuerzas, resistencias o texturas de manera controlada [12].

Los simuladores visuo-hápticos surgen precisamente de la combinación de estas capacidades. En ellos, el estudiante puede manipular variables físicas dentro de un entorno gráfico (por ejemplo, fuerza o presión) y, al mismo tiempo, sentir una respuesta táctil derivada de dichas variaciones [13]. De esta forma, la información visual se complementa con una sensación física que ayuda a reforzar el significado de las relaciones que se están estudiando [14]. En el caso de la física, esto abre la posibilidad de “experimentar” leyes y principios que, de otra forma, permanecerían como expresiones matemáticas abstractas en el pizarrón.

A pesar del avance en este campo, la investigación en educación en física con tecnologías visuo-hápticas se ha concentrado principalmente en fenómenos como la fricción, la flotación o el comportamiento de campos electromagnéticos. Existe, por otro lado, una menor cantidad de estudios que exploren el uso de este tipo de herramientas para trabajar con leyes de gases y, en particular, con la Ley de Boyle, a pesar de que la relación entre presión y volumen es un concepto fundamental en la termodinámica y en diversas aplicaciones de la ingeniería. Esta ausencia de evidencia empírica deja abierta la pregunta de cómo podría contribuir la integración de retroalimentación háptica y visual al compromiso y a la comprensión de estos contenidos específicos.

En este escenario se sitúa la presente tesis. El trabajo tiene como propósito diseñar, desarrollar y evaluar un simulador visuo-háptico orientado al aprendizaje activo de la Ley de Boyle en estudiantes de ingeniería. El simulador permite manipular un sistema pistón-cilindro virtual y experimentar, mediante un dispositivo háptico, cómo se incrementa la resistencia al comprimir el gas, mientras se visualizan en tiempo real cambios en la presión y en el volumen. De este

modo, se busca alinear la experiencia sensorial del estudiante con el modelo teórico de los gases ideales, integrando principios de cognición corporizada, aprendizaje activo y educación mediada por tecnología.

Objetivos

Objetivo general

Analizar, en el contexto de la enseñanza de la física en educación superior, de qué manera un simulador visuo-háptico orientado a la Ley de Boyle contribuye al aprendizaje activo, al compromiso de los estudiantes y a la valoración educativa de este tipo de recursos en comparación con enfoques tradicionales.

Objetivos específicos

- Diseñar un escenario de aprendizaje visuo-háptico que represente de forma interactiva la relación presión-volumen en un sistema pistón-cilindro, fundamentado en la teoría de la cognición corporizada y el aprendizaje activo.
- Desarrollar e implementar un prototipo funcional de simulador visuo-háptico en Unity, integrado con el framework HaDIU y dispositivos hápticos comerciales, que proporcione retroalimentación visual, numérica y táctil en tiempo real.
- Evaluar la satisfacción de los estudiantes con el simulador mediante el instrumento End-User Computing Satisfaction (EUCS), considerando dimensiones como contenido, precisión, formato, facilidad de uso y oportunidad.
- Analizar, a través de entrevistas semiestructuradas, las percepciones de los estudiantes sobre su compromiso, su comprensión conceptual de la Ley de Boyle y el valor educativo del simulador frente a métodos tradicionales de enseñanza.
- Identificar recomendaciones de diseño pedagógico y tecnológico para la integración de simuladores visuo-hápticos en cursos de física y, más ampliamente, en entornos de educación STEM.

Hipótesis

A partir del marco teórico sobre cognición corporizada, aprendizaje activo y educación mediada por tecnología, esta tesis plantea una relación central entre la interacción visuo-háptica, el compromiso estudiantil y la percepción de aprendizaje en torno a la Ley de Boyle. Al mismo tiempo, se asume que el diseño del simulador y su usabilidad influyan en la forma en que los estudiantes valoran este tipo de recursos frente a enfoques tradicionales. Con base en ello, se formulan las siguientes hipótesis de investigación:

- **Hipótesis 1 (H1):** El uso del simulador visuo-háptico se asocia con altos niveles de satisfacción de los estudiantes en las dimensiones de precisión, facilidad de uso y oportunidad, medidas a través del instrumento EUCS.
- **Hipótesis 2 (H2):** Los estudiantes que utilizan el simulador visuo-háptico reportan un mayor grado de compromiso con el estudio de la Ley de Boyle en comparación con su experiencia previa con métodos de enseñanza tradicionales centrados en la exposición y la resolución de problemas en el aula.
- **Hipótesis 3 (H3):** Un mayor nivel de compromiso reportado durante la interacción con el simulador visuo-háptico se asocia con una mejor percepción de comprensión conceptual de la relación presión–volumen en la Ley de Boyle.
- **Hipótesis 4 (H4):** Los estudiantes perciben al simulador visuo-háptico como un recurso con alto valor educativo y potencial de transferencia a otros temas de física y a otras asignaturas STEM, lo que refuerza su disposición a utilizar herramientas similares en futuros contextos de aprendizaje.

Estructura de la Tesis

La presente tesis se organiza en tres secciones principales que articulan el desarrollo del estudio. En primer lugar, en el apartado de la introducción se expuso el contexto general de la investigación y la problemática asociada a la enseñanza de conceptos abstractos de física, en particular la Ley de Boyle, en el nivel de educación superior. En esta sección se expuso la motivación del estudio, se describieron brevemente los fundamentos del aprendizaje activo y de la cognición corporizada, y se planteó el propósito de diseñar y evaluar un simulador visuo-háptico para apoyar el aprendizaje de la relación presión–volumen. Asimismo, se formularon el objetivo general, los objetivos específicos y las hipótesis de investigación que guían el trabajo realizado.

La segunda sección corresponde al Artículo de investigación, en el que se presenta de manera integrada el estudio empírico desarrollado. En esta parte se describen el diseño del simulador visuo-háptico, la metodología empleada para su evaluación con estudiantes de ingeniería, las características de la muestra participante, los instrumentos de recolección de datos cuantitativos y cualitativos y el procedimiento seguido durante las sesiones de uso. También se reportan los principales resultados obtenidos, organizados en torno a la satisfacción de los estudiantes, su compromiso con la actividad y sus percepciones sobre el valor educativo del simulador.

La tercera sección corresponde a la Discusión y está dedicada al análisis e interpretación de los hallazgos a la luz de las hipótesis planteadas y del marco conceptual en el que se inscribe el estudio. Finalmente, la cuarta sección corresponde a las Conclusiones, donde se sintetizan

las contribuciones centrales de la tesis y se retoman las preguntas de investigación a la luz de los resultados obtenidos.



Integrating Visuo-Haptic Simulators for Active Learning to Explore the Concept of Boyle's Law

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Scope Statement

This study presents a visuo-haptic simulator developed to enhance student engagement and conceptual understanding in physics education. Addressing the increasing demand for technology-mediated, experiential learning, it demonstrates how embodied and multisensory approaches can transform abstract concepts into concrete, meaningful experiences. By combining visual and tactile feedback, the simulator allows students to explore Boyle's Law interactively, illustrating how immersion and sensory integration foster motivation and deeper comprehension. The results further emphasize the importance of user-centered design, with student feedback informing future improvements in interface layout, accessibility, and onboarding procedures.

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Credit Author Statement

Daya Escobar-Castillejos: Data curation, Formal Analysis, Methodology, Resources, Supervision, Validation, Writing – review & editing. **David Escobar-Castillejos:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Writing – original draft, Writing – review & editing. **Lorena Alejandra Berumen-Gil:** Data curation, Formal Analysis, Methodology, Project administration, Supervision, Writing – review & editing. **Octavio Lozada-Florez:** Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sebastián Montes-Irujo:** Conceptualization, Investigation, Software, Writing – original draft, Writing – review & editing.

Keywords

visuo-haptic simulators, Embodied Cognition, Active Learning, student engagement, ideal gases, physics education, Educational innovation, higher education

Abstract

Word count: 254

The teaching process is essential for developing future professionals, particularly in fields that require a deep understanding of theoretical concepts. However, traditional classroom-based methods often struggle to engage students who have grown up with technology, especially with complex subjects like physics. Lectures and textbooks provide foundational knowledge but may fail to make the material feel relevant, resulting in lower retention rates. In recent years, interactive learning tools have enriched educational experiences, particularly through embodied cognition, which enhances learning by engaging students physically and emotionally. One promising approach is the use of visuo-haptic simulators. They enable students to interact with a concept's visual and tactile components. In this study, a visuo-haptic simulator was developed to help students understand the principles of ideal gases, specifically Boyle's Law. The simulator enables students to adjust variables such as pressure and volume, providing visual and tactile feedback that results in an immersive, hands-on learning experience. The objective was to evaluate students' perceptions of learning with the simulator compared to traditional methods. Surveys and interviews were conducted to gather qualitative data on students' engagement with the simulator. Results show that students felt more motivated to engage with the simulator than with traditional problem-solving approaches. Students also mentioned the potential of these simulators to support learning in other subjects. Visuo-haptic simulators encourage active learning by providing interactive environments that turn students from passive recipients into active participants. Future work will focus on assessing learning outcomes in real classroom settings and developing new simulators to cover additional concepts related to ideal gases.

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Studies involving animal subjects

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The author(s) verify and take full responsibility for the use of generative AI in the preparation of this manuscript. Generative AI was used to improve the grammar, style, and clarity of some sentences and paragraphs after initial human drafting. The authors verified all output for factual accuracy and scientific integrity, and the model was not used to generate paragraphs, summaries, display charts or tables, or analyze or interpret data. The model used was ChatGPT, based on GPT-5, the vendor is OpenAI, over the web app (chat.openai.com).

In review

Integrating Visuo-Haptic Simulators for Active Learning to Explore the Concept of Boyle's Law

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2 ABSTRACT

3 The teaching process is essential for developing future professionals, particularly in fields that
4 require a deep understanding of theoretical concepts. However, traditional classroom-based
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23 **Keywords:** visuo-haptic simulators, embodied cognition, active learning, student engagement, ideal gases, physics education, higher
24 education, and educational innovation.

1 INTRODUCTION

25 Education has undergone a substantial transformation in recent decades, shifting from passive, lecture-
26 oriented practices to more interactive, student-focused strategies (Torralba and Doo, 2020). This shift
27 reflects broader changes in pedagogical theory, the proliferation of digital technologies, and evolving
28 learner expectations. As educational research has demonstrated the significance of engagement in learning
29 outcomes, institutions are increasingly investigating diverse teaching strategies to address students'
30 needs and interests (Fisher et al., 2021). These strategies often aim to move beyond simple knowledge
31 transmission, focusing instead on active participation, collaborative problem-solving, and the authentic
32 application of concepts in real-world contexts.

33 Physics education, particularly in higher education, presents distinct challenges due to the theoretical
34 nature of its concepts and the mathematical thinking it involves (Lestari et al., 2021). Topics such as
35 thermodynamics and gas laws might appear abstract and unrelated to practical applications for many
36 undergraduate students, making them difficult to comprehend and internalize (Sokrat et al., 2014). The
37 traditional approach, characterized by reliance on textbooks, lectures, and standardized problem sets, has
38 been essential for disseminating knowledge and developing foundational skills. However, such methods
39 may not be sufficient to foster deep conceptual understanding or to sustain student motivation, especially in
40 increasingly diverse classrooms with a range of learning preferences.

41 The challenge resides not only in presenting the material but also in enabling students to connect abstract
42 principles to tangible experiences (Enyedy et al., 2011). Without this connection, learners may memorize
43 formulas without fully grasping the underlying phenomena. In recent years, educational approaches that
44 integrate theory and practice have gained prominence, aiming to transform learning from a passive reception
45 of information into an active, inquiry-based process. This educational advancement has been supported by
46 findings in cognitive science, which emphasize the role of active engagement and multi-modal interaction
47 in long-term retention and transfer of learning (Lombardi and Shipley, 2021).

48 Embodied cognition theory offers a particularly relevant framework in this context, suggesting that
49 cognitive processes are directly connected to the body's interactions with the physical environment (Farina,
50 2021). Rather than viewing thinking as an isolated, purely mental activity, embodied cognition posits
51 that sensory and motor experiences shape how we understand and remember information. This theory
52 aligns closely with active learning approaches in education, emphasizing student engagement through
53 participation, manipulation, and exploration (Michael and Modell, 2003). These approaches allow students
54 to construct their own knowledge by interacting with physical or simulated systems, experimenting with
55 variables, and observing the results of their actions. In STEM subjects, where abstract relationships often
56 require interpretation through multiple representations, such experiential methods can be particularly
57 beneficial (Hernández-de Menéndez et al., 2019; Abrahamson et al., 2020).

58 As society advances and students become more familiar with technology from an early age, there is a
59 growing demand for new teaching approaches that engage technologically proficient learners (Haleem et al.,
60 2022). Technology now provides educators with a wide array of innovative, interactive learning tools that
61 can support diverse educational objectives and cater to multiple learning styles. These tools can simulate
62 complex phenomena, provide real-time feedback, and offer students opportunities to explore content at
63 their own pace and depth. While many digital tools focus primarily on visual and auditory channels, physics
64 education often demands an additional layer of sensory interaction to make abstract phenomena tangible.
65 In this context, haptic devices stand out for their ability to provide users with tactile feedback, adding a
66 sensory dimension that complements visual and auditory information (Fouad et al., 2023).

67 Visuo-haptic simulators combine the advantages of visual and tactile interaction in a single learning
68 environment (Cox et al., 2025). They enable students to manipulate variables, such as force or pressure,
69 and to experience the effects through both visual observation and physical sensation. By experimenting
70 with forces, pressures, and visual cues, students can explore concepts actively and develop more robust
71 mental models of complex phenomena (Benex et al., 2024). This dual-sensory engagement can make
72 otherwise abstract relationships more concrete, enhance motivation, and promote a deeper understanding of
73 the subject matter. In physics education, such tools have the potential to bridge the gap between theoretical
74 derivations and experiential learning, providing students not only the opportunity to learn but also the
75 chance to feel the laws of nature in action.

76 Despite increasing attention to immersive technologies in STEM education, limited research has examined
77 how visuo-haptic simulators can enhance engagement and motivation in learning gas laws, particularly
78 Boyle's Law. To address this gap, this study developed and evaluated a visuo-haptic simulator that integrates
79 tactile and visual feedback to support active learning grounded in embodied cognition. The simulator allows
80 students to manipulate pressure and volume variables, providing an immersive, hands-on experience that
81 connects theoretical concepts to tangible interaction. The objective was to analyze students' perceptions
82 of usability, satisfaction, and motivation when learning through multi-sensory interaction compared with
83 traditional approaches. Accordingly, the following research questions were proposed:

- 84 • How does the use of visuo-haptic simulators impact students' engagement with complex physics
85 concepts, such as Boyle's Law?
86 • What are students' perceptions of the effectiveness and educational value of visuo-haptic simulators
87 compared to traditional instructional methods?

2 RELATED WORK

88 Haptic feedback technology has been widely explored in education for its ability to provide tactile sensations
89 that enhance conceptual understanding (Novak and Schwan, 2021). This modality complements traditional
90 visual and auditory instruction by engaging learners' kinesthetic channels, which are often underused
91 in conventional classrooms. Beyond replicating real-world sensations, haptic systems can highlight key
92 conceptual relationships and make invisible physical phenomena perceptible. The theoretical basis of
93 visuo-haptic simulators lies in embodied cognition and active learning (McAnally and Wallis, 2022; Yang
94 et al., 2021). These frameworks emphasize that knowledge is built more effectively when students interact
95 physically with learning materials rather than passively observe them. By allowing learners to manipulate
96 variables, experience resistance, and observe outcomes in real-time, visuo-haptic systems help form durable,
97 transferable mental models that connect perception and reasoning.

2.1 Visuo-haptic Learning Approaches in Physics Education

99 In physics education, haptic feedback has been integrated into multiple studies to strengthen understanding
100 of abstract and dynamic phenomena. Early work on embodied experience and kinesthetic learning
101 established its pedagogical value. Han and Black (2011) investigated computer-based simulations for
102 elementary students and found that those receiving both kinesthetic and force feedback achieved better
103 recall and transfer than peers using non-haptic versions. Likewise, Olympion and Zacharia (2012) showed
104 that combining physical and virtual interaction supported richer representations of light and color concepts
105 compared with single-modality conditions. Extending this evidence, Kontra et al. (2015) demonstrated

106 through neuro-imaging that physical interaction activates motor and somatosensory regions linked to
107 conceptual reasoning, reinforcing that embodied experience deepens scientific understanding.

108 Subsequent research examined how visuo-haptic systems model mechanical phenomena through
109 interactive simulations. Yuksel et al. (2017) created *HapStatics*, a friction simulator that lets users feel
110 resistance while manipulating virtual surfaces. Their constructivist design showed that combining visual
111 and tactile cues improved coherence and reasoning. Extending this line, Qi et al. (2020) developed a
112 visuo-haptic simulator for buoyancy, finding that learners using tactile feedback performed significantly
113 better than those using visual feedback alone. Similarly, Hamza-Lup and Goldbach (2021) presented a
114 gamified simulator for the Lorentz force that increased engagement and accuracy through real-time tactile
115 interaction.

116 Other developments focused on structured frameworks and methodological improvements for designing
117 visuo-haptic environments. Noguez et al. (2021) introduced the *VIS-HAPT* methodology, a systematic
118 approach for building visuo-haptic learning systems aligned with Education 4.0. This framework reduced
119 development time while improving usability and comprehension in physics simulations. In parallel, Magana
120 and Balachandran (2017) examined haptic feedback in learning electric fields, showing that students used
121 sensations of "push" and "pull" to form intuitive models of attraction, repulsion, and field geometry,
122 emphasizing the role of sensorimotor experience in understanding invisible phenomena.

123 Researchers have also explored hybrid designs that combine visuo-haptic systems with other technologies
124 to enhance motivation and autonomy. Garcia-Castelan et al. (2024) combined visuo-haptic simulation
125 with generative AI to teach inclined-plane dynamics. Students interacted with a simulator and then used
126 ChatGPT to test and refine their problem-solving skills, leading to higher learning gains and increased
127 engagement. Likewise, Buonocore et al. (2023) investigated embodiment in industrial visuo-haptic training
128 and found that greater perceived embodiment reduced workload and improved efficiency, underscoring
129 how subjective presence influences performance.

130 Further studies have highlighted the instructional value of visuo-haptic simulations for friction and
131 motion. Neri et al. (2023) applied the *VIS-HAPT* framework to a 3D simulator of frictional forces, showing
132 that multi-sensory feedback strengthened conceptual grasp and learner satisfaction. Walsh et al. (2020) and
133 Walsh and Magana (2023) analyzed sequencing and feedback modalities, finding that starting instruction
134 with haptic feedback promotes embodied reasoning and that visuo-haptic simulations outperform physical
135 interaction alone.

136 Together, this body of work demonstrates that combining visual and tactile feedback improves
137 comprehension, engagement, and retention in physics education. Multi-sensory interaction supports the
138 formation of embodied conceptual models that connect theory with tangible experience. However, most
139 studies have focused on topics such as friction, buoyancy, or electromagnetism, leaving gas laws and
140 thermodynamics largely unexplored. This gap motivates the present study, which applies visuo-haptic
141 simulation to Boyle's Law to examine how tactile-visual integration influences engagement and perceived
142 learning in conceptual physics.

143 2.2 Virtual and Immersive Environments in STEM Learning

144 Virtual and immersive learning environments play a central role in STEM education by fostering
145 experiential engagement, spatial understanding, and problem-solving. These approaches combine
146 interactive visualization, project-based exploration, and multi-sensory simulation to situate learners in
147 realistic contexts that enhance motivation and conceptual learning. Evidence shows that immersive tools

148 can improve both cognitive and affective outcomes by enabling students to experience phenomena directly
149 rather than observe them passively.

150 Talafian et al. (2019) examined immersive project-based STEM programs that support identity formation
151 among underrepresented students. Using the Projective Reflection framework in a space-themed program,
152 the authors found that immersive design and hands-on activities strengthened learners' identification
153 with STEM and increased interest in related careers. Similarly, Makransky et al. (2020) reported that
154 virtual reality experiences heightened situational interest and curiosity about science, influencing students'
155 long-term aspirations. Together, these studies highlight the motivational and identity-building potential of
156 immersive contexts in sustaining engagement with science learning.

157 A related line of research has focused on how immersive and augmented environments improve
158 spatial reasoning and conceptual understanding through 3D interaction. Montalbo (2021) developed
159 an augmented-reality chemistry platform that allowed learners to visualize and manipulate molecular
160 structures, significantly improving spatial reasoning. Acevedo et al. (2024) found that virtual environments
161 for exploring electric fields enhanced conceptual accuracy and engagement. These results are consistent
162 with Chiang and Liu (2023) who showed that extended reality systems with real-time feedback improved
163 concentration and comprehension in engineering education. Together, these findings suggest that immersive
164 visualization facilitates a connection between abstract concepts and perceptual experience, thereby
165 promoting a deeper understanding.

166 Immersive technologies have also been used as scalable alternatives to traditional laboratories and
167 workshops. Shu and Huang (2021) tested virtual Makerspaces that replaced physical workshops, revealing
168 that VR-based design instruction improved self-efficacy and creativity. In manufacturing education, El-
169 Mounayri et al. (2016) and Rogers et al. (2018) developed the Advanced Virtual Manufacturing Lab, a
170 VR system replicating CNC machining. Both studies showed that students achieved comparable learning
171 outcomes to those from physical training while benefiting from the safety and accessibility. Although
172 usability issues such as motion discomfort persisted, these results support immersive environments as
173 effective complements to hands-on laboratory instruction.

174 Beyond replicating physical spaces, immersive learning enhances collaboration and embodiment through
175 sensory engagement. Webb et al. (2022) developed a haptic-enabled VR model of a cell membrane that
176 helped students perceive nanoscale interactions, improving visualization and authenticity. In another study,
177 Johnson-Glenberg et al. (2021) compared desktop and embodied VR environments for teaching natural
178 selection, showing that while both improved learning, embodied VR promoted greater presence, enjoyment,
179 and spatial transfer. Zhao et al. (2020) reached similar conclusions in a comparison of virtual and physical
180 field trips, finding equal or higher satisfaction in virtual conditions. Collectively, these studies suggest that
181 embodiment and presence foster affective engagement, turning observation into participation.

182 Recent research emphasizes that the impact of immersive technologies depends on instructional design
183 more than immersion alone. Lee et al. (2024) found that VR and AR classrooms increased motivation
184 and engagement but produced no significant differences in test performance, suggesting that pedagogical
185 scaffolding remains essential for cognitive gains. Likewise, Buonocore et al. (2023) demonstrated that
186 perceived embodiment influences workload and task efficiency, emphasizing the importance of human
187 factors in immersive learning design.

188 Overall, research across AR, VR, and XR technologies shows that immersive environments can enhance
189 motivation, engagement, and understanding by combining visualization, manipulation, and feedback. Yet,
190 these systems often emphasize visual immersion while overlooking tactile or kinesiologic interaction as a

191 pathway to conceptual understanding. This limitation underscores the contribution of visuo-haptic systems,
192 which unite both sensory dimensions to promote embodied cognition. The present study extends this line
193 of inquiry by examining how a visuo-haptic simulator for Boyle's Law integrates immersive and tactile
194 feedback to support engagement and intuitive learning in physics.

195 2.3 Engagement in Technology-mediated Education

196 Beyond physics and visuo-haptic learning, research on engagement in technology-mediated education
197 provides insight into how interactivity and feedback sustain motivation and participation. Engagement,
198 typically described through behavioral, cognitive, and emotional dimensions, depends strongly on
199 instructional design, social interaction, and learner autonomy. These perspectives help explain how the
200 multi-sensory interactivity of visuo-haptic simulators can promote active involvement.

201 Li and Lam (2015) studied engagement in online courses and found that clear structure, instructor
202 presence, and peer support enhance behavioral, cognitive, and emotional participation. The study showed
203 that well-timed schedules and feedback improved behavioral engagement, while intrinsic motivation
204 strengthened cognitive investment. Similarly, Owusu-Agyeman and Larbi-Siaw (2018) reported that self-
205 regulated learning strategies, collaboration, and institutional support foster motivation in higher education,
206 emphasizing that structured interaction promotes active and reflective learning. Together, these studies
207 suggest that digital learning is most effective when it supports reciprocal interaction, autonomy, and
208 connectedness.

209 Studies during the COVID-19 pandemic further highlighted how interactivity and feedback shape
210 engagement in both synchronous and asynchronous settings. Lau et al. (2022) found that task-based
211 activities with immediate visual feedback improved engagement across all dimensions. Similarly, Yavani
212 (2023) showed that interactive pedagogical actions such as discussions and pair dialogues produced the
213 highest motivation, although infrastructure limitations sometimes hindered participation. Both studies
214 emphasized that technology should be combined with pedagogical creativity to maintain focus and
215 motivation in online learning.

216 Other research explored how digital platforms and constructivist approaches enhance engagement and self-
217 efficacy. Robillos (2023) demonstrated that combining metacognitive strategies with the FlipGrid platform
218 improved students' speaking confidence and reflection through peer feedback. Bray et al. (2015) integrated
219 Realistic Mathematics Education with the Bridge21 model, finding that project-based digital learning
220 increased engagement and confidence while linking theory with practice. These studies demonstrate that
221 meaningful engagement arises from integrating technology with learner-centered design, rather than relying
222 solely on technology use.

223 Technological mediation can also drive institutional and cultural change. Brown et al. (2019) analyzed
224 the shift of Russian higher education toward open, participatory, and gamified learning, showing that
225 technology-supported pedagogies enhanced motivation, autonomy, and creativity. Gamification elements
226 correlated with higher enjoyment and strategic thinking, demonstrating that digital interactivity can
227 influence educational culture and policy as well as individual engagement.

228 Research on mobile and experiential learning illustrates how technology fosters sensory and social
229 engagement in real-world settings. McClain and Zimmerman (2016) found that an iPad-based e-Trailguide
230 promoted observation, gesture, and tactile exploration during outdoor activities, supporting a "heads-up,
231 hands-on" learning approach. Mayer and Schwemmler (2023) extended this to higher education, showing
232 that technology-mediated experiential learning increases accessibility and autonomy but can reduce

233 spontaneous interaction, requiring instructors to act as proactive mentors to sustain motivation. These
234 findings suggest that effective engagement hinges on striking a balance between digital fluency and human
235 connection.

236 Finally, engagement frameworks have been applied to domain-specific physics education. Mohd Sharif
237 et al. (2021) developed a tangible Boyle's Law apparatus that improved understanding and interest
238 compared to lecture-based teaching, yet lacked digital or haptic interactivity. This highlights a clear gap:
239 while technology-mediated engagement is well established, few studies have examined how combining
240 tactile and visual feedback can enhance engagement with abstract physics concepts.

241 Overall, prior studies converge on three ideas. First, engagement in technology-mediated education
242 depends on aligning interactivity, feedback, and autonomy. Second, effective engagement requires a
243 balance between technological features and pedagogical goals to sustain attention. Third, sensory and
244 experiential modes promote deeper learning by transforming students from passive observers into active
245 participants. Building on these insights, the present study employs a visuo-haptic simulator that combines
246 interactivity, feedback, and embodiment to foster engagement with Boyle's Law through a direct, multi-
247 sensory experience.

248 2.4 Contributions of This Study

249 Building on the expanded body of research reviewed above, this study makes three main contributions to
250 the field of visuo-haptic and technology-mediated learning:

- 251 • Extension of visuo-haptic learning to gas laws: Previous research has primarily focused on friction,
252 buoyancy, or electromagnetism. This study introduces a visuo-haptic simulator specifically designed
253 for Boyle's Law, demonstrating that tactile-visual interaction can effectively support comprehension
254 of thermodynamic principles.
- 255 • Integration of embodied cognition within a multi-sensory, active-learning framework: The simulator
256 combines real-time tactile resistance and visual feedback to transform abstract physical relationships
257 into perceptible experiences, operationalizing embodied cognition through interactive exploration.
- 258 • Empirical evaluation of user engagement and perceived educational value: Using a mixed-method
259 approach, the study provides quantitative and qualitative evidence that visuo-haptic interaction enhances
260 students' engagement, motivation, and satisfaction compared with traditional learning. These findings
261 complement prior studies that emphasized conceptual outcomes but rarely assessed affective and
262 usability dimensions.

263 Through these contributions, the study aims to expand the scope of visuo-haptic research by situating
264 tactile-visual interactivity within thermodynamics and by linking embodied cognition to engagement theory
265 from technology-mediated education. The study demonstrates that meaningful learning arises not only from
266 sensory realism but from the alignment of interactivity, feedback, and autonomy—principles supported
267 by broader literature on immersive and digital learning environments. By addressing an underexplored
268 domain and integrating empirical evaluation of engagement, this work advances the understanding of how
269 visuo-haptic systems can enrich science education through experiential and motivational pathways.

3 MATERIALS AND METHODS

270 The study's main objective was to assess students' perceptions of learning with the simulator in comparison
271 to traditional methods. This section describes the materials and methods used to design, develop, and

272 implement the visuo-haptic simulator. A streamlined *VIS-HAPT* methodology (Noguez et al., 2021) was
 273 employed to ensure the accuracy of simulations of physical interactions. The HaDIU (Haptic Device
 274 Integration for Unity) framework (Escobar-Castillejos et al., 2020) was used to integrate haptic feedback
 275 seamlessly.

276 3.1 Design of the Visuo-Haptic Learning Experience

277 In physics, abstract concepts may be complex for some students to internalize because they involve
 278 relationships that are not directly observable. One such principle is Boyle's Law, which states that for an
 279 ideal gas in a closed system at constant temperature, the pressure is inversely proportional to the volume,
 280 meaning that the product of pressure and volume remains constant:

$$P_1V_1 = P_2V_2 \quad (1)$$

281 This subsection presents the design of a visuo-haptic learning scenario that provides students with an
 282 intuitive and engaging way to experience Boyle's Law through both visual representation and tactile
 283 interaction.

284 Figure 1 illustrates a simplified model of this phenomenon using a gas confined in a cylinder with a
 285 movable piston. This setup provides an accessible way to demonstrate that compression (decreasing the
 286 gas volume) increases pressure, while expansion decreases it, all under isothermal conditions.

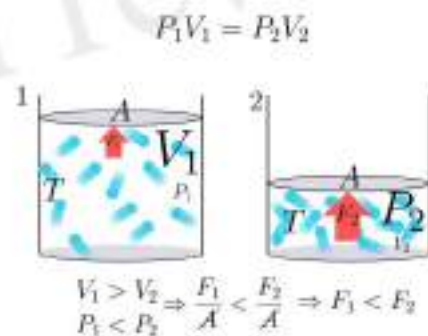


Figure 1. Illustration of Boyle's law showing the effects of compression on an ideal gas in a closed system: (1) initial state, where the gas occupies a larger volume with a lower pressure; and (2) compressed state, where the reduced volume increases the internal pressure and force exerted on the piston.

287 In the initial state (Figure 1.1), the piston is positioned higher, and the gas occupies a larger volume V_1 .
 288 The gas molecules are more widely spaced, so the frequency of collisions with the piston surface is lower,
 289 resulting in a relatively small pressure P_1 . This pressure produces a force F_1 on the piston, determined by
 290 the relationship $F = P \cdot A$, where A is the cross-sectional area of the piston.

291 In the second state (Figure 1.2), the piston is pushed downward, reducing the available volume to V_2 .
 292 As the same number of molecules now occupies a smaller space, their density increases, leading to more
 293 frequent collisions with the piston surface. This greater collision rate elevates the pressure to P_2 , thereby



Figure 2. Visuo-haptic simulator interaction process illustrating piston displacement and corresponding hand movement on the haptic device. As the piston is displaced, the simulator calculates the corresponding pressure values and displays them in real time, while also delivering proportional resistance through the haptic device. This combination of visual and tactile feedback highlights the inverse relationship between pressure and volume.

294 increasing the exerted force to F_2 . Because A is constant, the increase in pressure directly translates into
 295 a proportional increase in force, so that $F_2 > F_1$. This direct cause-and-effect relationship exemplifies
 296 the inverse relationship between volume and pressure, enabling learners to connect microscopic particle
 297 interactions with macroscopic quantities such as pressure and force.

298 The visuo-haptic simulator designed for this learning experience extends the explanatory power of the
 299 traditional diagram. Students not only observe the compression process visually but also *feel* the increased
 300 resistance on the piston through haptic feedback. This dual-channel engagement strengthens conceptual
 301 understanding by linking the abstract inverse relationship between pressure and volume to tangible sensory
 302 experience. By situating learners in an active role, the simulation motivates exploration and reinforces
 303 comprehension of one of the foundational gas laws in physics.

304 3.2 Visuo-haptic Simulator Design and Development

305 The visuo-haptic simulator was developed in *Unity 2021.3 LTS* (64-bit) and integrated with the *HaDIU*
 306 framework, the latest stable in-house version described in Escobar-Castillejos et al. (2020). The framework
 307 enabled communication between the Unity environment and external haptic devices, facilitating real-time
 308 bidirectional feedback. The simulator employed Unity's built-in physics engine to accurately model the
 309 inverse relationship between gas pressure and volume under isothermal conditions, allowing users to both
 310 visualize and physically experience this phenomenon through synchronized visual and tactile feedback.

311 The simulation centers on a virtual piston-cylinder system that users manipulate via a lever connected to
 312 the piston. As the lever is pressed downward, the available gas volume decreases, and the system calculates
 313 the corresponding pressure changes in real time. The pressure values are displayed numerically and mapped
 314 to proportional tactile resistance using the linear function $F = P \cdot A$, where A represents the piston's
 315 cross-sectional area. This relationship ensures that an increase in pressure directly translates into greater
 316 force feedback, reinforcing Boyle's Law ($P_1V_1 = P_2V_2$) through embodied interaction (Fig. 2).

317 3.2.1 Technical Implementation.

318 The simulator was executed on *Windows 11* workstations equipped with *Intel Core i7-10700K CPUs*, *32*
 319 *GB RAM*, and *Nvidia GeForce RTX 3070 GPUs*, ensuring stable rendering and low-latency haptic response.
 320 Device calibration was performed through the HaDIU configuration module to standardize stiffness
 321 coefficients (0.8 N/mm) and force-feedback ranges (0–8 N) across the *Novint Falcon* and *Geomagic Touch*
 322 systems. Each device was pretested to verify positional accuracy and equivalent resistance under identical
 323 pressure conditions, ensuring consistent tactile perception across users.

324 The graphical user interface (GUI) was designed for clarity and usability (Fig. 3). Two sliders allow for
 325 the adjustment of initial parameters, including cylinder height and area. At the same time, an informational
 326 panel provides a concise overview of Boyle's Law, situating the simulation within its theoretical context.
 327 A real-time data panel displays pressure, height, and piston position values, allowing students to verify
 328 simulated outcomes and cross-check them with theoretical expectations.



Figure 3. Graphical user interface of the visuo-haptic simulator. The GUI includes adjustable parameters, real-time feedback on system variables, and an informational panel on Boyle's Law to support conceptual understanding.

329 By integrating visual, textual, and haptic modalities, the simulator provides an active, multi-sensory
 330 environment in which students can experimentally explore the pressure–volume relationship, transforming
 331 abstract gas laws into tangible learning experiences.

332 3.3 Testing of the Visuo-Haptic Simulator

333 3.3.1 Measures

334 To evaluate the effectiveness and user experience of the visuo-haptic simulator, a mixed-methods approach
 335 was adopted, combining standardized survey instruments with qualitative interviews. It allowed both
 336 quantitative insights into students' satisfaction and qualitative insights into their perceptions, engagement,
 337 and challenges.

338 3.3.1.1 End-User Satisfaction Survey.

339 The study employed Doll and Torkzadeh (1988)'s End-User Computing Satisfaction (EUCS) survey, an
340 established instrument for assessing user satisfaction with interactive computer systems. This instrument
341 was selected for its comprehensive coverage of factors critical to educational technologies. The EUCS
342 survey evaluates five principal dimensions:

- 343 • **Content:** Assesses the relevance, precision, and comprehensiveness of the information supplied by the
344 simulator.
- 345 • **Accuracy:** Evaluates the reliability of the simulator outputs, specifically whether the pressure–volume
346 data and haptic responses reflected Boyle's Law correctly.
- 347 • **Format:** Examines the clarity of information presentation, including the GUI layout, data visualization,
348 and interpretability of simulation results.
- 349 • **Ease of Use:** Measures the user-friendliness of the simulator, focusing on navigation, interaction with
350 the lever, and intuitiveness of parameter adjustments.
- 351 • **Timeliness:** Evaluates the responsiveness of the simulator in generating outputs and haptic feedback
352 in real time.

353 Responses were collected using Google Forms on a 5-point Likert scale, where 1 indicated strong
354 dissatisfaction and 5 showed strong satisfaction. Quantitative data were analyzed using Python, leveraging
355 the `pandas` library for data processing and `matplotlib` for statistical visualization. This analysis
356 provided descriptive statistics, comparative distributions across dimensions, and graphical summaries of
357 student satisfaction.

358 3.3.1.2 Qualitative Interviews.

359 To complement the EUCS survey, semi-structured individual interviews were conducted with participants
360 to gain a more profound understanding of their engagement with the visuo-haptic simulator. Interviews
361 were particularly valuable for eliciting reflections on experiential learning, identifying potential usability
362 issues, and uncovering perceptions that quantitative scores alone could not capture. The open-ended
363 questions included:

- 364 • Can you describe your experience using the visuo-haptic simulator to learn about Boyle's Law?
- 365 • In what ways did the interaction with the simulator help you understand the inverse relationship
366 between pressure and volume?
- 367 • How engaging did you find the simulator compared to traditional classroom-based learning?
- 368 • What challenges or difficulties did you encounter while using the simulator, and how did these affect
369 your learning experience?
- 370 • Do you believe the simulator provided advantages over conventional learning methods, and if so,
371 which were most valuable?
- 372 • In your opinion, how could visuo-haptic simulators be applied to other areas of physics or to different
373 subjects?

374 3.3.2 Participants and Recruitment

375 A total of 39 undergraduate engineering students from Universidad Panamericana voluntarily participated
376 between August and November 2024. Participants were enrolled in the engineering program and had taken,

377 or were currently taking, physics-related courses as part of their curriculum. Recruitment was conducted
378 through course announcements and faculty-distributed invitations. Participation was voluntary, with no
379 academic incentives or rewards.

380 Inclusion criteria required enrollment in the engineering program and the ability to attend one simulator
381 session. Students with prior experience in haptic research were excluded to minimize bias. The final
382 sample included 25 male and 14 female students, with ages ranging from 18 to 22 years ($M = 20.1$,
383 $SD = 1.4$). Figure 4 shows the semester distribution, which ranged from the first to the seventh semester.
384 The largest cohort was in the fifth semester (9 students), followed by the fourth (7 students) and the
385 second (6 students). This range reflects a progression from early to advanced stages of the engineering
386 program, ensuring diversity in prior physics experience and familiarity with simulation-based learning.
387 Lower-division students (semesters 1–3) were typically 18–19 years old and had completed introductory
388 physics courses, while upper-division students (semesters 4–7) were generally 21–22 years old and had
389 prior laboratory experience with computer-based learning tools.

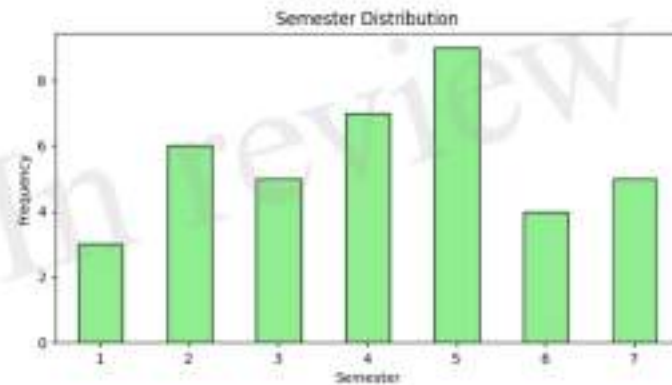


Figure 4. Semester Distribution of Participants.

390 The sample size ($n = 39$) was determined by equipment and scheduling constraints, as only twelve
391 haptic devices were available per session. This number provided a balance between logistical feasibility
392 and the opportunity to observe diverse user responses across semesters. Because the study was exploratory
393 and focused on perceptions rather than statistical inference, no formal power analysis was conducted.
394 The implications of this sample size are further discussed in the Limitations subsection of the Discussion.
395 Nonetheless, the sample size is consistent with those used in comparable visuo-haptic simulator studies
396 (e.g., Yuksel et al., 2017; Qi et al., 2020).

397 Additional demographic information, such as GPA, was not collected, as the focus of this study was
398 on students' perceptions of usability, satisfaction, and engagement rather than academic performance.
399 Although drawn from a single institution, participants represented a cross-section of students within
400 the engineering program, offering reasonable variation in prior physics experience and familiarity with
401 technology-enhanced learning environments.

402 **3.3.2.1 Experimental Devices and Control of Variability.**

403 Two haptic devices were employed: ten *Novint Falcon* and two *Geomagic Touch* systems. Both were
404 calibrated using identical parameters within the HaDIU framework to ensure consistent force feedback
405 ranges and stiffness coefficients. Each simulation was pre-tested for equivalent tactile resistance under
406 identical virtual pressure settings. While both devices delivered comparable perceptual experiences, minor
407 differences in ergonomics and movement range may have influenced users' tactile perception. This
408 variability is acknowledged as a potential confounding factor and is further discussed in the study's
409 limitations.

410 **3.3.2.2 Procedure.**

411 Each session followed a structured sequence:

412 **1. Introduction (10 minutes).** The facilitator welcomed students, explained the objectives of the study, and
413 presented an overview of the visuo-haptic simulator. Instructions on using the GUI, adjusting parameters,
414 and interpreting outputs were provided during a live demonstration.

415 **2. Initial Interaction (5 minutes).** Participants were encouraged to freely explore the simulator, navigating
416 the GUI and experimenting with adjustable variables. This familiarization stage reduced potential usability
417 barriers and allowed students to gain confidence with the device.

418 **3. Guided Exploration (15 minutes).** Participants manipulated the simulator in a structured way to observe
419 Boyle's Law in action. They were guided to note how reducing the piston's height increased pressure and
420 to compare real-time haptic and visual feedback, reinforcing theoretical-experimental connections.

421 **4. Independent Use (20 minutes).** Each student worked individually with the simulator, exploring different
422 scenarios and noting observations. This stage provided ample time for hands-on experimentation, allowing
423 participants to apply concepts independently and reinforce understanding through practice.

424 **5. Feedback Collection (10 minutes).** At the end of each session, students completed the EUCS
425 questionnaire for quantitative feedback. Immediately afterward, individual interviews were conducted
426 with selected participants to reflect on their learning experience, challenges, and perceived advantages of
427 the simulator compared to traditional methods.

428 **3.3.2.3 Interview Sampling and Qualitative Analysis.**

429 Following completion of the EUCS survey, participants were invited for interviews using purposive
430 sampling to capture a range of satisfaction levels and perspectives based on survey responses and availability.
431 Interviews were transcribed verbatim from written notes and analyzed using thematic analysis following
432 Kiger and Varpio (2020). Two researchers independently coded transcripts, identified recurring patterns
433 related to engagement, usability, and conceptual understanding, and refined themes through consensus to
434 ensure interpretive validity.

435 **3.3.2.4 Data Collection and Rationale.**

436 By combining the EUCS survey data with qualitative interviews, the evaluation captured both broad
437 patterns of satisfaction and individual perceptions of motivation and usefulness. This mixed-methods
438 approach ensured that findings reflected not only the simulator's usability but also students' attitudes
439 toward its potential to support learning in classroom contexts.

4 RESULTS

440 The analysis combined quantitative survey data and qualitative thematic coding of interview transcripts
 441 to provide a comprehensive view of students' perceptions of the visuo-haptic simulator. Overall, results
 442 indicate high satisfaction with usability and responsiveness, as well as positive affective engagement
 443 with the learning experience. Qualitative findings complement these patterns by revealing more profound
 444 insights into how students experienced interactivity, comprehension, and motivation.

4.1 End-User Satisfaction Survey Results

446 The content dimension received an average score of 3.35, indicating an acceptable level of satisfaction
 447 with the simulator's relevance, precision, and comprehensiveness (Fig. 5). Although students found the
 448 content helpful, several suggested that expanding the explanations and providing additional supporting
 449 information could offer a richer conceptual context. This indicates that while the simulator effectively
 450 conveys Boyle's Law, it may benefit from supplementary guidance or more detailed annotations.

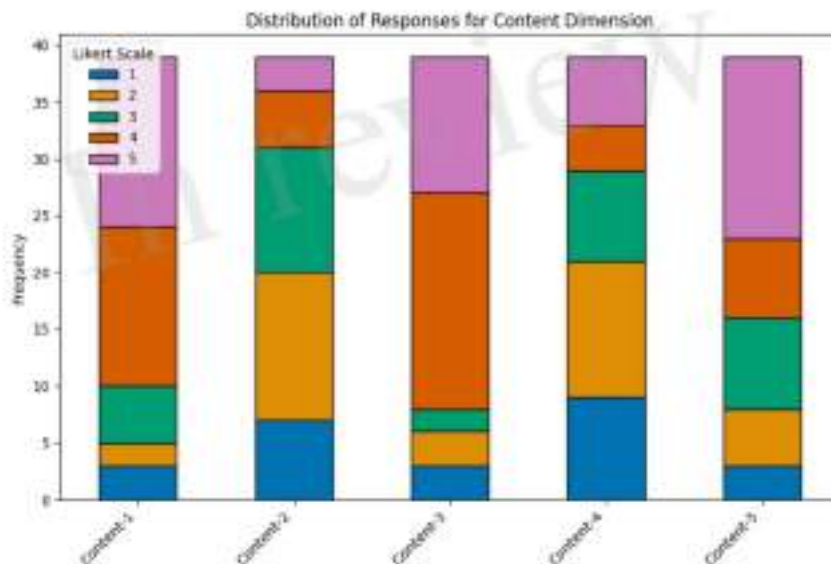


Figure 5. Distribution of Responses for the Content Dimension.

451 The accuracy dimension averaged 4.26, indicating strong confidence in the simulator's ability to provide
 452 reliable outputs (Fig. 6). Students consistently perceived that the displayed values and haptic responses
 453 aligned with Boyle's Law. This high rating reflects the trustworthiness of the mathematical model and the
 454 physical interactions, a crucial factor for educational tools where conceptual accuracy is central to learning
 455 outcomes.

456 The format dimension, related to the structuring and clarity of information, attained an average score of
 457 3.16 (Fig. 7), the lowest among the five dimensions. This finding suggests that some students experienced

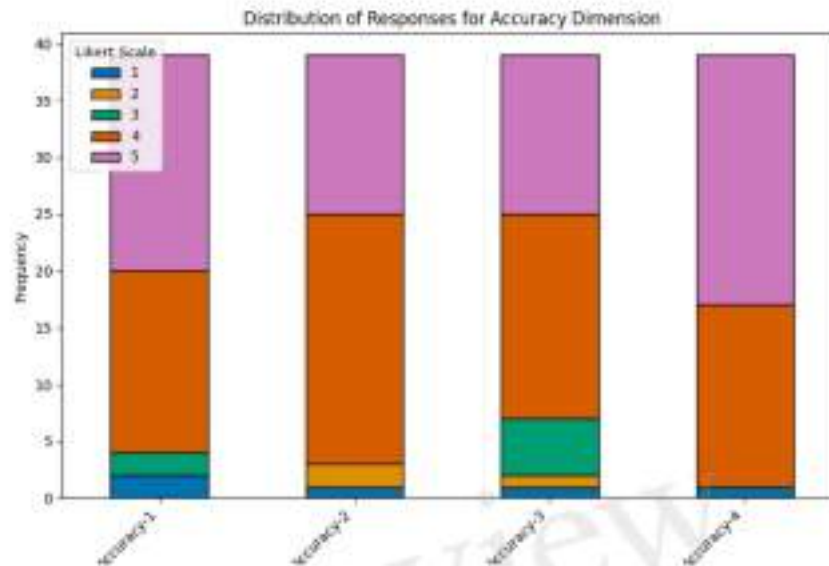


Figure 6. Distribution of Responses for the Accuracy Dimension.

458 difficulties with the interface's visual layout. Open comments suggested that dense text blocks and the 3D
 459 navigation posed challenges. Enhancing visual hierarchy, spacing, and navigation cues could substantially
 460 improve students' perception of the simulator's usability.

461 The ease of use dimension scored an average of 4.14, showing that students generally found the simulator
 462 intuitive (Fig. 8). Most participants reported minimal difficulty in adjusting parameters and interpreting
 463 outputs after the brief introduction phase. This suggests that the simulator achieved a balance between
 464 functionality and simplicity, making it accessible even for students with limited experience in haptic
 465 technologies.

466 The highest average score was attained in the timeliness dimension, with a mean of 4.40 (Fig. 9). Students
 467 particularly valued the immediacy of visual updates and haptic responses when manipulating the piston.
 468 The real-time feedback helped sustain engagement and supported experiential learning by linking cause
 469 and effect in real time.

470 4.2 Thematic Analysis of Interviews

471 Semi-structured interviews were analyzed using a reflexive thematic analysis approach following
 472 Kiger and Varpio (2020). Two researchers independently reviewed all transcripts, conducted open
 473 coding, and iteratively grouped codes into themes that reflected recurring patterns in participants'
 474 experiences. Discrepancies were resolved through consensus discussions to enhance interpretive validity.
 475 This process yielded four major themes: (1) *Engagement and Enjoyment*, (2) *Usability and Interface*
 476 *Design*, (3) *Conceptual Understanding and Embodied Learning*, and (4) *Perceived Educational Value and*
 477 *Transferability*. Table 1 summarizes these themes with representative quotations.

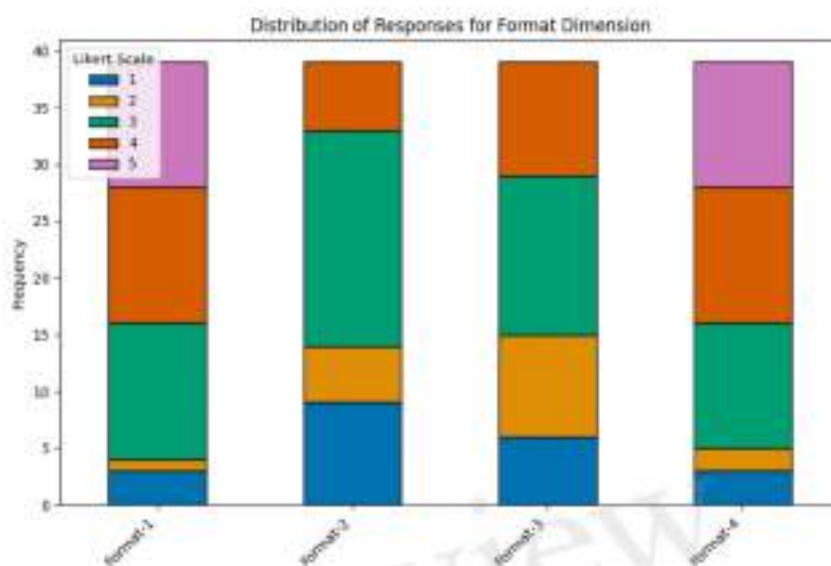


Figure 7. Distribution of Responses for the Format Dimension.

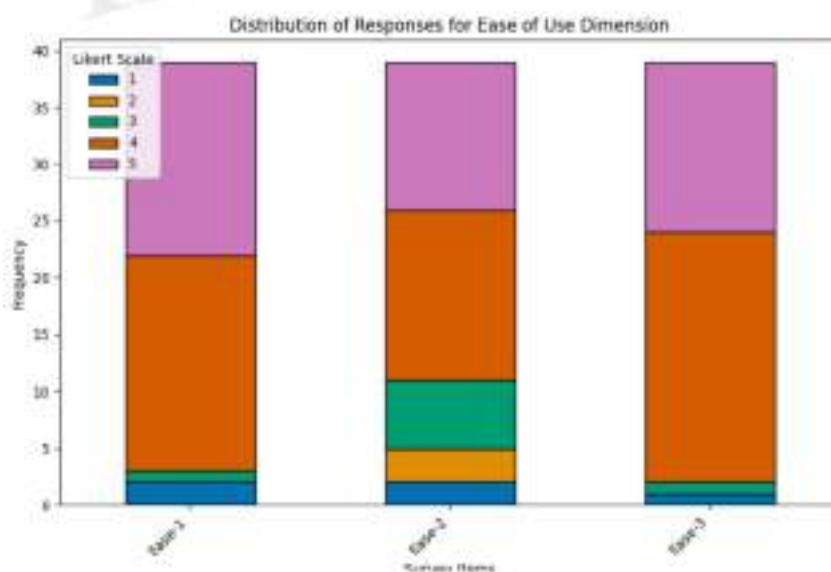


Figure 8. Distribution of Responses for the Ease of Use Dimension.

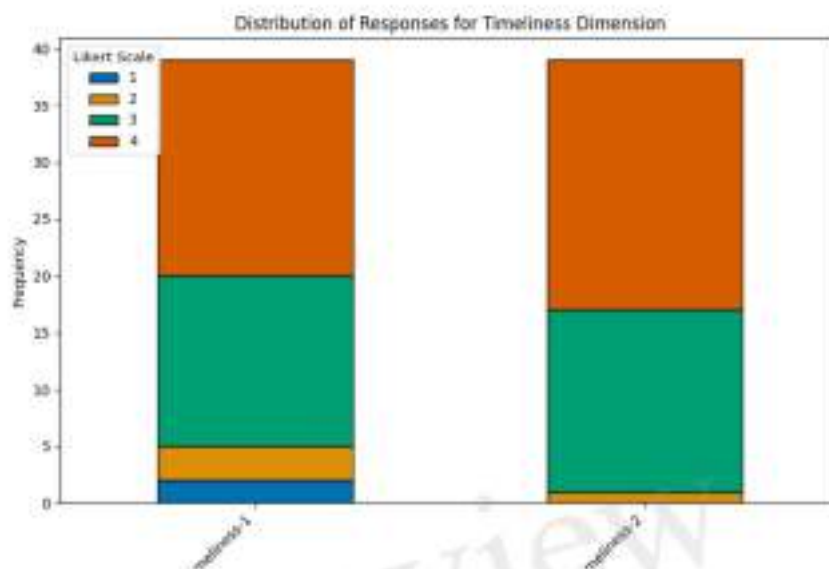


Figure 9. Distribution of Responses for the Timeliness Dimension.

Table 1. Main Themes Identified through Thematic Analysis of Interviews

Theme	Illustrative Student Comments
Engagement and Enjoyment	"It was fun and felt like a game, but I was actually learning something." "I stayed interested the whole time because I could see and feel the pressure changing."
Usability and Interface Design	"The controls were intuitive after a few minutes." "Some buttons and text were small; a short tutorial would help new users."
Conceptual Understanding and Embodied Learning	"Feeling the resistance made the concept of pressure-volume easier to grasp." "When I moved the piston and felt it get harder to push, I understood what the formula really means."
Perceived Educational Value and Transferability	"This tool could help in other topics like thermodynamics or chemistry." "It's a good complement to theory because you can experiment safely and repeat as much as you want."

478 4.3 Integration of Quantitative and Qualitative Findings

479 The convergence between survey and interview data reinforced the reliability of the results. High scores
480 in the *accuracy*, *ease of use*, and *timeliness* dimensions corresponded with qualitative reports describing the
481 simulator as "precise," "responsive," and "easy to use." Conversely, the lower score in the *format* dimension
482 aligned with comments about dense on-screen information and the need for more precise guidance.

483 Students' remarks consistently reflected greater motivation and curiosity when using the simulator than
484 during traditional instruction. The tactile interaction was frequently cited as a distinctive feature that
485 made the learning process more memorable and intuitive. Participants also expressed interest in broader

486 applications of visuo-haptic tools to other physics topics, emphasizing their potential to transform abstract
487 equations into interactive, exploratory experiences.

488 4.4 Summary of Key Patterns

489 Across both data sources, four recurrent patterns emerged:

- 490 1. **High affective engagement:** Students described the experience as enjoyable and motivating.
- 491 2. **Positive usability perceptions:** Most participants found the simulator intuitive after minimal guidance.
- 492 3. **Enhanced conceptual linkage:** Tactile feedback helped connect theoretical relationships to sensory
493 experience.
- 494 4. **Transferability potential:** Students envisioned using visuo-haptic simulators in other STEM subjects.

495 These themes provide a coherent interpretation of how multi-sensory interaction supports engagement,
496 understanding, and perceived educational value in technology-mediated physics learning.

5 DISCUSSION

497 The results of this study demonstrate that the visuo-haptic simulator for understanding Boyle's Law was
498 positively received by students and promoted strong engagement with a traditionally abstract concept. The
499 combination of tactile and visual components appears to have benefited both the intuitive grasp of theoretical
500 relationships and students' motivation to interact with the material. Participants consistently described the
501 experience as interactive, entertaining, and more engaging than conventional approaches, indicating that
502 the simulator supported a transition from passive observation to active exploration. This finding aligns with
503 broader discussions in educational technology, emphasizing the importance of immersion, interactivity,
504 and experiential engagement as essential components for meaningful learning experiences.

505 One of the central contributions of the simulator lies in its capacity to render abstract physical principles
506 into tangible interactions. The simulator allowed participants to manipulate the piston and observe pressure
507 changes in real-time. This corresponds with the principles of embodied cognition, which suggest that
508 learning is strengthened when abstract concepts are anchored in sensory and motor experiences. This
509 approach differs from conventional didactic instruction, in which students may memorize formulas without
510 developing an intuitive understanding of the concepts. Although this study did not directly measure
511 learning outcomes, participants' responses suggest that multi-sensory interaction could increase curiosity
512 and perceived comprehension of complex scientific relationships.

513 The motivational aspect is equally significant. Participants' preference for the simulator over traditional
514 methods suggests that interactive, technology-enhanced environments may encourage more positive
515 attitudes toward physics, a discipline often perceived as challenging. Engagement is essential for
516 maintaining interest in STEM fields, and tools such as this simulator may help counteract disengagement
517 by fostering motivation and enjoyment. The tactile dimension, in particular, introduced an element of
518 playfulness and exploration into the learning process, reinforcing the notion that affective experiences
519 can enhance willingness to learn. Previous research on haptic interfaces in education has reported similar
520 outcomes, indicating that touch-based interactivity can enhance curiosity and promote sustained attention.
521 The present study extends these observations by situating haptic learning within the context of gas laws.

5.1 Comparison with Prior Studies

The engagement outcomes observed in this study align with previous research demonstrating that interactivity and multi-sensory feedback play central roles in promoting active learning. Similar to Qi et al. (2020) and Walsh and Magana (2023), students in this study emphasized the experiential value of physically feeling the pressure–volume relationship, suggesting that the synchronization of tactile and visual feedback reinforces intuitive understanding of abstract concepts. Both prior studies reported that combining haptic and visual cues improved motivation and conceptual clarity—findings consistent with the high engagement and satisfaction reported here. However, while those investigations focused on buoyancy and friction, the present work extends visuo-haptic learning to gas laws, providing empirical evidence that multi-sensory interaction can facilitate understanding in thermodynamics, a topic largely unexplored through haptic simulation.

Beyond visuo-haptic contexts, the findings also resonate with research on engagement in technology-mediated and immersive learning environments. Consistent with Lau et al. (2022), interactive structures and immediate feedback emerged as major drivers of motivation and sustained attention. These dynamics parallel the behavioral, cognitive, and affective engagement mechanisms described by Li and Lam (2015) and Owusu-Agyeman and Larbi-Siaw (2018), where learner autonomy and reciprocal feedback loops enhance participation and persistence. In this study, tactile resistance and real-time visual updates served comparable functions, creating a responsive dialogue between the learner and system that sustained curiosity and focus.

Comparable trends have been observed in immersive and virtual reality studies (e.g., Talafian et al., 2019; Shu and Huang, 2021; Johnson-Glenberg et al., 2021), where experiential design and sensory presence foster engagement and self-efficacy. The present study reinforces these observations while demonstrating that similar benefits can be achieved through localized visuo-haptic interaction without the infrastructural demands of large-scale immersive setups. This distinction highlights the scalability and accessibility of visuo-haptic tools for classroom implementation, particularly in resource-limited educational environments.

These comparisons position the present study as a bridge between three domains: (1) visuo-haptic learning focused on embodied cognition, (2) immersive and extended-reality research emphasizing presence and spatial interaction, and (3) engagement studies examining feedback and autonomy in digital education. By integrating these perspectives, the study contributes to a more comprehensive understanding of how tactile–visual feedback can simultaneously support conceptual, motivational, and experiential dimensions of learning in physics education.

5.2 Design and Usability Considerations

Despite these strengths, several areas for improvement became evident. The relatively lower ratings in the format dimension indicate that the simulator's visual presentation and interface design could be optimized. Some students reported difficulty quickly interpreting information when the layout appeared dense. Such findings underscore the importance of applying usability principles in educational tool design, where clarity and simplicity are crucial to prevent cognitive overload. Addressing these concerns in future iterations could involve restructuring the display to emphasize key variables, using color coding, or integrating progressive disclosure to minimize distractions. Additionally, qualitative feedback suggested that including a short tutorial or guided walkthrough would improve accessibility for first-time users. These recommendations emphasize the importance of considering not only core functionality but also the broader user experience, encompassing onboarding and learner guidance.

5.3 Perceived Educational Value and Future Applications

Another notable outcome of the study is the students' expressed interest in extending the use of visuo-haptic simulators beyond Boyle's Law. Participants suggested potential applications in chemistry and other areas of physics where abstract or counterintuitive concepts pose challenges to understanding. This feedback underscores the approach's versatility and its potential to support learning across disciplines. While the present study did not evaluate the educational impact or learning gains, students perceived the simulator as a valuable complement to classroom instruction, which could facilitate knowledge exploration and conceptual visualization. Extending visuo-haptic simulations across scientific domains could promote a broader pedagogical shift toward experiential, embodied learning in science.

5.4 Limitations

Several limitations must be acknowledged. First, the study employed a convenience sample limited to a single institution and a modest cohort ($n = 39$), primarily determined by laboratory capacity and equipment availability. Consequently, the findings may not generalize to larger or more diverse populations. Second, two types of haptic devices (*Novint Falcon* and *Geomagic Touch*) were used. Despite standard calibration, subtle differences in mechanical response could have influenced tactile perception, introducing a potential confounding variable. Future research should employ a uniform hardware setup or statistically control for device type to ensure consistency. Third, qualitative interviews involved purposive sampling, which may have introduced selection bias toward more communicative participants. Finally, the evaluation focused on satisfaction, motivation, and perceived usefulness rather than measured learning outcomes. Subsequent studies should include pre- and post-test designs or control groups to assess actual learning gains and retention. They should use mixed-method triangulation with larger, more diverse samples to strengthen validity.

5.5 Broader Implications

The favorable reception of the visuo-haptic simulator suggests that integrating multi-sensory experiences into science education can help bridge the gap between abstract theory and tangible experience. As educational contexts increasingly adopt digital tools, interactive and embodied technologies have the potential to enrich students' engagement with scientific concepts. Moving forward, interdisciplinary collaboration among educators, designers, and engineers will be essential to refine visuo-haptic tools, integrate instructional scaffolds, and expand the range of scientific phenomena that can be represented haptically. With continued development and empirical evaluation, such tools hold promise for enhancing motivation and supporting more meaningful, experiential approaches to science learning.

6 CONCLUSIONS

This study explored the potential of a visuo-haptic simulator to enhance students' engagement and understanding of Boyle's Law. By integrating tactile and visual feedback, the simulator provided an interactive environment that encouraged intuitive exploration of the pressure-volume relationship. Rather than assessing learning outcomes directly, the study focused on students' perceptions of satisfaction, usability, and the simulator's perceived value in supporting classroom learning. Survey and interview results indicated high satisfaction in dimensions such as accuracy, ease of use, and responsiveness, underscoring the simulator's effectiveness as a motivational and experiential learning tool.

602 Feedback also revealed areas for refinement, particularly simplifying the graphical interface and providing
603 a guided tutorial for first-time users. Participants expressed interest in applying visuo-haptic simulators to
604 other topics, suggesting their potential for broader adoption across STEM disciplines.

605 Future research should focus on measuring learning outcomes and assessing long-term effects. Studies
606 involving larger and more diverse participant groups, ideally in authentic classroom settings, would enable
607 stronger comparisons between visuo-haptic and traditional teaching methods. Incorporating pre- and
608 post-test assessments, transfer-of-knowledge evaluations, and control groups will provide deeper insights
609 into how embodied, multi-sensory interaction supports conceptual understanding. Expanding hardware
610 availability and ensuring consistent device performance will also be necessary for scaling to classroom-level
611 deployment.

612 Advancing visuo-haptic learning will require interdisciplinary collaboration among educators, designers,
613 and engineers. Continued refinement of interface design, pedagogical scaffolding, and content alignment
614 will help ensure the effective integration of this approach into STEM curricula. While this study focused
615 on students' perceptions and motivational responses, its findings highlight the potential of visuo-haptic
616 tools as engaging and pedagogically supportive resources for experiential science learning.

ETHICS STATEMENT

617 Ethical review and approval were waived for this study as it was deemed "research without risk," and the
618 research intervention poses a risk comparable to that of a standard classroom environment. Moreover,
619 because the visuo-haptic simulator was not invasive, the rights of the experimental students were respected
620 in accordance with the Declaration of Helsinki.

CONFLICT OF INTEREST STATEMENT

621 The authors declare that the research was conducted without any commercial or financial relationships that
622 could potentially create a conflict of interest.

AUTHOR CONTRIBUTIONS

623 SM-I: Conceptualization, Investigation, Software, Writing – original draft, Writing – review & editing. OL-
624 F: Conceptualization, Investigation, Methodology, Validation, Funding acquisition, Visualization, Writing –
625 original draft, Writing – review & editing. LAB-G: Data curation, Methodology, Formal Analysis, Project
626 administration, Supervision, Writing – review & editing. DaiE-C: Data curation, Methodology, Formal
627 Analysis, Supervision, Validation, Resources, Writing – review & editing. Dave-C: Conceptualization,
628 Investigation, Methodology, Software, Supervision, Funding acquisition, Resources, Writing – original
629 draft, Writing – review & editing.

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Discusión

Los resultados obtenidos en este estudio permiten analizar el potencial educativo de un simulador visuo-háptico para apoyar la comprensión de la Ley de Boyle en estudiantes de ingeniería. En términos generales, los hallazgos muestran que los participantes percibieron la experiencia como satisfactoria, intuitiva y útil para vincular los modelos teóricos con una representación sensorial más concreta del fenómeno físico. Este conjunto de percepciones se alinea con los principios del aprendizaje activo y con las propuestas de la cognición corporizada, que sostienen que la interacción física y multimodal con los contenidos favorece la construcción de significados más profundos.

En primer lugar, los resultados del instrumento EUCS indican niveles altos de satisfacción en dimensiones como precisión, facilidad de uso, formato y oportunidad. Estos datos respaldan la Hipótesis 1 (H1), al mostrar que los estudiantes valoraron positivamente tanto el diseño como el funcionamiento del simulador. La claridad visual de los indicadores de presión y volumen, junto con la respuesta háptica asociada al movimiento del pistón, contribuyó a que los usuarios percibieran coherencia entre la simulación y la ley física subyacente. En varias entrevistas, los participantes mencionaron que “sentir la resistencia” al comprimir el gas les permitió comprender con mayor claridad la relación inversa entre presión y volumen, lo que sugiere una conexión significativa entre la experiencia sensorial y los conceptos teóricos.

En relación con el compromiso estudiantil, los resultados cualitativos muestran que el simulador actuó como un elemento motivador, generando interés y participación activa durante la sesión. Los estudiantes destacaron que la posibilidad de manipular directamente el sistema, observar cambios en tiempo real y recibir retroalimentación táctil hizo que la actividad resultara más inmersiva y menos abstracta que los enfoques tradicionales. Este patrón de respuestas apoya la Hipótesis 2 (H2), según la cual el simulador visuo-háptico incrementa el compromiso en comparación con experiencias previas centradas en clases expositivas o resolución mecánica de problemas.

Asimismo, los hallazgos sugieren que un mayor nivel de compromiso se asoció con una mejor percepción de comprensión conceptual, lo que respalda parcialmente la Hipótesis 3 (H3). Aunque el presente estudio no midió directamente el rendimiento académico ni la ganancia conceptual mediante pruebas pretest–postest, la información cualitativa indica que los estudiantes sintieron que comprendían mejor el significado físico de la ley al relacionarlo con una experiencia manipulable y corporalmente significativa. Este resultado coincide con investigaciones previas que señalan que las experiencias hápticas pueden facilitar la internalización de relaciones matemáticas abstractas al vincularlas con sensaciones físicas interpretables.

Finalmente, los estudiantes expresaron una valoración positiva del potencial educativo del simulador, no solo para la Ley de Boyle sino también para otros temas de física y asignaturas STEM. Muchos participantes afirmaron que tecnologías visuo-hápticas podrían ayudar a “hacer tangible” otros conceptos tradicionalmente difíciles de visualizar, como fuerzas, gradientes de presión o interacciones en sistemas mecánicos. Estas percepciones respaldan la Hipótesis 4 (H4), al mostrar que los estudiantes consideran viable y deseable el uso de este tipo de herramientas en el futuro.

A pesar de estos resultados favorables, es importante reconocer diversas limitaciones del estudio. La muestra fue relativamente pequeña y estuvo conformada por estudiantes de ingeniería con familiaridad básica en temas de física, lo que limita la generalización de los hallazgos a otros perfiles académicos. Además, el estudio se centró en percepciones y satisfacción, pero no midió aprendizajes de manera cuantitativa. Esto abre la oportunidad de realizar investigaciones futuras que comparen el rendimiento conceptual entre estudiantes que utilizan simuladores hápticos y aquellos que emplean métodos tradicionales. Sin embargo, la cuestión actitudinal y la apertura de los métodos abre camino para diferentes tipos de estudios posteriores. Otra limitación es que la experiencia fue breve y realizada en un entorno controlado; futuros trabajos podrían explorar el uso prolongado del simulador dentro de cursos completos o actividades de laboratorio, que pudiera desencadenar en la generación de protocolos de laboratorio que se integren a los planes formales de estudios.

En conjunto, los resultados sugieren que la integración de tecnologías visuo-hápticas en la enseñanza de la física puede mejorar el compromiso estudiantil, facilitar la comprensión conceptual y ofrecer experiencias educativas más significativas. El simulador desarrollado en esta tesis representa un paso hacia la creación de entornos de aprendizaje más humanos que conecten de manera más estrecha la teoría física con la experiencia sensorial, alineándose con las tendencias contemporáneas de educación STEM y los principios de la cognición corporizada.

Conclusiones

El presente estudio tuvo como propósito diseñar, desarrollar y evaluar un simulador visuo-háptico orientado al aprendizaje activo de la Ley de Boyle en estudiantes de ingeniería. A partir de los resultados obtenidos, es posible afirmar que la integración de retroalimentación visual y háptica constituye una vía prometedora para apoyar la comprensión de conceptos abstractos en física, al proporcionar experiencias manipulables y sensorialmente significativas que complementan los enfoques tradicionales de enseñanza.

Las evaluaciones realizadas mediante el instrumento EUCS mostraron niveles elevados de satisfacción en dimensiones como precisión, formato, facilidad de uso y oportunidad. Estos

resultados sugieren que el simulador no solo fue percibido como una herramienta funcional y coherente con los modelos teóricos, sino también como un recurso didáctico accesible y atractivo. Asimismo, el análisis cualitativo de las entrevistas reveló que la interacción física con el sistema pistón–cilindro contribuyó a incrementar el compromiso de los estudiantes, permitiéndoles vincular la relación presión–volumen con sensaciones corporales directas. Estas percepciones respaldan las hipótesis planteadas y coinciden con los postulados de la cognición corporizada y del aprendizaje activo, al mostrar cómo la experiencia multimodal favorece la construcción de significados más profundos.

Aunque los resultados son alentadores, esta tesis presenta limitaciones que deben considerarse. La muestra fue reducida y el estudio se centró en percepciones, sin incorporar mediciones directas de ganancia conceptual. En el futuro, será necesario evaluar el impacto del simulador en el rendimiento académico mediante diseños experimentales más amplios y comparativos. También sería valioso explorar la integración del simulador en cursos completos de física, así como su adaptación para abordar otros fenómenos donde la relación entre variables físicas pueda representarse mediante retroalimentación háptica.

En conjunto, los hallazgos de esta tesis aportan evidencia sobre el potencial de los simuladores visuo-hápticos como herramientas educativas en el ámbito STEM. El trabajo realizado demuestra que es posible diseñar experiencias de aprendizaje que combinen teoría, visualización y sensación física de manera armónica, generando entornos más inmersivos, motivadores y pedagógicamente relevantes. Este tipo de tecnologías abre oportunidades para repensar cómo se enseñan conceptos complejos y para promover un aprendizaje más significativo mediante la interacción directa con representaciones digitales del mundo físico.

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