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RESEARCH ARTICLE

# The utility of mechanical objects: Aiding students' learning of abstract and difficult engineering concepts

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**Abstract**

**Background:** Undergraduate students consistently struggle with mastering concepts related to thermodynamics. Prior work has shown that haptic technology and intensive hands-on workshops help improve learning outcomes relative to traditional lecture-based thermodynamics instruction. The current study takes a more feasible approach to improving thermal understanding by incorporating simple mechanical objects into individual problem-solving exercises.

**Purpose/Hypotheses:** This study tests the impact of simple mechanical objects on learning outcomes (specifically, problem-solving performance and conceptual understanding) for third-year undergraduate engineering students in a thermodynamics course across a semester.

**Design/Method:** During the semester, 119 engineering students in two sections of an undergraduate thermodynamics course completed three 15-min, self-guided problem-solving tasks, one section without and the other with a simple and relevant physical object. Performance on the tasks and improvements in thermodynamics comprehension (measured via Thermal and Transport Concept Inventory scores) were compared between the two sections.

**Results:** Students who had a simple, relevant object available to solve three thermodynamics problems consistently outperformed their counterparts without objects, although only to statistical significance when examining the simple effects for the third problem. At the end of the semester, students who had completed the tasks with the objects displayed significantly greater improvements in thermodynamics comprehension than their peers without the relevant object. Higher mechanical aptitude facilitated the beneficial effect of object availability on comprehension improvements.

**Conclusion:** Findings suggest that the incorporation of simple mechanical objects into active learning exercises in thermodynamics curricula could facilitate student learning in thermodynamics and potentially other abstract domains.

KEYWORDS

active learning, cognitive theories, conceptual learning, instructional methods, knowledge transfer

# 1 | INTRODUCTION

The nature of mechanical objects as simultaneously tangible and functional entities makes them well suited to learning (Houkes & Meijers, 2006). Objects can serve as visual representations of concepts and can provide a learner with a means of applying and testing their mental conceptualizations in a concrete way (Baker, 2006). For these reasons, they have been utilized in an intentional educational capacity since the early 19th century, when Froebel shared his then-innovative idea of learning through play with objects (Liebschner, 1992). For engineers whose careers often focus on object manipulation and production, object-based learning may be particularly effective.

In this study, we examine the value of mechanical objects in learning thermodynamics concepts among engineering students. Prior work in thermal science education indicates that students struggle to learn concepts fundamental to thermodynamics (Ogunwuyi, 2013; Streveler et al., 2008; Young et al., 2011). To combat student difficulties in mastering thermodynamics, researchers and educators have developed intensive hands-on workshops that have shown promise in improving learning outcomes (Cirenza et al., 2018; Nottis et al., 2010; Nottis et al., 2018; Pizzolato et al., 2014). Empirical results pertaining to the use of haptic technology in teaching abstract concepts are also promising (e.g., Kim et al., 2010; Okamura et al., 2002; Sanchez et al., 2013; Tan et al., 2011; Young et al., 2011). However, haptic technology and hands-on workshops often require significant resource investment (Nottis et al., 2018). This study aims to provide guidance as to how simple mechanical objects incorporated into student-guided active learning tasks could be used as educational tools in the context of thermodynamics education for engineering students. We describe an educational intervention that uses simple mechanical objects in problem-solving exercises to improve learning outcomes related to thermodynamics comprehension.

# 2 | BACKGROUND

## 2.1 | Difficult concepts in thermodynamics

Thermodynamics is a course taught across multiple engineering disciplines, which focuses on energy, its movement between systems, and related entities like heat, temperature, and work (Balmer, 2011; Drake, 2021). Students often struggle with this course, for example, with grasping processes fundamental to thermodynamics such as heat transfer, equilibrium, as well as the difference between heat, energy, and temperature (Nottis et al., 2010; Ogunwuyi, 2013; Young et al., 2011). Researchers have contended that the abstract nature of thermodynamic processes underlies some of students' struggle with understanding thermodynamic concepts. Unlike mechanics, which deals with macroscopic-level processes that we observe and interact with each day, thermodynamics deals with abstract concepts such as entropy and energy, which cannot be touched and are more difficult to comprehend than more familiar macroscopic processes (Streveler et al., 2003).

Streveler et al. (2008) identified several specific difficulties and misconceptions that are barriers for students to effectively learn thermodynamics. First, students often lack prior knowledge of thermodynamics. Second, students tend to view temperature and heat as equivalent because of reliance on false intuition regarding temperature. Third, students particularly struggle with the concept of thermal equilibrium and the nature of thermal steady state. Fourth, students often hold misconceptions with respect to the association between heat transfer rate and the amount of energy transferred, an important process to thermodynamics.

Prior educational research in the natural sciences has identified similar struggles from undergraduates trying to grasp thermodynamic concepts. Undergraduate students often consider thermodynamics classes to be their hardest because of advanced thermodynamics concepts such as equilibrium, heat, and entropy (Thomas, 1997). In particular, students carry with them into their undergraduate work misconceptions from colloquial treatment of such concepts, misinterpretations of the mathematics underlying these concepts, and an inability to apply concepts to the microscopic level (Bennett & Sözbilir, 2007; see Bain et al., 2014, for a review). In learning entropy, students tended to rely on visual interpretations of terminology and to base their understanding of entropy on applications to the macrophysical world (Abell & Bretz, 2019; Bennett & Sözbilir, 2007). Furthermore, reliance on metaphors to teach entropy by relating the phenomenon to concrete, visual stimuli verbally has exacerbated misconceptions (Haglund et al., 2015), as has traditional verbal classroom instruction (Foroushani, 2019). We hope that providing a physical demonstration of difficult concepts like entropy will leverage students' reliance on physical illustrations in a productive way to guide them toward an accurate understanding of thermodynamics.

Our research goal was to lower barriers toward understanding thermal science using mechanical objects to explicitly link difficult concepts to physical phenomena surrounding thermodynamic concepts. Specifically, in our study we aimed to improve understanding in three topics related to these features of thermodynamics with which students often struggle: work and heat, psychrometric applications, and entropy. Work and heat are the two most important concepts in thermodynamics (Moran et al., 2010). They are highly related but are not the same. The main difference between work and heat is that work transfers the mechanical energy between two systems, while heat is the transfer of thermal energy between systems. Psychrometrics pertains to the thermodynamic properties of air–vapor mixtures, or moist air (Hall & Allinson, 2010). Applications of psychrometrics typically investigate how temperature, partial pressures, and enthalpy interact in a system. Entropy, the subject of the second law of thermodynamics, is a state variable that always increases for irreversible processes (Moran et al., 2010). More colloquially, entropy represents disorder. The amount by which entropy for a system changes equals the proportion between heat transfer and temperature.

Each of these topics is important to thermodynamics comprehension, yet each presents the obstacles listed above, wherein students lack prior familiarity with how these concepts are treated scientifically and instead rely on colloquial, everyday interpretations of these concepts that are inappropriate (Bain et al., 2014). While students need to grasp concepts such as heat versus temperature, thermal equilibrium, and heat versus energy transfer in order to successfully master these topics, traditional verbal instruction has often failed to clarify student misconceptions that thwart their ability to grasp and apply these concepts (Foroushani, 2019). By providing physical demonstrations of key concepts related to work and heat, psychrometrics, and entropy, we expected that our incorporation of physical objects into class activities would supplement traditional classroom instruction methods (i.e., lecture, book reading, homework problems) to help students better grasp the thermodynamic concepts from the class.

## 2.2 | Learning thermodynamics with mechanical objects and problem-solving tasks

The abstract nature of thermodynamics presents challenges to hands-on approaches to instruction. Yet, seeing physical demonstrations of these phenomena with which students hold misconceptions could potentially help illuminate misunderstandings and correct false senses of intuition (Nottis et al., 2010).

One solution to this obstacle is haptic technology. Haptic technology is an emerging technology that has shown potential in enhancing learning of abstract concepts by supporting learners' interactions with multimodal environments. In engineering education, haptic technology has been used in teaching concepts related to "invisible forces" such as magnetism and buoyancy (Kim et al., 2010; Sanchez et al., 2013; Tan et al., 2011; Young et al., 2011) and mechanical properties such as resonance in a dynamic system (Okamura et al., 2002). For example, simulations of van der Waal forces at the nanoscale have been developed to give learners a hands-on experience of phenomena such as "snap to contact," thereby providing a more visceral understanding of the forces at play during atomic force microscopy scanning (Tan et al., 2011).

Moreno and Mayer's (2007) cognitive-affective theory of learning with media (CATLM) supports the notion of such technology's utility in education. This theory considers the learners as sense-makers who select, organize, and assimilate new information with existing knowledge by interacting with learning environments that integrate verbal with non-verbal information. Given that difficulties with thermodynamics comprehension often stem from reliance on misleading colloquialisms in language, a physical (i.e., non-verbal) learning environment could be particularly helpful to mastering thermodynamics. Accordingly, Ogunwuyi (2013) found that higher performing thermodynamics students were more likely to incorporate visual representations into their explanations of concepts, as facilitated by prior interaction with a computer simulation tool in learning thermodynamics. Students also report being more engaged in and visualizing abstract concepts better from learning activities with haptic feedback than without (Jones et al., 2016). However, results on the efficacy of haptic information remains mixed, as not all pre- to post-tests show significant improvements (e.g., Jones et al., 2016).

We hope to further enhance the efficacy of object-based active learning by incorporating the objects into problem-solving tasks, as active learning strategies have shown promise in improving thermodynamics comprehension outcomes in engineering students. For example, Aziz et al. (2014) found that the addition of problem-solving exercises to a third-year undergraduate thermal science curriculum improved learning outcomes relative to students who received only traditional lecture-style instruction (i.e., without problem-solving exercises). Similarly, Cirenza et al. (2018) showed that students regularly engaging in hands-on workshops displayed greater improvements on a thermal concept inventory than students who received only lecture-based instruction. The authors note the resource-intensive nature of this experimental intervention, wherein the workshops were held for one class period each week of the semester, materials were brought in to model thermal processes, and students were split into multiple groups to allow for more individualized attention from instructors and teaching assistants.

In particular, inquiry-based learning has been utilized in thermodynamics education contexts. Inquiry-based activities are similar to problem-solving activities in that they represent a style of active learning in which students interact with phenomena and build their own understanding (Pizzolato et al., 2014). These activities are meant to challenge students to ask and answer questions, make real-world connections, and solve problems.

Nottis et al. (2010) executed inquiry-based activities with a group of 23 undergraduate chemical engineering students. The instructor performed three inquiry-based activities, two of which involved demonstrations using physical objects (boiling liquid nitrogen and comparing heat transfer in block vs. chipped ice) and one that involved computer simulation (heat transfer between two identical metal blocks). On a 10-question heat transfer concept inventory that the authors developed, students showed statistically and practically significant improvements from before to after participating in the activities. The median score improved from 70% to 100%, with mean score improvements on all 10 questions. The authors suggest that the visualization aided in the students' understanding and helped them to clarify concepts such as heat versus energy.

Pizzolato et al. (2014) performed a 6-week open-inquiry activity with 30 mechanical engineering undergraduates, also aimed at improving comprehension of thermodynamics concepts. Open-inquiry activities differ from guided inquiry-based activities, such as that in Nottis et al. (2010), by having the students come up with the questions, rather than the instructor. Although less similar to the problem-solving activities administered in the current study, wherein the instructor posed the questions to be solved, open-inquiry activities share the same active learning and physical demonstration elements as the current study's problem-solving tasks. In Pizzolato et al.'s (2014) activity, students used physical objects in the lab space (e.g., plywood, aluminum sheets, polystyrene boxes) to explore and test hypotheses they had developed related to designing a thermodynamically efficient space base in the Martian environment. As in the Nottis et al. (2010) study, students took an author-developed thermal concept inventory before and after the activity to examine changes in their comprehension of thermodynamics. The authors reported improvements in the students' problem-solving skills and strategies. They also noted that fewer students relied on their intuition in explaining thermal phenomena. The authors did caution that some misconceptions persisted, such as confusion between heat and energy, and that guided inquiry may be more suitable to repairing misconceptions.

Nottis and colleagues performed another inquiry-based learning experiment with undergraduate engineering students to investigate whether computer simulation would prove as effective as physical demonstration in improving thermodynamics learning outcomes (Nottis et al., 2018). Inquiry-based learning activities entail extensive resource dedication, as instructors must be trained and the curriculum modified. When using physical objects to demonstrate phenomena, further resources must be expended to purchase materials and ensure safety. In their activities, which involved steam pipes, sun lamps, cooling beverages, and melting ice, the researchers found that students performing primarily physical experiments showed double the improvements on a thermal concept inventory (on rate vs. amount of heat transferred and thermal radiation) than students using exclusively computer simulations. These results suggest that interacting with physical objects aids in student comprehension of thermal concepts above and beyond active learning.

Our study adds to the debate surrounding the efficacy of haptic feedback in resolving student misconceptions of thermodynamics by testing the value of physical objects in thermodynamics instruction in an active learning context. Similar to the studies detailed above, we administer a pre- to post-test in the form of the Thermo Inventory from the Thermal and Transport Concept Inventory (TTCI; Nelson et al., 2007) to evaluate improvements in thermodynamics comprehension. TTCI's Thermo Inventory consists of questions related to topics covered in the current study's thermodynamics course, such as entropy and internal energy versus enthalpy, while the TTCI's other two inventories (Fluids Inventory and Heat Inventory) pertain to concepts covered in later coursework.

While the objects used in this study are more rudimentary than haptic technology and the active learning strategy less intensive than inquiry-based workshops, we pull from CATLM theory in believing that the objects can enhance student thermodynamics education by promoting integration of non-verbal information into existing knowledge. Problem-solving tasks force students to test assertions they hold and allow new mental connections to form based on the success or failure of the outcomes of those tests. Incorporating physical objects gives students a physical environment in which to test their hypotheses and gives them access to new avenues for knowledge creation. Therefore, the incorporation of mechanical objects into thermodynamics instruction via problem-solving exercises enables students to link abstract thermodynamic concepts with physical phenomena to enhance learning.

## 2.3 | Mechanical aptitude in learning thermodynamics with mechanical objects

Mechanical aptitude can be thought of as an individual's potential for mechanical ability (Snow, 1992), which is a useful construct in the context of mechanical engineering students who are training to reach their highest possible mechanical ability. Aptitude is similar to ability in that it incorporates an individual's cognitive resources, but this construct takes a more multidimensional approach to capturing an individual's capabilities. Aptitude also encompasses motivational and affective capabilities, which include self-regulatory processes, self-efficacy, goal-directed behavior, and persistence in tasks (Shavelson et al., 2002; Snow, 1989). An individual with more aptitude is expected to have more commitment to the task at hand, display more goal-oriented behavior, and better harness their cognitive capabilities toward achievement (Shavelson et al., 2002). These skills are likely relevant to the current study context, for example, to link conceptual lessons from lecture with the physical phenomena playing out in the objects and thereby improve understanding.

Prior studies have supported the notion that mechanical aptitude influences students' learning and performance outcomes (e.g., Bowd, 1973; Brush, 1941). In his meta-analysis on engineering performance, Beard (2015) found that greater mechanical aptitude predicted higher performance on tests. Bairaktarova et al. (2017) demonstrated that engineering undergraduate students with more mechanical aptitude were more successful in a hands-on active learning task. Similarly, Lau and Roeser (2002) found that cognitive and motivational processes together predicted student performance on science tests, and motivational factors predicted the level of engagement in science-related tests, classes, and activities. Therefore, we account for the possibility that aptitude influences performance and learning outcomes by incorporating individual differences in mechanical aptitude into our analyses.

Snow's (1989) theorizing also contends that an individual's aptitude interacts with their situation, which in this case is the study context of presence/absence of mechanical objects in problem-solving tasks. Particularly with thermodynamics concepts being intangible and the problem-solving exercises being self-guided, students higher in mechanical aptitude may be able to more effectively utilize mechanical objects toward grasping the target thermodynamic principles. However, we acknowledge that the simplicity of the objects used in our study and dearth of empirical support for such an interaction effect (e.g., Bairaktarova et al., 2017) undermine this notion. So we leave as an exploratory analysis the test of a moderation effect of mechanical aptitude on the influence of presence/absence of mechanical objects on performance and learning outcomes.

## 2.4 | The current study

The goal of the current study is to investigate whether incorporating physical objects into thermodynamics education by way of problem-solving tasks can enhance student learning. Existing theory and prior empirical work have suggested that object interaction and haptic feedback in active learning contexts can promote learning of abstract thermodynamic concepts, as detailed in our brief review of the literature. Furthermore, studies of student comprehension of difficult thermodynamic concepts such as entropy have revealed that student misconceptions are often perpetuated by colloquial treatment of the concepts in everyday language (Bain et al., 2014; Foroushani, 2019) and that students tend to rely on concrete and visual demonstrations of concepts (Abell & Bretz, 2019; Bennett & Sözbilir, 2007). Therefore, we aim to supplement traditional classroom instruction methods (i.e., lecture, book reading, homework problems) and verbal metaphors with physical illustrations of key concepts.

Prior empirical work that has incorporated physical demonstration into the teaching of abstract concepts such as thermodynamics has often utilized advanced haptic technology or resource-intensive student workshops to do so. Inquiry-based learning in particular has been used to combine physical demonstration with active learning in thermodynamics courses, but obstacles to implementation of such activities include instructor training, money for both materials and training, and curriculum redevelopment (Nottis et al., 2018). The current study extends this research by applying simple, low-priced mechanical objects to student learning of thermal science concepts through student-guided problem-solving tasks.

Using a quasi-experimental design, students from two sections of a third-year undergraduate thermodynamics engineering course were instructed to solve three thermodynamics-related engineering problems throughout the semester, spending 15 min on each task. Both sections participated in the active learning activity, but only one class section had corresponding mechanical objects present—the experimental "objects" group; the other section did not have access to mechanical objects—the control "no-objects" group. The problem-solving tasks required application of thermodynamic concepts taught in recent lectures and thus tested near transfer of knowledge (Moreno & Mayer, 2007). The three problems and corresponding objects are described in detail in Section 4.2 and are included in the Appendix in full. At the beginning of the course, all students completed a test of mechanical aptitude, as well as a concept inventory for thermodynamics in the form of the TTCI (Nelson et al., 2007). TTCI is a test of student understanding of thermodynamics-related concepts identified as both fundamental to and often problematic in the comprehension of thermodynamics. The students took the TTCI again at the end of the course to gauge the extent of thermodynamics knowledge acquired.

The hypotheses guiding this study are as follows:

**Hypothesis 1.** The presence of mechanical objects will facilitate engineering students' performance on thermodynamics-related engineering problems relative to the performance of students who do not have access to the objects.

**Hypothesis 2.** The presence of mechanical objects in engineering students' thermodynamics problem-solving tasks will enhance comprehension of thermodynamics concepts across the semester relative to the students who engaged in the problem-solving tasks without the objects.

We also ask the following question for exploratory purposes:

**Research Question 1.** Will individual differences in mechanical aptitude moderate the effectiveness of giving engineering students access to mechanical objects when solving thermodynamics problems?

## 3 | POSITIONALITY STATEMENT

As the authors of this study, our diverse and complementary backgrounds contribute to the depth and breadth of our research. The first author, a psychology graduate student, brings expertise in research design and quantitative methods, ensuring a methodologically robust and data-driven exploration of the subject. This commitment aligns with our overarching goal of providing a rigorous analysis. The second author, an engineering education researcher and mechanical engineer with extensive industry experience, enriches the study with practical insights that bridge theoretical concepts with real-world applications. Our utilization of "practitioners' rules of thumb" (McGuire, 1983, 1999) underscores the importance of incorporating guidance from industry experts, which in our study is relevant to the utility of mechanical objects. The third author, a faculty member in mechanical engineering, contributes a deep disciplinary knowledge focused on enhancing student learning experiences in energy-related engineering concepts. This expertise is pivotal in providing a comprehensive perspective on the challenges and opportunities within energy-related engineering education.

Our collaborative effort aims to blend science education insights with industry relevance and engineering expertise. We aim to offer a holistic view of the use of tangible mechanical objects in the thermodynamics classroom to enhance students' learning of abstract and difficult concepts. Our emphasis on transparent and reproducible evidence-based practices, along with practice-informed classroom pedagogies, reflects our commitment to high-quality research. With one author with graduate training as an educational researcher, another pursuing a Ph.D. in psychology, and all of us engaged in STEM education research, our combined mid-career and early-career perspectives contribute to a well-rounded and multifaceted study. Additionally, our shared experience in teaching undergraduate students, including two authors who have taught undergraduate engineering thermodynamics, further strengthens the practical implications and relevance of our work.

## 4 | METHOD

### 4.1 | Procedure

Data were collected in the fall 2018 from students in two sections of a third-year undergraduate thermodynamics engineering course, both taught by the same instructor (the third author). The topics for this course included understanding (i) the relationship between work and heat for thermodynamic processes, (ii) the properties of air and water vapor mixtures, and (iii) the fundamentals of entropy and the second law of thermodynamics. At the beginning of the course, all students completed online surveys containing a thermodynamics-related concept inventory, a measure of mechanical aptitude, and demographic information. The surveys were completed during class time on Qualtrics survey management system.

In our quasi-experimental study design, two treatment groups were created according to class section membership: one class section was the experimental group with mechanical objects ("objects group"), and the other class section was the control group without mechanical objects ("no-objects group"). These two conditions pertained to the completion of three thermodynamics-related engineering problem-solving tasks administered across the semester. Each problem tested skills and concepts covered in recent course material. These problems were carefully chosen to represent three different topics (work and heat, psychrometrics, and entropy), where each could potentially benefit from the use of a small and inexpensive object (piston-cylinder, washer, and rubber band), as described below. The problem-solving tasks are provided in full in the Appendix. The objects used in the experimental section were pre-selected and theorized to demonstrate and thus aid in the comprehension of the concept tested in the respective problem-solving task.

The first problem pertained to concepts related to work and heat. Many thermodynamics students struggle in understanding the differences between heat transfer (the movement of energy between substances at different temperatures) and temperature (a measure of the average kinetic energy of atoms or molecules within a substance). Additionally, students often have difficulty with the conversion of mechanical work into thermal energy. With the piston-cylinder, the students could quicky and easily demonstrate that rapid compression of the air inside the piston (mechanical work done on the air) would increase the temperature of the air enough to ignite a small piece of cotton inside the cylinder. Slow compression would not increase the air temperature as much because of a lesser amount of work input to the system, as well as because of more air leakage around the piston and heat transfer through the system. Thus, the simple piston-cylinder arrangement allows for a quick and easy demonstration of the important concepts of temperature, heat transfer, and conversion of mechanical work into thermal energy. This problem involved a situation (work done to compress a gas) that was discussed frequently in the class but was something that most students do not have any real hands-on experience with.

The second problem tested psychrometrics concepts. The area of psychrometrics (the study of atmospheric air, which is a mixture of dry air and water vapor) is another challenging area for students. In this case, the object given to students in the experimental group was a simple metal washer that had been cooled. With the relatively dry air in the room, the washer was not cold enough to condense moisture out of the air. However, with a deep breath of warm and humid air from a student's lungs, it was easy to condense moisture on the washer. The students were given some prompts to try this simple experiment and to discuss their findings. So, this object was chosen as it provided a simple platform to demonstrate key concepts such as condensation, dew point, and humidity. This problem described several situations that most students have encountered, but having the object present allowed students to do several quick experiments to validate their intuition or experience.

The third problem applied concepts related to entropy, or the second law of thermodynamics. The experimental group students were given a typical rubber band. Entropy is a notoriously difficult concept to understand, but it can be thought of as a measure of the disorder in a system. A simple unstretched rubber band is made up of long polymer chains that are tangled together, meaning they are disordered and have a high degree of entropy. When the rubber band is stretched, the polymer chains become partially aligned and the entropy decreases. These entropy changes are accompanied by small but observable changes in temperature. By stretching and releasing the rubber band while it is in contact with the back of one's hand or lips, this temperature change is easily detectable by the human body without the need for a specialized temperature sensor. Thus, we chose the rubber band because it is a simple object that students are familiar with, yet it easily illustrates the relationships between disorder, entropy, and heat transfer. This rubber band corresponded to the description of rubber as a polymer with long molecular chains as described in the problem statement. This problem gave an example of a complex topic (entropy) with a simple example involving a familiar object (a rubber band), but in a context (sensing heat released or absorbed using one's skin or lips) that would be new to most students.

All students individually solved the same three problems, spending approximately 15 min of class time on each task. The use of quasi-experimental brief interventions has been seen in educational research (e.g., Lin & Powell, 2023; Strunk, 2012; Wisman et al., 2019) and is more common in psychological research, for example, in the treatment of self-injurious behaviors (see Dobias et al., 2023 for a review), substance abuse (Center for Substance Abuse Treatment, 1999), and anxiety and depression (see Roach et al., 2023 for a review). For the control section, the instructor simply handed each student the problem statement sheet. For the experimental section, the instructor and a graduate student first handed out the object corresponding to that problem, followed by a sheet of paper with the problem printed on it. The experimental group students were not given any direct instructions on how to use the object, but each problem statement contained some description of a situation where use of the object would be rather obvious.

In general, the vast majority of students handled the objects. In the first problem, the students compressed the piston, and many students compressed it several times while attempting to ignite the cotton inside the cylinder. Again, with the rubber band in the second problem, nearly all the students stretched the rubber band multiple times while holding it next to their cheek or lips to get a sense of the temperature change. For the washer in the third problem, while most students used the washer as we intended, some did not handle it. For this task, we assumed that students had some previous experience with similar situations, thus they may have relied on their prior knowledge rather than using the washer.

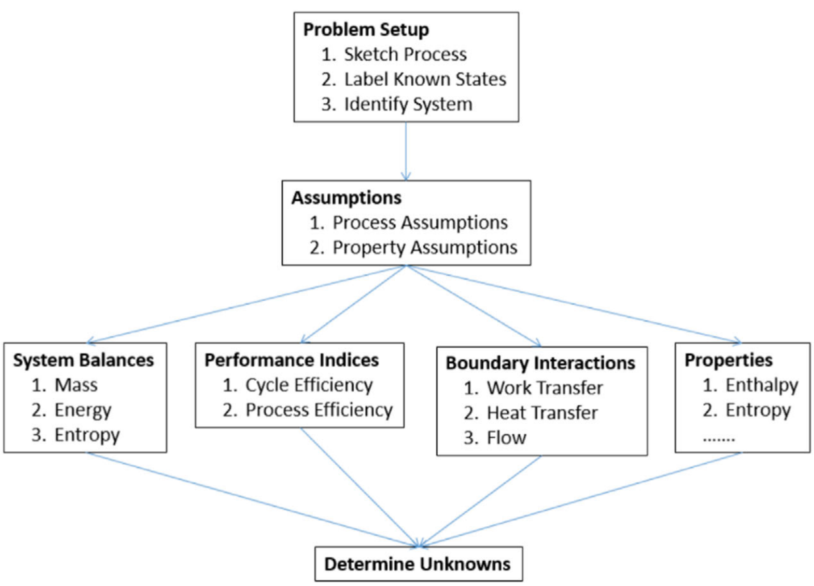
Students' problem solutions were collected and graded with a rubric by two graduate teaching assistants blind to the treatment conditions. The rubric was developed following the systematic seven-step thermodynamics problem-solving procedure described in Reardon (2001). This procedure and the current study's rubric are shown in Figure 1. Grades from the problem-solving activities for the research study were used for research purposes only and were not included in the calculation of the students' final grades in either section. Additionally, in a follow-up course the next semester, we had one class period where all students were introduced to the objects in problem-solving activities to ensure all students were offered the same learning opportunities. We also offered a follow-up workshop in that semester where all students who were interested could interact and use objects in problem-solving settings.

At the end of the semester, students re-took the same concept inventory that they had completed at the beginning of the semester for comparison purposes.

## 4.2 | Measures and materials

### 4.2.1 | Thermodynamics-related engineering problems

Each thermodynamics problem-solving task tested skills and concepts covered in recent course material. Thus, the problems tested near transfer of knowledge, meaning transfer between very similar but not identical contexts (Moreno & Mayer, 2007). The topics selected were identified in the literature as conceptually difficult for students to understand: work and heat, psychrometric applications, and the second law of thermodynamics. Accordingly, the first problem focused on pistons, the second on psychrometry, and the third on entropy. The first problem was designed to demonstrate that work done on a gas (compressing the gas) can be converted to heat. The second problem showed the




| Procedure | Max Points |
|---|---|
| Problem Setup | 3 |
| Assumptions | 2 |
| System Balance | 3 |
| Performance Indices | 2 |
| Boundary Interactions | 3 |
| Properties | 2 |
| Determine Unknowns | 2 |

FIGURE 1 Thermodynamics problem-solving procedure and grading rubric.

relationship between temperature and condensation for moist and dry air. The third problem illustrated how entropy in a simple system is related to heat transfer.

The respective mechanical objects to aid the experimental group in solving these three problems were a handheld piston-cylinder arrangement (for work and heat), a cold metal washer (for psychrometry), and a rubber band (for entropy). The piston-cylinder was chosen to physically demonstrate the relationship between work input and heat, as the rapidly compressed piston generated enough heat to ignite a small cotton sample. Although simple, the cold metal washer could be used to illustrate condensation of moist air (e.g., moist air from one's breath). The rubber band gave a useful example of the relationship between the heat transfer associated with the decrease in entropy of a system.

Students' problem solutions were collected and graded by two graduate teaching assistants blind to the treatment conditions, using a rubric developed according to Reardon's (2001) thermodynamics problem-solving steps. The first problem was scored out of 60 points, and the second and third were scored out of 40 points each.

### 4.2.2 | Thermodynamics-related concept inventory

Students completed the TTCI (Nelson et al., 2007) as a measure of their conceptual understanding of thermodynamics concepts. We administered the latest version of the TTCI, version 3.04 (Miller et al., 2011). This test targets important concepts in thermal and transport sciences (i.e., thermodynamics, fluid mechanics, and heat transfer) with which students often have fundamental misconceptions (Streveler et al., 2003). The test was developed by first identifying common student misconceptions in a Delphi study performed by expert engineering faculty (Streveler et al., 2003). Since its inception, it has undergone psychometric analysis, tests of validity in multiple studies, and redevelopment (Douglas & Purzer, 2015; Streveler et al., 2011). Only questions from the Thermo Inventory subscale were administered to the students, containing 17 questions related to the topics covered in the current course, such as entropy and internal energy versus enthalpy. We did not use any questions from the other two subscales, that is, the Heat Inventory and the Fluids Inventory, as these topics are studied in courses that students take after they complete the thermodynamics course (in heat transfer and fluid dynamics courses, respectively).

### 4.2.3 | Mechanical aptitude test

Mechanical aptitude reflects one's potential for mechanical ability and incorporates cognitive and motivational individual differences (Snow, 1992). Students were administered Bairaktarova and Reeping's (2019) mechanical aptitude test (MAT). The test contains 17 multiple-choice questions, but we dropped 3 questions for reasons outlined in Section 4.5. This 14-question version of the MAT used in our analyses had an internal consistency, as measured by Cronbach's-$\alpha$, of .64.

## 4.3 | Participants

The student participants were taking a thermodynamics engineering course at a large university in the southern United States. The course was meant to be taken by undergraduate mechanical engineering majors in their third year. As such, the vast majority of students were undergraduates in their third year (91.6%; 7.6% were in their fourth year and 0.8% were graduate students), and all were majoring in mechanical engineering.

One-hundred and twenty-seven students took part in the study. Four students who did not complete any thermodynamics problem-solving tasks were removed from statistical analyses, as they effectively did not participate in the study. Of the remaining 123 students, 4 did not complete the MAT and were subsequently removed because of the inclusion of mechanical aptitude in all statistical analyses.

Thus, the final sample contained 119 students ($N = 119$). As 126 students completed the course, this represents a 94.4% response rate. The objects (i.e., treatment) group contained 61 participants (51.3% of the total sample) and the no-objects (i.e., control) group contained 58 participants (48.7% of the total sample). Ninety-five students (79.8%) completed all three thermodynamics problems, 22 students (18.5%) did two of three, and three students (2.5%) did just one of three problems.

Of the final sample, 91 students (76.5%) were men and 28 students (23.5%) were women; the proportions were similar within each experimental condition (80.3% men, 19.7% women in the objects group; 72.4% men, 27.6% women in the no-objects group). The sample was predominantly White, with remaining students being Asian, Black, and of other ethnicity; the experimental conditions each contained a similar makeup of students.

## 4.4 | Statistical analyses

Hypothesis 1 was tested primarily using mixed modeling, which enabled analysis of all three thermodynamics problems simultaneously in relation to treatment group (i.e., objects vs. no-objects). Mixed modeling is a powerful and flexible form of linear regression that accounts for complexities in the data collected, as outlined below.

First, the data collected were repeated-measures data, with each student completing a thermodynamic problem at three time points. The scores of these problems represent three measurements of the outcome variable from a single subject, making the data multilevel in nature (Cohen et al., 2003). Multilevel data, sometimes called clustered data, contain multiple observations arising from a single source (Hedeker & Gibbons, 1994)—in this case, the student. The consequent dependency in the three data per student violates the independence assumption in linear regression and would introduce biased standard errors into an ordinary regression analysis. Mixed modeling, however, accounts for this dependency by allowing inclusion of the clustering agent (in our case, the student) as a random effect.

Second, given that completion of all three thermodynamics problems relied on students attending all three respective lectures, many students completed only a subset of the three problems. Unlike mixed ANOVA, which removes a student from analysis given any missingness (i.e., performs listwise deletion), mixed modeling retains a greater proportion of the data by including students with at least one measurement on the outcome variable.

Third, aggregating this data (i.e., averaging the problem-solving scores such that each participant now corresponds to a single measure of the dependent variable) would result in data loss. By collapsing variation into a single aggregated value, aggregation analyses assume that the amount of change at each measurement point is the same, which is often not the case (Cohen et al., 2003). This type of analysis also makes assessing the impact of problem identity on participant outcomes impossible.

To avoid sacrificing this information due to aggregation while also accounting for the complexities in our data, we employed a mixed model to test our first hypothesis, that is, the presence of mechanical objects would facilitate problem-solving performance. We specified the student as a random effect and converted the thermodynamics scores into percentages to give all three measures of this outcome variable the same scale. We included the problem identity (as a categorical variable) and interaction term between treatment condition and problem identity as predictors to account for variation due to the difference in both course topics covered and mechanical objects used in solving the problems. We also added mechanical aptitude as a covariate to account for between-group differences, as explained in Section 5.1.

In addition to testing the impact of mechanical object availability on problem-solving performance using mixed modeling, we also evaluated this relationship using univariate ANCOVA. In this analysis, we tested the three thermodynamics problems separately in relation to treatment group, controlling for mechanical aptitude. These tests account for the possibility that certain mechanical objects are more effective in aiding certain thermodynamics problems while accounting for the different number of participants who completed each problem.

Hypothesis 2, which evaluated the impact of treatment condition on improvement in thermodynamics comprehension, was tested using univariate ANCOVA. The end-of-semester TTCI score was entered as the dependent variable. The predictors were treatment condition as a fixed factor and beginning-of-semester TTCI score and mechanical aptitude as covariates due to their continuous nature.

Research Question 1, which investigated whether mechanical aptitude moderated the efficacy of object-based learning in the form of thermodynamics problem-solving and improvement in thermodynamics comprehension, was evaluated by adding the interaction between mechanical aptitude and experimental condition as a predictor to the respective models from Hypotheses 1 and 2.

We ran all analyses in IBM SPSS (Version 27.0.1.0).

## 4.5 | Measurement of mechanical aptitude

The MAT was developed primarily with samples of first-year engineering students (Bairaktarova & Reeping, 2019), but our sample of third-year mechanical engineering students likely had a different experience taking the test given their gained experience and knowledge. Heeding Douglas and Purzer's (2015) admonition that assessments may operate differently in different settings, we evaluated the performance of MAT in our sample. The results of a confirmatory factor analysis (CFA) of a one-factor model indicated adequate model fit ($\chi^2[119] = 120.81$; RMSEA = .01; CFI = .97; SRMR = .15), but three items loaded very poorly (i.e., non-statistically significantly) onto the one factor shown to underlie the instrument in its initial development (Bairaktarova & Reeping, 2019).

Taking a closer look at these three items, we found that one item (related to spatial manipulation of an object) was presented with ambiguous wording, inconsistent with the instrument's validated text. Possibly due to this discrepancy, only 12% of respondents answered this question correctly, which is lower than the recommended 20% threshold (Jorion et al., 2015). The other two items (related to the definition of an ampere and to the measurement depicted in a figure) were answered correctly by 96.6% and 91.6% of participants, respectively, both at rates above the recommended 80% threshold. The high incidence of correct responses for these two questions could stem from the discrepancy in tenure between the samples in the current study and in the instrument's original validation study. Therefore, in line with Douglas and Purzer's (2015) recommended developmental approach to assessments, we revised the MAT for our third-year cohort to exclude these three items. In the resulting version of the MAT, a CFA showed that all 14 items loaded onto the same factor and produced adequate model fit ($\chi^2[77] = 80.40$; RMSEA = .02; CFI = .95; SRMR = .14).

# 5 | RESULTS

## 5.1 | Descriptive results

We checked the data for univariate outliers by computing the z-scores of the focal variables. We found one z-score in the third thermodynamics problem that exceeded the 3.29 threshold recommended by Tabachnick and Fidell (2001, p. 67). Accordingly, we removed this value from the dataset. Computation of the Mahalanobis distance did not indicate any multivariate outliers in the data.

Correlations, means, standard deviations, and internal consistencies are shown in Table 1. Because mechanical aptitude was associated with both outcomes tested in this study (i.e., problem-solving task scores and TTCI scores), we included mechanical aptitude as a covariate in all hypothesis tests to control for the potential for between-group discrepancies.

## 5.2 | Hypothesis 1

Our main hypothesis is not supported for the data as a whole, as the overall mixed model does not indicate support for the presence of objects relating to student performance on thermodynamics problems ($F = 4.08$, ns). Table 2 displays these statistical test results for the impact of the objects treatment on thermodynamics problem-solving performance. However, we do observe a statistically significant simple main effect for the impact of the treatment condition on problem-solving performance in specifically Task 3. Table 3 shows these simple main effects, which measure the effect at specific values (in this case, tasks; UCLA: Statistical Consulting Group, 2021), along with the predicted percentage

**TABLE 1** Descriptive statistics: Means, standard deviations, and bivariate correlations among study variables.

| | *M* | SD | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|
| 1. Objects group | – | – | – | | | | | |
| 2. Mechanical aptitude | 10.84 | 2.33 | −.15 | – | | | | |
| 3. Task 1 | 64.74 | 15.42 | −.02 | .45** | – | | | |
| 4. Task 2 | 79.26 | 17.99 | .05 | .24* | .29** | – | | |
| 5. Task 3 | 79.34 | 14.98 | .15 | .08 | .16 | .20* | – | |
| 6. TTCI pre-test | 5.70 | 2.57 | −.14 | .31** | .33** | .17 | .19* | – |
| 7. TTCI post-test | 7.82 | 3.01 | .08 | .37** | .40** | .19* | .16 | .45** |

*Note*: $N = 119$ participants. The objects group variable is coded such that 0 refers to the no-objects group and 1 refers to the objects group. Task scores are shown in terms of percentage points.

Abbreviation: TTCI, Thermal and Transport Concept Inventory.

*$p < .05$; **$p < .01$.

TABLE 2 Mixed model results of problem-solving task performance.

| | $F$ | $p$-Value |
|---|---|---|
| Intercept | 132.90 | <.001 |
| Objects group | 2.56 | .112 |
| Mechanical aptitude | 19.74 | <.001 |
| Task identity | 37.64 | <.001 |
| Objects group × task identity | 1.03 | .358 |

*Note*: $N = 119$ participants.

TABLE 3 Estimated percentage scores and simple effects of treatment condition on each problem-solving task from the mixed model results.

| | | Group $M$ | $M$ Dif | $F$ | $p$-Value |
|---|---|---|---|---|---|
| Task 1 | Objects | 64.83 | .36 | .02 | .904 |
| | No-objects | 64.47 | | | |
| Task 2 | Objects | 80.91 | 3.21 | 1.16 | .282 |
| | No-objects | 77.69 | | | |
| Task 3 | Objects | 82.21 | 5.96 | 3.93 | .048 |
| | No-objects | 76.25 | | | |

*Note*: $N = 119$ participants. Estimates are derived at a MAT score of 10.77. Each $F$-test evaluates the simple effects of the treatment condition (i.e., objects group vs. no-objects group) within each task relative to the other effects; these evaluations are derived from the linearly independent pairwise comparisons among the estimated marginal means.

TABLE 4 Results of statistical analyses for the individual problem-solving tasks.

| | Task 1 | | Task 2 | | Task 3 | |
|---|---|---|---|---|---|---|
| | $F$ | $p$-Value | $F$ | $p$-Value | $F$ | $p$-Value |
| Intercept | 26.61[a] | <.001 | 55.21[b] | <.001 | 112.54[c] | <.001 |
| Objects group | .13 | .719 | .88 | .350 | 2.94 | .089 |
| Mechanical aptitude | 27.24 | <.001 | 7.21 | .008 | 1.20 | .276 |

[a]$N = 109$ participants.
[b]$N = 111$ participants.
[c]$N = 109$ participants.

score of each thermodynamics problem by treatment group. As illustrated in Table 3, the average predicted score for the objects group is higher than that for the non-objects group in each problem-solving task.

We also examined our research question in relation to each thermodynamics problem individually using ANCOVA, as the objects might be differentially effective in helping students to solve the problems, just as certain thermodynamic concepts might be more receptive to object-based aid. Results of statistical tests are shown in Table 4, and the estimates for each task by treatment condition are shown in Table 5. The treatment condition appears to have a larger impact with each passing problem. Controlling for variation in mechanical aptitude, the difference in estimated mean percentage scores between groups is .97 for the first thermodynamics problem, 3.17 for the second, and 4.94 for the third. In each case, the group with objects has a higher mean score. However, the results do not reach statistical significance for any task when analyzing them separately.

## 5.3 | Hypothesis 2

Tables 6 and 7 show the results for the impact of this object-based learning strategy on student comprehension of thermodynamics concepts. The results show a greater improvement in TTCI scores across the semester for students in the

TABLE 5 Estimated individual problem-solving task percentage scores.

| | Objects group | | No-objects group | |
|---|---|---|---|---|
| | Mean | SE | Mean | SE |
| Task 1 | 65.21[a] | 1.86 | 64.24[a] | 1.91 |
| Task 2 | 80.80[b] | 2.34 | 77.63[b] | 2.41 |
| Task 3 | 81.78[c] | 2.02 | 76.84[c] | 2.04 |

Abbreviation: SE, standard error.
[a] $N = 109$ participants. Estimates are derived at a MAT score of 10.82.
[b] $N = 111$ participants. Estimates are derived at a MAT score of 10.72.
[c] $N = 109$ participants. Estimates are derived at a MAT score of 10.77.

TABLE 6 Results of statistical analyses for TTCI post-test scores.

| | $F$ | $p$-Value |
|---|---|---|
| Intercept | 1.12 | .268 |
| Objects group | 4.64 | .033 |
| Mechanical aptitude | 11.62 | <.001 |
| TTCI pre-test | 21.27 | <.001 |

*Note*: $N = 119$ participants.
Abbreviation: TTCI, Thermal and Transport Concept Inventory.

TABLE 7 Estimated TTCI post-test scores.

| Objects group | | No-objects group | |
|---|---|---|---|
| Mean | SE | Mean | SE |
| 8.32 | .33 | 7.29 | .34 |

*Note*: $N = 119$ participants. Maximum TTCI score is 17. Estimates are derived at a TTCI pre-test score of 5.70 and MAT of 10.84.
Abbreviation: TTCI, Thermal and Transport Concept Inventory.

TABLE 8 TTCI pre- and post-test raw score averages by treatment condition.

| | Objects group | | No-objects group | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| TTCI pre-test | 5.34 | 2.56 | 6.07 | 2.55 |
| TTCI post-test | 8.03 | 3.24 | 7.57 | 2.76 |

*Note*: $N = 61$ participants in the objects group; 58 participants in the no-objects group. Maximum TTCI score is 17.
Abbreviation: TTCI, Thermal and Transport Concept Inventory.

objects group relative to students in the no-objects group ($F = 4.64$, $p < .05$). As shown in Table 7, controlling for TTCI pre-test and MAT scores, the average TTCI post-test score for students in the objects group is 1.03 points (out of a maximum score of 17) higher than for no-objects students. In fact, looking at the group means alone (i.e., without covariates) in Table 8, the objects group has a lower mean TTCI score than the no-objects group in the pre-test but a higher TTCI score than the no-objects group in the post-test.

## 5.4 | Supplemental analysis

We also investigated which topics within thermodynamics students experienced the most progress in conceptual understanding by evaluating pre- to post-TTCI score changes by conceptual category. Table 9 displays these results, with

**TABLE 9** TTCI improvements by question content category.

| | Proportion improved | | |
|---|---|---|---|
| **Category** | **Total sample** | **No-objects group** | **Objects group** |
| Internal energy versus enthalpy | 1.51 | 1.16 | 2.03 |
| Ideal gas law | 1.39 | 1.17 | 1.57 |
| Conservation of mass | 1.20 | 1.24 | 1.17 |
| Entropy | 1.62 | 1.46 | 1.82 |
| Steady state versus equilibrium | 1.09 | 0.91 | 1.33 |

*Note*: The proportion improved represents the proportion of the group who answered the question correctly in the post-test divided by the proportion who answered the question correctly in the pre-test. Therefore, a value of 2.00 indicates that double the number of group members answered the question correctly in the post-test than in the pre-test. A value below 1 indicates that fewer group members answered the question correctly in the post-test than in the pre-test.

categories representing the thermal topics most relevant to the question content (Miller et al., 2011). Although the total sample of students shows improvements across all categories, the students overall show the largest improvements in questions related to internal energy versus enthalpy and entropy. Internal energy versus enthalpy questions relate to both the work and heat problem (as internal energy is a heat of reaction at a constant volume, and enthalpy is a heat of reaction plus pressure-volume work at constant pressure) and to the psychrometrics problem (as it studies the thermodynamic properties of air–vapor mixtures, focusing on the interrelation among temperature, partial pressures, and enthalpy). Entropy questions, of course, relate to the entropy problem.

Regarding differences in performance improvements between the experimental and control groups, improvements by students in the objects group outpace those of the no-objects group in four of five categories. The most substantial improvements in the objects group relative to the no-objects group are in the internal energy versus enthalpy category, which relates to two of the tasks as described above, as well as in the steady state versus equilibrium category, which incorporates elements from all three problems. For example, we evaluate work and heat when equilibrium is reached at the individual states, equilibrium of states at inlets and exits is important for psychrometrics, and knowing whether a system is in steady state is necessary to solve for entropy generation to determine if a process is possible.

### 5.5 | Research Question 1

We explored how the presence of objects might affect learning outcomes differently for students with varying levels of mechanical aptitude. We ran the mixed models from Hypotheses 1 and 2 with the additional predictor of the interaction between mechanical aptitude and experimental condition. We found support for a moderating effect between mechanical aptitude and treatment condition on TTCI improvements ($F = 4.93$, $p < .05$) but not on problem-solving performance ($F = .12$, ns). These results are displayed in Table 10.

## 6 | DISCUSSION

All students in the current study received an active learning intervention in the form of three problem-solving tasks, yet the students who also had access to physical objects displayed greater thermodynamics comprehension than the students who only solved the problems (i.e., without objects). The objects group (i.e., the students with access to objects) outperformed the no-objects group in all three problem-solving tasks, and to a statistically significant degree in the third task. The objects group also showed enhanced comprehension across a semester relative to the no-objects group in the form of statistically significant greater improvements in their TTCI scores. These conceptual improvements in the objects group outpaced those of the no-objects group across four of five content categories covered in the TTCI Thermo Inventory.

The intervention used in the current study to improve thermodynamics comprehension is one that is easy to implement, especially relative to other hands-on interventions focused on thermodynamics education. The current intervention entailed three on-paper, student-guided problem-solving tasks in combination with three simple objects—

TABLE 10 Mixed-model results of problem-solving task performance and TTCI improvements.

| | Task performance | | TTCI post-test scores | |
|---|---|---|---|---|
| | *F* | *p*-Value | *F* | *p*-Value |
| Intercept | 133.43 | <.001 | 2.11 | .150 |
| Objects group | .57 | .450 | 2.94 | .089 |
| Mechanical aptitude | 18.15 | <.001 | 9.94 | .002 |
| Task identity | 37.84 | <.001 | | |
| Objects group × task identity | 1.05 | .353 | | |
| TTCI pre-test | | | 22.46 | <.001 |
| Mechanical aptitude × objects group | 1.25 | .267 | 4.93 | .028 |

*Note*: $N = 119$ participants.
Abbreviation: TTCI, Thermal and Transport Concept Inventory.

piston-cylinder, washer, and rubber band—that encompassed just 45 min of time across the semester (15 min per task). The brevity of these activities makes them feasibly incorporable into existing thermodynamics curricula. The materials needed are inexpensive and the procedure is easy to implement and does not require additional training or instruction, also contributing to the practicality of this intervention. In contrast, while successful in improving learning outcomes, Cirenza et al. (2018) proposed a hands-on thermal workshop that required teaching assistants, a full class period each week of the semester, and special materials. The hands-on activities performed by Pizzolato et al. (2014) and Nottis et al. (2018) similarly required more elaborate materials than in the current study (e.g., plywood, steam pipes), as well as specific training and curriculum modification. Thus, the current intervention presents novelty and utility in its cost effectiveness, ease of implementation, and time efficiency.

The object-based intervention provided students with haptic feedback, which we reasoned would be particularly effective for thermodynamics education. According to CATLM (Moreno & Mayer, 2007), students learn by integrating verbal with non-verbal information from their learning environment. However, because thermodynamics is abstract and plays out at the non-observable microscopic level, students have tended to rely on verbal interpretations of thermodynamic principles (Bain et al., 2014). Doing so has perpetuated misconceptions with the fundamentals of this field because use of the concepts in everyday language is often misleading (Bain et al., 2014; Foroushani, 2019). The haptic feedback received from interacting with our targeted physical demonstrations of thermodynamic phenomena gave students a new landscape of information, a physical (i.e., non-verbal) learning environment that likely helped clarify their misconceptions of thermodynamic fundamentals.

An improved understanding of thermodynamics at its core could explain how we observed broad improvements in the objects group over the no-objects group. The objects group showed greater improvements in four of five content categories covered in the TTCI Thermo Inventory. Furthermore, according to TTCI scores, the objects group began the semester with a lesser understanding of thermodynamics concepts than the no-objects group but ended the semester with a greater understanding. We similarly observed a growing discrepancy in problem-solving performance between the objects and no-objects group across the semester, whereby the objects group scored higher than the no-objects group by a wider margin in each subsequent task. This growing margin of difference could be attributed to a successively better grasp of thermodynamic fundamentals across the semester. Alternatively, this finding partially aligns with our theorizing that objects would be particularly beneficial in solving abstract and difficult problems, as the third problem-solving task surrounded entropy and was the most abstract and difficult of the three tasks. However, contrary to this theorizing, the work and heat task scores showed less between-group difference than the psychrometry task scores despite covering more abstract material.

Finally, our data indicate that a higher mechanical aptitude enhanced the beneficial effect of object availability on thermodynamics comprehension gains. Namely, objects-group students with higher mechanical aptitude improved their TTCI scores more than those with lower mechanical aptitude. Aptitude may have been particularly relevant to the current study given that students received little guidance in how to utilize the objects in solving the assigned tasks and that thermodynamics concepts are intangible. Snow's (1989) theorizing suggests that students higher in mechanical aptitude would be better equipped to direct their cognitive resources toward linking the macro-level phenomena they are seeing to the underlying thermodynamic fundamentals. Factors outside of cognitive ability such as self-efficacy in making conceptual connections, the drive to persist in challenging tasks, and goal-directed behavior likely also play important roles in learning and performance outcomes (Lau & Roeser, 2002; Shavelson et al., 2002). We encourage educational researchers to examine whether the multidimensional view of the learner taken by aptitude is useful toward understanding how students learn from active learning exercises and acquire abstract knowledge.

## 6.1 | Limitations and future directions

Questions implied by the results of our study present avenues for future research. Although our results indicate that objects are useful in acquiring thermodynamics knowledge, information remains unknown regarding *why* the objects helped. Our finding that mechanical aptitude bolstered the TTCI improvements in objects-group students suggests that how the students interacted with objects played a role in their conceptual understanding of thermodynamics. Given the lack of guidance surrounding how to handle the objects, students higher in mechanical aptitude may have utilized the objects more productively toward gaining insight into the underlying thermodynamic principles controlling the observed phenomena. However, this role of mechanical aptitude in successfully making thermodynamic inferences from physical objects is speculative, resting on Snow's theorizing that motivational and temperamental factors help students to apply their cognitive resources toward challenging intellectual tasks (Shavelson et al., 2002; Snow, 1989, 1992). The current study did not collect data on student motivation and temperament, nor did we collect data on how students interacted with the objects (e.g., we did not measure how many students used the objects or for how long). Therefore, we suggest that future investigations explore the role of mechanical aptitude and its subfacets in enhancing student comprehension of complex topics through active learning. Additionally, future studies that involve student handling of objects could record experimental sessions in order to quantify person–object interactions, allowing for nuanced examination of these research questions.

The objects selected to accompany the problem-solving tasks were chosen based on theory rather than on prior empirical testing. The accompanying problems were also devised to apply to a range of thermal concepts, making mapping the objects to specific gains in concepts difficult. Other objects could be studied in relation to the concepts covered in these problem-solving tasks (i.e., work and heat, psychrometry, and entropy) as well as in relation to other abstract engineering concepts. Through comparative analyses of different objects, researchers may be able to uncover what features an object requires to be useful to problem-solving performance and improving conceptual understanding.

The problem-solving tasks themselves encompassed just 45 min of time across the semester (15 min per task). Although the brevity of these activities makes them more easily implemented in thermodynamics curricula, longer activities may prove more beneficial to learning outcomes. The hands-on workshops described in the literature review were generally much longer, with one filling an entire class period each week (Cirenza et al., 2018) and another totaling to about 40 h across 6 weeks (Pizzolato et al., 2014). Future studies could administer more and longer problem-solving tasks and entail stricter participation to enable a more thorough investigation of whether more experience in solving problems with objects gradually improves a skill in applying objects to solving problems and gaining understanding, as the cognitive perspective of learning would suggest.

In their influential editorial on instrument validity in engineering education research, Douglas and Purzer (2015) asserted that "the process of reevaluating the appropriateness of an instrument's use is ongoing," particularly in the context of education-related assessments (p. 111). The current study used the MAT in a third-year sample, a more educated group than was used to finalize the MAT (Bairaktarova & Reeping, 2019), which could threaten the instrument's validity in the current context. Unfortunately, this study's sample size was insufficient to perform the steps necessary for a thorough re-evaluation of the assessment, such as cross-validation. Therefore, we note the potential limitations in instrument validity stemming from our more educated sample and our test modification (i.e., dropping three questions) based on our 119-student sample size. Heeding Douglas and Purzer's (2015) message of ongoing, developmental validity for assessments in engineering education, we encourage future researchers to validate the MAT in other settings, especially for more experienced engineering student samples.

Finally, our data contain some missingness, as just under 80% of participants completed all three problems. Future studies could examine more variation with respect to the sample, too. Our sample was comprised of 119 mostly mechanical engineering third-year undergraduate students. In addition to including more participants, other samples would ideally contain a larger proportion of women. We refrained from investigating gender differences because of our sample only including 28 women and our questionnaire assuming a binary gender construct, which is an additional limitation of our study. In an effort to reduce bias and increase inclusivity, we encourage researchers to refrain from conflating gender with sex and to acknowledge a range of gender identities.

## 7 | SUMMARY

This study provides support for the incorporation of object-based learning into thermodynamics curricula. Thermodynamics is a field with which engineering students traditionally struggle because of its abstract nature and commonly held misconceptions related to fundamental thermal concepts such as heat, energy, and temperature (Streveler et al., 2003; Streveler et al., 2008). Prior research has indicated that haptic feedback can aid in student comprehension of abstract concepts (Jones et al., 2016) and that hands-on active learning workshops can improve understanding of thermodynamics concepts (e.g., Cirenza et al., 2018; Pizzolato et al., 2014). However, haptic technology can be expensive and hands-on workshops can require significant resource investment (Nottis et al., 2018).

Our findings indicate that incorporating relevant and simple physical objects into student-guided problem-solving tasks may enhance students' problem-solving performance over time as well as their understanding of thermodynamics concepts. Students with simple objects available for aid in solving thermodynamics problems displayed greater pre- to post-test improvements in a thermal concept inventory relative to their peers without objects. Students with objects also scored higher than their peers without objects in three problem-solving tasks, with the gap between the two groups growing across the semester.

Based on these findings, we recommend that engineering educators extend their application of object-based learning to thermodynamics curricula. Our results indicate that availability of relevant objects and an aptitude for manipulating objects enhance comprehension of abstract thermodynamics concepts and their application to problem-solving tasks. Additionally, students who had objects available outpaced their no-objects peers in problem-solving performance to a greater extent as the semester progressed. Engineering education researchers can explore in future studies which objects and which methods of interaction with objects best facilitate learning of particular thermodynamics concepts. Our study contributes to an ongoing debate surrounding the value of haptic feedback in learning abstract concepts by supporting the notion that physical objects—even simple, accessible ones—can facilitate thermodynamics comprehension.

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### REFERENCES

Abell, T. N., & Bretz, S. L. (2019). Macroscopic observations of dissolving, insolubility, and precipitation: General chemistry and physical chemistry students' ideas about entropy changes and spontaneity. *Journal of Chemical Education*, *96*(3), 469–478. https://doi.org/10.1021/acs.jchemed.8b01007

Aziz, M. S., Zain, A. N. M., Samsudin, M. A. B., & Saleh, S. B. (2014). The impact of PBL on undergraduate physics students' understanding of thermodynamics. *International Journal of Academic Research in Economics and Management Sciences*, *3*(4), 126-137. https://doi.org/10.6007/IJAREMS/v3-i4/1088

Bain, K., Moon, A., Mack, M. R., & Towns, M. H. (2014). A review of research on the teaching and learning of thermodynamics at the university level. *Chemistry Education Research and Practice*, *15*(3), 320–335. https://doi.org/10.1039/C4RP00011K

Bairaktarova, D., Graziano, W., & Cox, M. (2017). Enhancing engineering students' performance on design task: The box of parts. *Journal of Mechanical Design*, *139*(5), 052001-1-9. https://doi.org/10.1115/1.4036128

Bairaktarova, D., & Reeping, D. (2019). Development and psychometrics of a freely available mechanical aptitude test. *The International Journal of Engineering Education*, *35*(6), 1839–1850. https://www.ijee.ie/1atestissues/Vol35-6A/22_ijee3849.pdf

Baker, L. R. (2006). On the twofold nature of artefacts. *Studies in History and Philosophy of Science Part A*, *37*(1), 132–136. https://doi.org/10.1016/j.shpsa.2005.12.014

Balmer, R. T. (2011). *Modern engineering thermodynamics—Textbook with tables booklet*. Academic Press.

Beard, M. W. (2015). *Correlates of engineer job performance: A meta-analysis* (Master's thesis). North Carolina State University. https://repository.lib.ncsu.edu/bitstream/handle/1840.16/10826/etd.pdf

Bennett, J. M., & Sözbilir, M. (2007). A study of Turkish chemistry undergraduates' understanding of entropy. *Journal of Chemical Education*, *84*(7), 1204-1208. https://doi.org/10.1021/ed084p1204

Bowd, A. D. (1973). A cross-cultural study of the factorial composition of mechanical aptitude. *Canadian Journal of Behavioural Science/Revue Canadienne Des Sciences du Comportement*, *5*(1), 13–23. https://doi.org/10.1037/h0082324

Brush, E. N. (1941). Mechanical ability as a factor in engineering aptitude. *Journal of Applied Psychology*, *25*(3), 300–312. https://doi.org/10.1037/h0053635

Center for Substance Abuse Treatment. (1999). *Brief interventions and brief therapies for substance abuse: Treatment improvement protocol (TIP) series* (No. 34). US Department of Health and Human Services. https://www.ncbi.nlm.nih.gov/books/NBK64950/

Cirenza, C. F., Diller, T. E., & Williams, C. B. (2018). Hands-on workshops to assist in students' conceptual understanding of heat transfer. *Journal of Heat Transfer*, *140*(9), 092001-1-10. https://doi.org/10.1115/1.4039759

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2003). *Applied multiple regression/correlation analysis for the behavioral sciences* (3rd ed.). Routledge.

Dobias, M. L., Chen, S., Fox, K. R., & Schleider, J. L. (2023). Brief interventions for self-injurious thoughts and behaviors in young people: A systematic review. *Clinical Child and Family Psychology Review*, *26*(2), 482–568. https://doi.org/10.1007/s10567-023-00424-9

Douglas, K. A., & Purzer, Ş. (2015). Validity: Meaning and relevancy in assessment for engineering education research. *Journal of Engineering Education*, *104*(2), 108–118. https://doi.org/10.1002/jee.20070

Drake, G. W. F. (2021). Thermodynamics. *Encyclopedia Britannica*. https://www.britannica.com/science/thermodynamics

Foroushani, S. (2019). Misconceptions in engineering thermodynamics: A review. *International Journal of Mechanical Engineering Education*, *47*(3), 195–209. https://doi.org/10.1177/0306419018754396

Haglund, J., Andersson, S., & Elmgren, M. (2015). Chemical engineering students' ideas of entropy. *Chemistry Education Research and Practice*, *16*(3), 537–551. https://doi.org/10.1039/C5RP00047E

Hall, M. R., & Allinson, D. (2010). Heat and mass transport processes in building materials. In M. Hall (Ed.), *Materials for energy efficiency and thermal comfort in buildings* (pp. 3–53). Woodhead Publishing.

Hedeker, D., & Gibbons, R. D. (1994). A random-effects ordinal regression model for multilevel analysis. *Biometrics*, *50*(4), 933–944. https://doi.org/10.2307/2533433

Houkes, W., & Meijers, A. (2006). The ontology of artefacts: The hard problem. *Studies in History and Philosophy of Science Part A*, *37*(1), 118–131. https://doi.org/10.1016/j.shpsa.2005.12.013

Jones, M. G., Childers, G., Emig, B., Chevrier, J., Stevens, V., & Tan, H. (2016). The efficacy of visuohaptic simulations in teaching concepts of thermal energy, pressure, and random motion. In N. Papadouris, A. Hadjigeorgiou, & C. Constantinou (Eds.), *Insights from research in science teaching and learning* (pp. 73–86). Springer.

Jorion, N., Gane, B. D., James, K., Schroeder, L., DiBello, L. V., & Pellegrino, J. W. (2015). An analytic framework for evaluating the validity of concept inventory claims. *Journal of Engineering Education*, *104*(4), 454–496. https://doi.org/10.1002/jee.20104

Kim, L., Park, W., Cho, H., & Park, S. (2010). A universal remote control with haptic interface for customer electronic devices. *IEEE Transactions on Consumer Electronics*, *56*(2), 913–918. https://doi.org/10.1109/TCE.2010.5506019

Lau, S., & Roeser, R. W. (2002). Cognitive abilities and motivational processes in high school students' situational engagement and achievement in science. *Educational Assessment*, *8*(2), 139–162. https://doi.org/10.1207/S15326977EA0802_04

Liebschner, J. (1992). *A child's work freedom and play in Froebel's educational theory and practice*. Lutterworth Press.

Lin, X., & Powell, S. R. (2023). Initial efficacy of a fraction-vocabulary intervention for students experiencing mathematics difficulty in grade 4. *Learning Disabilities Research & Practice.*, *38*(4), 253–262. https://doi.org/10.1111/ldrp.12321

McGuire, W. J. (1983). A contextualist theory of knowledge: Its implications for innovation and reform in psychological research. *Advances in Experimental Social Psychology*, *16*, 1–47. https://doi.org/10.1016/S0065-2601(08)60393-7

McGuire, W. J. (1999). *Constructing social psychology: Creative and critical aspects*. Cambridge University Press.

Miller, R. L., Streveler, R. A., Yang, D., & Román, A. I. S. (2011). Fundamental research in engineering education—Identifying and repairing student misconceptions in thermal and transport science: Concept inventories and schema training studies. *Chemical Engineering Education*, *45*(3), 203–210. http://cee.che.ufl.edu/Journals/Summer%202011%20v45.3/Miller453.html

Moran, M. J., Shapiro, H. N., Boettner, D. D., & Bailey, M. B. (2010). *Fundamentals of engineering thermodynamics*. John Wiley & Sons.

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

Nelson, M. A., Geist, M. R., Miller, R. L., Streveler, R. A., & Olds, B. M. (2007). *How to create a concept inventory: The thermal and transport concept inventory*. Paper presented at the Annual Conference of the American Educational Research Association, Chicago, IL.

Nottis, K. E., Prince, M. J., & Vigeant, M. A. (2010). Building an understanding of heat transfer concepts in undergraduate chemical engineering courses. *US–China Education Review*, *7*(2), 1–9. https://files.eric.ed.gov/fulltext/ED511218.pdf

Nottis, K. E., Vigeant, M. A., Prince, M. J., Golightly, A. F., & Gadoury, C. M. (2018). *Computer simulations vs. physical experiments: A gender comparison of implementation methods for inquiry-based heat transfer activities*. Paper presented at the ASEE Annual Conference and Exposition, Salt Lake City, UT. https://doi.org/10.18260/1-2–30214

Ogunwuyi, O. (2013). *Examining the effects of computational tools on students' understanding of thermodynamics of material concepts and representations* (Doctoral dissertation). Purdue University.

Okamura, A. M., Richard, C., & Cutkosky, M. R. (2002). Feeling is believing: Using a force-feedback joystick to teach dynamic systems. *Journal of Engineering Education*, *91*(3), 345–349. https://doi.org/10.1002/j.2168-9830.2002.tb00713.x

Pizzolato, N., Fazio, C., Mineo, R. M. S., & Adorno, D. P. (2014). Open-inquiry driven overcoming of epistemological difficulties in engineering undergraduates: A case study in the context of thermal science. *Physical Review Special Topics—Physics Education Research*, *10*(1), 010107-1-25.

Reardon, F. H. (2001). *Developing problem-solving skills in thermodynamics courses*. Paper presented at the ASEE Annual Conference andExposition, Albuquerque, NM. https://doi.org/10.18260/1-2-9108

Roach, A., Cullinan, S., Shafran, R., Heyman, I., & Bennett, S. (2023). Implementing brief and low-intensity psychological interventions for children and young people with internalizing disorders: A rapid realist review. *British Medical Bulletin*, *145*(1), 120–131. https://doi.org/10.1093/bmb/ldad001

Sanchez, K. L., Magana, A. J., Sederberg, D., Richards, G. P., Jones, M. G., & Tan, H. Z. (2013). *Investigating the impact of visuohaptic simulations for conceptual understanding in electricity and magnetism*. Paper presented at the ASEE Annual Conference and Exposition, Atlanta, GA. https://doi.org/10.18260/1-2-19845

Shavelson, R. J., Roeser, R. W., Kupermintz, H., Lau, S., Ayala, C., Haydel, A., Schultz, S., Gallagher, L. & Quihuis, G. (2002). Richard E. Snow's remaking of the concept of aptitude and multidimensional test validity: Introduction to the special issue. *Educational Assessment*, *8*(2), 77–99. https://doi.org/10.1207/S15326977EA0802_01

Snow, R. E. (1989). Cognitive–conative aptitude interactions in learning. In R. Kanfer, P. L. Ackerman, & R. Cudeck (Eds.), *Abilities, motivation, and methodology* (pp. 435–474). Lawrence Erlbaum Associates.

Snow, R. E. (1992). Aptitude theory: Yesterday, today, and tomorrow. *Educational Psychologist*, *27*(1), 5–32. https://doi.org/10.1207/s15326985ep2701_3

Streveler, R., Olds, B., Miller, R., & Nelson, M. (2003). *Using a Delphi study to identify the most difficult concepts for students to master in thermal and transport sciences*. Paper presented at the American Society of Engineering Education Annual Conference, Nashville, TN. https://doi.org/10.18260/1-2–12592

Streveler, R. A., Litzinger, T. A., Miller, R. L., & Steif, P. S. (2008). Learning conceptual knowledge in the engineering sciences: Overview and future research directions. *Journal of Engineering Education*, *97*(3), 279–294. https://doi.org/10.1002/j.2168-9830.2008.tb00979.x

Streveler, R. A., Miller, R. L., Santiago-Roman, A. I., Nelson, M. A., Geist, M. R., & Olds, B. M. (2011). Rigorous methodology for concept inventory development: Using the 'assessment triangle' to develop and test the Thermal and Transport Science Concept Inventory (TTCI). *International Journal of Engineering Education*, *27*(5), 968–984.

Strunk, K. (2012). A brief intervention for reducing procrastination. *Academic Exchange Quarterly*, *16*(1), 91–96. https://doi.org/10.31235/osf.io/ks8r7

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics* (5th ed.). Pearson.

Tan, H. Z., Bennett, D., Bertoline, G., Chevrier, J., Jones, G., & Reifenberger, R. (2011). *The role of visuohaptic simulations in conceptualizing non-contact electrostatic forces*. Paper presented at the 9th Conference of the European Science Education Research Association (ESERA), Lyon, France.

Thomas, P. L. (1997). *Student conceptions of equilibrium and fundamental thermodynamic concepts in college physical chemistry* (Publication No. 9729078; Doctoral dissertation; University of Northern Colorado). ProQuest Dissertations Publishing.

UCLA: Statistical Consulting Group. (2021). *Statistical computing workshop: Using the SPSS mixed command*. UCLA Statistical Methods and Data Analytics. https://stats.oarc.ucla.edu/spss/seminars/spss-mixed-command/

Wisman, R. A., Muñoz, M. A., & Stevens, P. T. (2019). Evaluating the efficacy of short-cycle mathematic interventions in a high-minority/high-poverty urban public middle school. *Journal for Leadership, Equity, and Research*, *5*(1–2), 6–25.

Young, J. J., Stolfi, C., Tan, H. Z., Chevrier, J., Dick, B., & Bertoline, G. (2011). *Learning force concepts using visual trajectory and haptic force information at the elementary school level*. Paper presented at the IEEE World Haptics Conference. https://doi.org/10.1109/WHC.2011.5945518


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