Received: 24 May 2019 | Accepted: 14 July 2019
DOI: 10.1002/cae.22157

RESEARCH ARTICLE

WILEY

Visuohaptic experiments: Exploring the effects of visual and haptic feedback on students' learning of friction concepts

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Funding information
Division of Engineering Education and Centers, Grant/Award Number: 1606396

Abstract
In this study, we analyzed students' reasoning and explanations of friction concepts before and after engaging in guided experimentation with visuohaptic (VH) simulations. The VH experimentation included two affordances: visual cues and haptic feedback. Specifically, we analyzed the outcomes of two treatment groups with different sequences of affordance introduction. The first treatment group started with visual cues, with haptic feedback added later, while the second treatment group started with haptic feedback and added the visual cues later. We recruited 48 students who had previously taken at least one physics course. Participants completed a pre- and posttest assessment, which included both procedural and conceptual questions about friction before and after the guided experimentation task. The results show that the participants from both treatment groups benefited from using VH simulations. Both treatment groups showed statistically significant pre/post improvements in their understanding of friction. Moreover, both treatment groups showed a statistically significant increase in the conceptual understanding of friction concepts from pretest to posttest with moderate to strong effect sizes. Implications for laboratory instruction are also discussed.

KEYWORDS
embodied learning, haptic technology, physics education, science laboratories, simulations

1 | INTRODUCTION

Recent arguments about improving the quality of science teaching and learning have concentrated on the significance of science and engineering practices and the application of content knowledge [11,57]. Constructivist learning theories also suggest that learning occurs best by doing [18,68]. According to embodied cognition, which is a relatively new area in cognitive psychology, interaction between body and physical environment is essential to gather perception and knowledge that lead to conceptual understanding [3,4,28]. Physical interaction helps conceptualization, particularly the concepts that are abstract and not directly observable. Teaching and learning environments supported with visual and tactile feedback may promote deeper connections between abstract ideas [12].

Previous work reported that visual and tactile feedback provide a constructivist form of applied learning and facilitate students' conceptual understanding of challenging science concepts [13,37]. Considering the affordances of visual and haptic feedback, we designed a visuohaptic (VH) simulation, which blends virtual reality and haptic technology to improve students' conceptual knowledge of friction concepts in a statics course. We introduced two affordances along with the simulation, visual cues, and haptic feedback. The two treatment conditions corresponded to the ordering of access to those affordances. Particularly, this study examined engineering students' conceptual learning of friction concepts in two different experimental settings: (a) adding visual cues after students received haptic feedback only, and (b) adding haptic feedback after students received visual cues only during their engagement with a VH simulation. Previous work from Magana et al. [46,49] has hypothesized that sequencing the visual and feedback modalities may be better than presenting them together at the same time. What previous research has not identified is the optimal configuration when integrating two different learning modalities for serving as cognitive mediators for learning friction concepts. We particularly focus on understanding the effect of using VH simulations when learning static friction concepts. We focused our investigation on friction because (a) it is a science and engineering concept where misconceptions, errors, and difficulties have been well-documented, and (b) it is a significant source of difficulties for undergraduate students, in terms of both conceptual understanding and problem-solving ability [74].

Our study was guided by the following research questions:

1) What is the effect of combining visual cues and haptic feedback in a sequenced approach on engineering technology undergraduate students' conceptual and procedural learning about the concept of friction?
2) What are the effects of the order of a sequenced approach of visual cues and haptic feedback (i.e., receiving haptic feedback without visual cues first and then adding visual cues versus receiving visual cues without haptic feedback first and then adding haptic feedback) on engineering technology undergraduate students' conceptual and procedural learning about the concept of friction?

2 | CONCEPTUAL DIFFICULTIES IN LEARNING ABOUT FRICTION

Statics concepts are an important keystone in physics and engineering programs [24]. Because statics focuses on objects or systems in equilibrium, it provides a fundamental analytical and design perspective to engineers in different branches such as mechanical, civil, and environmental engineering [24,29,76]. Understanding fundamental statics concepts in core engineering courses is essential for students' overall conceptual learning [75]. Students' misconceptions of statics were described by Halloun and Hestenes [26] and further explored using the force concept inventory [31]. This attempt was later extended by engineering education researchers with another concept inventory for statics [17,53,75]. Because forces and moments exerted on objects cannot be "seen," students sometimes struggle to comprehend the associated conceptual facts (or declarative knowledge according to Turns and Van Meter [82]), despite being able to make the necessary calculations [76]. Attaining conceptual learning can enable students to use their understanding to establish relationships between different pieces of domain knowledge [64]. Students also often struggle when problems are presented in unfamiliar configurations or when problems require the combination of several concepts to reach an answer.

Previous work suggests that friction between two solid surfaces is a key statics conceptual misunderstanding, likely related to the challenge of visualizing contact and friction forces [74]. Steif and Dantzler [75], through development and testing of the statics concept inventory (SCI), found eleven "conceptual errors." Most of these errors are related to conceptual difficulties rather than procedural challenges [75]. Three of these challenges relate directly or indirectly to the concept of friction. SCI studies have indicated that students' performance increases after completing a statics course, and that these performance improvements were generally between 43% and 76% [10,73,77]. Steele et al. [73] prepared a curricular feedback loop to facilitate improvements in students' conceptual understanding. To do that, they provided feedback on conceptual portions of students' worksheet and discussions in class and applied the SCI after each course to monitor students' conceptual improvement. They found that students continued to hold conceptual misunderstandings about static equilibrium, representing unknown loads and Newton's third law. Moreover, appropriately representing interaction forces due to contact or friction (and their directionality) is another common challenge for students [6]. Students commonly represent the friction force as always being equal to the weight of the object multiplied by the coefficient of friction of the surface, regardless of the state of sticking or slipping [77,91]. That is, students often believe that they can calculate the magnitude of the horizontal force via multiplying weight with the corresponding coefficient friction, even if the horizontal force applied to the object may not be enough to move the object. These types of errors seem to be deeply rooted and prevent students from achieving complete and accurate conceptual understanding so important for their future course work.

3 | INQUIRY LEARNING WITH SIMULATIONS FOR PROMOTING CONCEPTUAL LEARNING

Inquiry-based as well as hands-on learning are considered forms of active engagement [36]. Inquiry-based learning activities involve laboratory activities that encourage students to analyze, evaluate, revise, and refine every piece of information available [5]. Many educational researchers have explored educational technologies to enhance students' active engagement, motivation for learning, and improvement of their conceptual learning, especially when dealing with abstract and complex phenomena.

Hands-on engagement and physical manipulatives offer learners' more tangible experiences and facilitate their comprehension of abstract and complex concepts [28,33,61,71]. Haptic technology has been integrated into laboratory experiences because it allows learners to have tactile and kinesthetic (or proprioceptive) feedback while using simulations. Many empirical studies have shown that using virtual apparatus and computer-based simulations can increase students' understanding of physics concepts [67,80,92,93], as well as their motivation and positive attitudes toward science classes [32,38,79,92]. However, there has been a growing discussion about how virtual interaction offers limited conceptual understanding [16,78,84]. Research about the effectiveness of computer simulations reported that without real-world or authentic experiences and interactions, students may not internalize and meaningfully acquire a comprehensive understanding of scientific phenomena [50,90]. These findings suggested that integrating touch sense, the key component of physical manipulatives, into virtual experimentation may enhance the effectiveness of both learning mediums [95].

3.1 | VH simulations for promoting conceptual learning

VH simulations are considered to be multimodal applications that enable users to interact with a virtual object via haptic feedback with real-life responses [27]. Due to its multiple sense affordances, VH simulation has been used in a variety of fields from medical training [19,21,27,44,51] to entertainment [20,40] and education [34,46,47,49,55,60].

VH simulations facilitate comprehension of some science concepts that are abstract or quite complicated. They have been used to support learning of forces and fields [62], gears (and forces) [25], point charges [60], and electricity and magnetism [48]. Park et al. [60], for example, developed a VH simulation about point charges and implemented it with 38 undergraduate students from a physics lab course. Half of these students used the VH simulation which allowed students to see as well as feel interaction forces, the rest used only visual simulation without haptic feedback. The researchers found that although there was no significant difference between the two treatments, qualitative data showed that students seemed to show better engagement and motivation when they used VH. Their knowledge also lasted longer.

Studies that combined visual simulations with haptic features, called VH simulation, have shown mixed results in terms of student learning. Some studies [34,55,60] have concluded that although significant differences have been identified using a pretest and posttest for two different conditions (visual to visual + haptic and haptic to visual + haptic), no significant difference between students who engaged with a VH simulation and those who used a visual simulation alone, were identified. Sanchez et al. [66] also conducted a similar study with 66 freshman students and found similar results. Each of these studies also captured students' positive attitudes and perceptions about the immediate haptic feedback of the VH simulation.

Magana and Balachandran [47] and later on Magana et al. [49], conducted studies with undergraduate students to explain why VH simulations may or may not provide a learning advantage. The students first used a haptic simulation with minimal visual cues and then they were exposed to more visual cues with the same haptic feedback. The results indicated that a sequenced approach to learning with haptic devices gave students an extra resource to explain their reasoning. While students mentioned that haptic features helped them understand the concepts, many of them stated that enriched visual cues with haptic feedback allowed them to confirm and retain their understanding. This intriguing result about the potential role of the sequencing of affordances was the inspiration for the study reported here.

4 | EMBODIED LEARNING DESIGN

We used embodied cognition as the theoretical foundation for the design of our learning intervention, as well as for the interpretation of our findings. Similar to Vygotsky's [85] social constructivist theory of how humans learn through social interaction and mental activities, some cognitive theorists claimed that intelligence emerges through the interaction of body with the real world [3,4,22,23,28,43,72,89]. Varela et al. [83] defined the term embodiment saying "by using the term embodied we mean to highlight two points: first, that cognition depends upon the kinds of experience that comes from having a body with various sensorimotor capacities, and second, that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context" (pp. 172–173). These definitions and the nonconventional perspective of cognitive science assert that cognitive processes are not just the result of internal processing but also the result of interaction between body, environment, and mind activities [15]. As a result, knowledge partially relies on neural mechanisms pertaining to sensory and motoric processes [30]. Grounding scientifically abstract concepts in sensorimotor representations may provide students with a mechanism for placing such abstractions in a readily available, concrete conceptual framework [30].

The implications of embodied cognition to our study relate to the proper orchestration between visual and touch modalities to avoid or reduce cognitive overload, and promote intentional bodily interactions by combining physical manipulatives and visual affordances. In this case, bodily interactions are somatic actions that can range from moving a single finger to moving the entire body [1]. The combination of physical and visual manipulatives can harness embodied cognition for learning in a way that visual feedback alone may not provide. Among the many benefits of both learning environments such as motivation, active engagement, multilearning environments, and so forth, the most important of all is the sensory feedback. Different feedback forms via different senses may enhance individuals' precise comprehension of physical phenomena [35,46,47].

5 | METHODS AND RESEARCH QUESTIONS

This study used a pretest–posttest comparative study design to investigate the following two research questions:

1) What is the effect of combining visual cues and haptic feedback in a sequenced approach on engineering technology undergraduate students' conceptual and procedural learning about the concept of friction?
2) What are the effects of the order of a sequenced approach of visual cues and haptic feedback (i.e., V → V + H vs. H → V + H) on engineering technology undergraduate students' conceptual and procedural learning about the concept of friction?

5.1 | Experimental context

This experiment focused on friction phenomena at the interface between two rigid bodies, including both stick-to-slip transitions and steady sliding. The goal of the experiment was to systematically examine the roles of object mass, object size, and contacting surface (i.e., friction coefficient) in the manifestations of friction force. Since contact friction phenomena are known to be conceptually challenging for undergraduate students [26,74], yet are crucial for understanding of more advanced structural concepts and applications in several engineering disciplines. We designed our learning materials to reveal and enhance students' understanding of these concepts. In what follows, the scenarios used to explore friction phenomena employ cube-shaped rigid bodies with various physical properties, as well as several surfaces (with different friction coefficients) with which they come into contact. Participants interact with the cubes in various ways, in each case exploring the role of physical properties in the friction behaviors at the contact interface. The three cubes and their physical properties (mass and size) used in this experiment are described in Figure 1.

Abrahamson and Lindgren [1] provided three principles for embodied learning experiences that guided the design of our VH learning environment to implement the friction experiments: materials, activities, and facilitation. Next, we

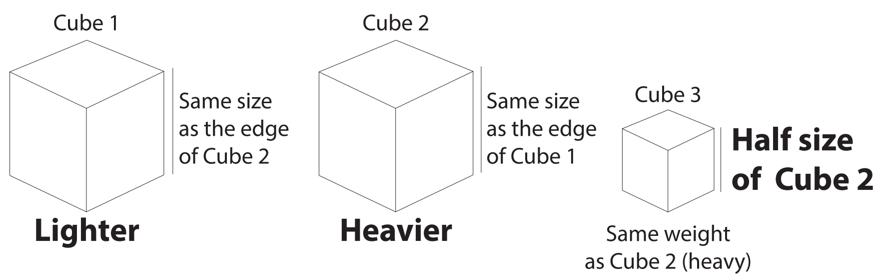

FIGURE 1 Conceptual explanations of the cubes presented in the experiments

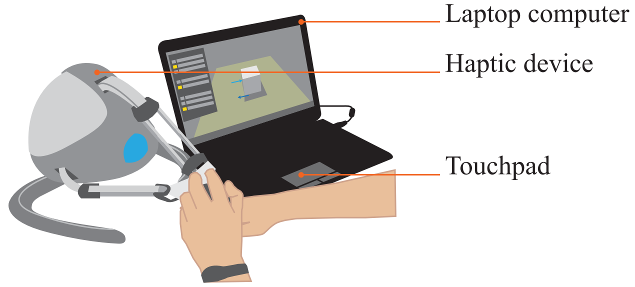

FIGURE 2 Elements of the visuohaptic simulation

explain how these principles were embedded in the learning design.

5.2 | Materials: The VH simulation

According to Abrahamson and Lindgren [1], learning environments should be designed so that somatic actions (i.e., body movements) are coupled with the environment via action-feedback loops. Our VH simulation is a learning tool designed to teach friction concepts via haptic feedback. It was implemented in C++ using Chai3D, OpenGL, and GLSL. It has been deployed on a laptop equipped with Intel i7, CPU clocked at 2.2 Ghz 16 GB of memory, and Intel® Iris™ Graphics 540 card. The haptic device used by learners was the Falcon Novint® with 3D touch workspace and a force capability of 2 lbs. Figure 2 shows the elements of the tool.

The VH simulation provides two types of feedback, kinesthetic and visual, that are coupled through the simulation. There are two types of visual cues: minimal and enhanced. Visual cues are provided via the computer screen. The force feedback was provided by the haptic device. The graphical user interface of the VH simulation allowed activating and deactivating the visual enhanced cues and the kinesthetic feedback. Minimal visual cues were always activated. The haptic device provided the kinesthetic feedback. Participants used the haptic device to interact with the cubes, including pushing and lifting (Figure 2). Participants with the haptic feedback enabled felt the forces acting on the cube while pushing and lifting the cubes (i.e., heavier cubes are harder to lift). The amount of force required to lift or push the cubes determined the magnitude of the force. When the haptic feedback was deactivated, the participant felt no force feedback.

With the minimal visual cues, students were able to see the cubes' position, distance traveled, and velocity. The ruler allowed learners to measure the distance traveled by the cubes when they were pushed. The velocity was depicted qualitatively. That is, students were able to see that a lighter cube traveled faster than a heavier cube, but students were not able to determine by how much. The cubes' dimensions and the coefficient of static friction were also described qualitatively (i.e., big, heavy, light, rough). Numerical values (i.e., force magnitude) along with the force vectors were only shown when the enhanced visual cues were turned on. Force vectors depicted the normal force, the gravitational force, the applied force and the friction force. Learners could hide and show the four force vectors through the control panel. The vectors of the normal force, gravitational force, applied force, and friction force depended on the cube and the surface. For instance, cube 1 (big/light) experienced a friction force of 0.47 N in fabric, 1.87 N in fabric, 3.74 N in sandpaper. Cube 2 (big/heavy) and cube 3 (small/heavy) experienced a friction force of 0.79 N in cardboard, 3.14 N in fabric, and 6.28 N in sandpaper. Values of the size of the cubes and the coefficient of the static friction of the surfaces were not provided. Figure 3 shows two screenshots of the minimal visual cues (Figure 3a) and the visual enhanced cues (Figure 3b).

5.3 | Activities: A sequenced approach

Embodied learning experiences should be designed with scaffolding appropriate to the learner's developmental

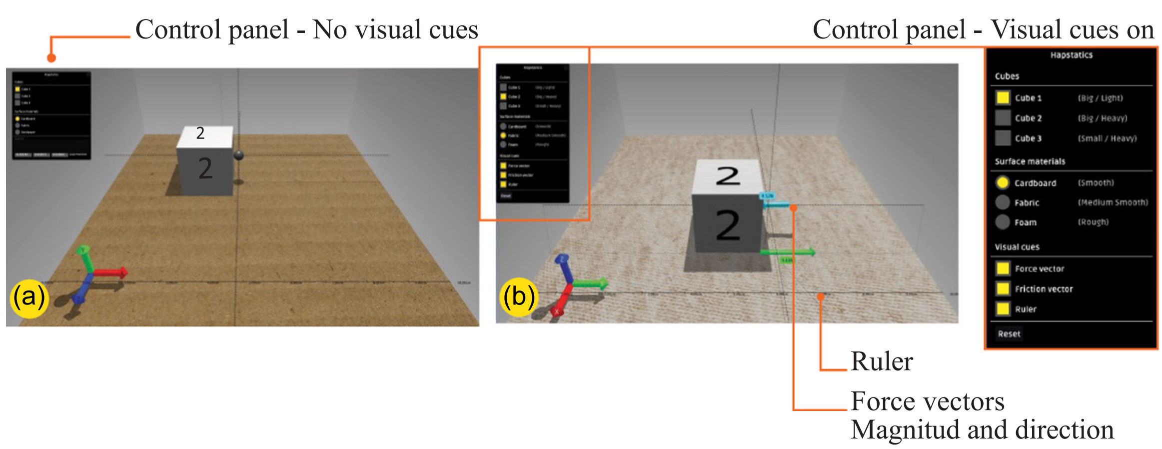

FIGURE 3 Two types of visual cues: (a) minimal, (b) enhanced

stage and the complexity of the learning task [1]. This principle was embedded in our study in the form of a sequenced approach [46,47], where one form of sensory modality was provided first, and then, once students completed an initial task, a second sensory modality was provided as an addition. The first sequenced approach is the visual enhanced to visual enhanced and haptic feedback. Learners started with visual enhanced cues, and then the haptic feedback was introduced (V → V + H). In this group, students first received visual cues such as arrows in different lengths and colors depicting the force vectors, the coordinate system, the different surfaces, and the blocks. Then, they switched on the "haptic on" mode and felt the magnitude of the forces as well. The second sequenced approach is the haptic feedback and minimal visual cues, and then the visual enhanced cues were introduced (H → V + H). Learners started feeling the force magnitudes and seeing the traveled distance of the cubes and then they saw the force vectors (magnitude and direction of the forces). In both sequenced approaches, students interacted with the VH simulation using the mouse and the haptic device. The mouse was used to change the settings of the control panel (see Figure 3), and the haptic device was used for the interaction with the objects to slide and lift the cubes, even when the haptic feedback was not enabled.

5.4 | Facilitation: Learning guidance

Facilitation refers to the scaffolding overlay that can help students to take actions and move their bodies in the intended ways [1]. Effective pedagogical practices should be embedded in the learning materials that will demonstrate and coach students through the learning process. Facilitation was provided in two ways in our study. One was through instructor demonstration and the other was through guidance provided on a worksheet.

Instructor demonstration was intended to help students understand the technology, and how to operate it. This demonstration also included a pretraining session, so students could get accustomed to the haptic feedback. In addition, a worksheet was designed to guide students throughout their engagement with VH simulations and to reveal their learning/reasoning process throughout. We were inspired by the three-phase approach of White and Gunstone [88] to develop the worksheet. We added recall and confirmation phases in addition to prediction, observation, and explanation. These phases were:

1. Recall: participants were encouraged to remember their prior knowledge about friction, as learned in a previous physics course or during the course lecture that preceded the lab session.
2. Prediction: participants predicted the outcome of a given scenario or experiment.
3. Observation: participants made an experimental observation (using the VH simulation) about the given scenario.
4. Reflection: participants used their understanding based on their observation to answer similar question(s) in different contexts than the ones in observation stage and compared these answers with their answers in the prediction phase.
5. Confirmation: participants compared and contrasted their predictions and observations, including further review of VH simulation results with and without various visual cues.

The five-phased approach [88] guided students throughout their engagement with VH simulation. We first carefully reviewed existing literature about students' challenges with friction concepts and the SCI by Steif and Dantzler [75], and then we started developing new questions for each phase. Since our VH simulation did not cover all the questions in the SCI, we did not use it in our pre- and post-testing. The questions were prepared by an expert in the physics education field and reviewed and revised by two other experts in physics and engineering departments, both professors in discipline-based education research.

5.5 | Participants

Forty-eight ($n = 48$) undergraduate students enrolled in an engineering technology program participated in this study. Participants were enrolled in an undergraduate statics course during the spring semester of 2017. The course consisted of two lectures per week (1 hr each) and students attended one laboratory session after the lecture. Since they registered for the laboratory session at the beginning of the semester, researchers did not have control of the number of students per laboratory session or the sessions that students attended. During the laboratory sessions, students interacted with the VH simulation using a sequenced approach described in the Section 5.3 (V → V + H or H → V + H). The first treatment group completed the experiment with the visual enhanced to visual enhanced to haptic feedback (V → V + H). The other group started with haptic feedback enabled and minimal visual cues, and then the visual enhanced cues were introduced (H → V + H). Each condition had 24 participants. Students self-reported their academic level and experience in physics courses.

TABLE 1 Demographic backgrounds of study participants

Treatment groups	Academic level F	So	J	S	# with HS physics only	# with college physics only	# with HS and college physics	# with no physics courses
V → V + H ($n = 24$)	15	5	2	0	12	3	8	1
H → V + H ($n = 24$)	17	2	3	2	11	1	10	1

Note: Two participants from the V → V + H group did not indicate their academic level. One participant in the H → V + H did not indicate prior courses in physics. # with HS physics = number who took at least one physics course in high school. # with university physics = number who took at least one physics course in college.
Abbreviations: F, freshman; J, junior; S, senior; So, sophomore.

Table 1 summarizes the demographic backgrounds of study participants.

5.6 | Data collection method

The initial physical hardware experiment that we conducted as a pilot study shed light on students' conceptual learning of the friction between (a) a cube and different surfaces with different coefficients of friction (low, medium, and high), (b) two cubes having the same size but different weights, and (c) two cubes having the same weight but different sizes (see Figure 1) when cubes transit from rest to slipping status (i.e., friction limit) [74]. The questions used as pre- and post-tests in the present study were derived from literature and were piloted during a previous study. Students were first asked to verbally predict and then observe the four scenarios to compare these conditions. The scenarios were:

1) What happens if you push two cubes made from the same material and with the same size, but with different weights (one half the weight of the other) on a low friction surface?
2) What if you push the same objects on a high friction surface?
3) What if you push two cubes with the same weight but different sizes (one is half the size of the other) on a low friction surface?
4) What if you push the previous objects on a high friction surface?

In addition to these four predictive conceptual questions, two basic procedural questions (PQs) were included. The first one asked participant to calculate if a 30 kg cube, with dimensions of 0.45 m width, 1 m length, and 0.2 m height would start to move or remain in equilibrium on a surface with a coefficient of static friction of 0.2 when a horizontal 60 N force was applied to the center of mass (see Figure 4; PQ 1). The first PQ was designed to find out if students knew how to calculate the friction force by using correct parameters such as gravitational force and coefficient of friction. With given data, the block would slide because the applied force $F_{\text{app}} = 60$ N was greater than the maximum static friction force $F_s = 58.86$ N.

The second PQ included two blocks of different sizes resting on each other in two different configurations (Figure 4a,b; PQ 2) on a surface with a coefficient of static friction equal to 0.3. Participants were asked to determine whether the objects would slide or remain in equilibrium when we applied a 65 N force as shown in the figure (relative motion between the two objects was not considered). The horizontally applied force needed to make two rigid bodies slide in both cases (A and B) was $F_s = 191.3$ N, which was much larger than the applied force. Therefore, the blocks remained at rest in both cases independent of their configuration since the friction force did not depend on the contact area.

To avoid interfering with students' thought processes and reasoning, we did not utilize any technical words related to friction such as force, coefficient of friction, or

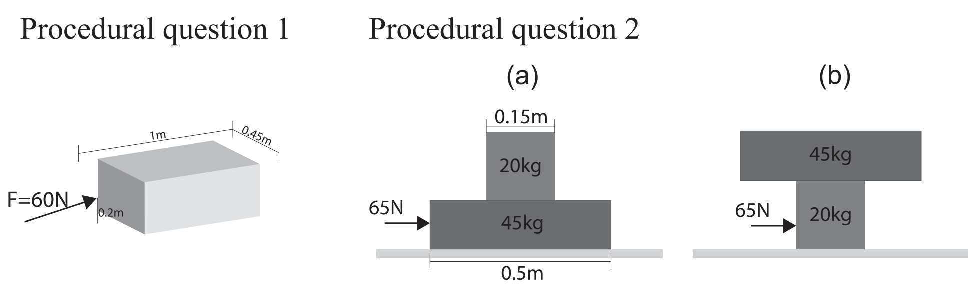

FIGURE 4 The procedural questions

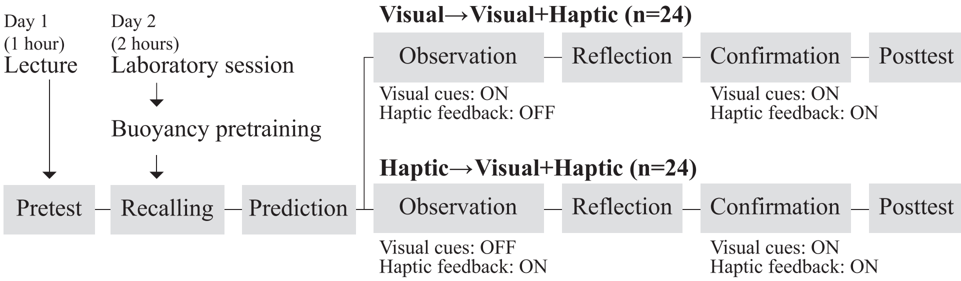

FIGURE 5 Overview of procedures for data collection

vector when developing all predictive conceptual and the PQs.

Both PQs were aligned with conceptual questions, which asked whether the size of the cubes contribute the friction force. These questions helped us to determine whether students could demonstrate a coherence between conceptual and procedural understanding within the same context.

5.7 | Procedures

Our procedure consisted of a 2-day intervention and seven main steps encompassing both classroom and laboratory settings, as shown in Figure 5. The process started with a 40-min in-class lecture about friction accompanied immediately by a pretest. Forty-one participants took the pretest right after the friction lecture and a few days before the laboratory session. Seven participants did not attend the lecture, so they took the pretest right before we started the lab session (five from treatment group V → V + H and two from treatment group H → V + H). The lecture was the only activity in the study where the students started and finished the activities at the same time. During the lab session, students were informed that they should finish all activities (i.e., recalling, prediction, observation, reflection, confirmation, and posttest) in 2 hr or less. Researchers did not record the time per student. All the students finished the laboratory session in <2 hr. Researchers did not intervene in any way in the design or delivery of the lecture. The professor of the course continued his regular friction lecture as planned. Figure 5 illustrates the overview of the procedures followed by those students who attended the lecture ($n = 41$).

Students came to their regular lab sections a few days after attending the lecture, completed the pretest and engaged with the learning materials in their assigned group as a part of VH implementation. First, all participants received an introduction to haptic technology (i.e., what is a haptic device, what can you do with a haptic device), followed by a pretraining session. To familiarize all participants with the haptic device and VH simulation, we provided another VH simulation about buoyancy as a pretraining activity [86]. The pretraining activity helped students learn how to manipulate the device and follow the guidance embedded in the simulation as well as the worksheets. During the pretraining session, students answered questions about the force required to move an object in a liquid with different densities. Fifteen minutes were spent on the pretraining session.

After the pretraining activity, the participants were given the friction worksheets and asked to follow the instructions on the worksheets. The worksheet started with recall and prediction phases (see Section 5.4 for more details). During the first two phases, students did not interact with the simulation. Students answered questions regarding the forces acting on stationary objects in the recall phase. During the prediction phase, students answered questions about the differences between sliding objects on surfaces with low, medium, and high friction coefficients. Numerical values were not included in the recall and prediction phases.

After they finished writing down their predictions, they were told to turn on the VH simulation and open the observation worksheet. Once they started the observation phase, treatment groups were differentiated. Treatment group 1 started with visual cues on/haptic feedback off and treatment group 2 started with visual cues off and haptic feedback on. The visual cues on/haptic feedback off group only saw the arrows depicting the force vectors in different lengths and colors based on the magnitude of forces exerted on the cubes. Once they finished their observations and took notes, they went to the next stage called reflection. During the reflection phase, students completed two exercises. First, they characterized the force required to slide objects. Second, students drew the free body diagram of the forces acting on the object that was being pushed. Once students answered the reflection phase questions, they moved on to the confirmation phase. In the confirmation phase, students were asked to turn on the second feedback. That is, students in the first condition turned on the haptic feedback. Students in the second condition turned on the visual enhanced cues.

With the two forms of feedback enabled (V + H), students revised the answers provided during the observation phase. During the confirmation phase, students could add or modify the answers they had provided in the observation phase. After finishing the confirmation phase, students answered the posttest. Post- and pre-test had the same questions. For this study, we only considered the pretest and posttest answers.

5.8 | Data analysis methods

Students' answers were classified into five categories: correct and complete (CC), correct and incomplete (CN), incorrect and correct (CI), incorrect (I), and not applicable (NA). Table 2 explains what the categories mean, the scores given per category, and samples of student responses.

The number of statements varied among participants. For example, one student might have answered a question by using four statements in the pretest and two statements in the posttest. Participants that provided a CC or CN answer demonstrated scientific accuracy consistent with physics laws. The difference between CC and CN was the number of variables used to answer; that is, CC answers were those answers that were scientifically accurate according to the laws of physics and had details that reinforced the idea. An expected CC answer would include explanations such as mass differences, roughness of the surfaces, the comparison of applied forces (e.g., a lighter cube would require less force to start sliding than a heavier cube). All participants answered all questions and there were no questions left blank.

The classification used in the case of PQs was CC, correct but incomplete, CI, incorrect, and NA. PQs did not include the categories CI since students did not combine correct with incorrect statements in these questions; incorrect calculations led to incorrect answers.

Paired t tests were used to answer the first research question about the effect of the visual and haptic feedback on the students' conceptual understanding of friction. We compared the students' scores in the pre- and the posttest. To compare the learning gains of students per condition, we used independent t tests. We also ran independent t tests to compare pretest results and determine the students' conceptual understanding before the intervention. Figure 6 shows the relationship between the research questions and the t tests. The α used through our data analysis was $\alpha = .05$.

The Cohen's d effect size was used to compare the effect of the VH simulation on students' conceptual learning. We consider a strong effect size when $|d| > 0.8$; a moderate to strong effect size when $0.65 < |d| < 0.8$; a

TABLE 2 Classification of students answers

Categories	Definition and score	Example: Student answer	Example: Variables identified
Correct and complete	Students correctly answered the questions. Students included two or more variables (i.e., speed, applied force, friction) in their answers. Answers in this category received three points	Cube 1 (light) would move easier than cube 2 (heavy). Cube 1 would take less force to start moving than cube 2. Cube 2 will start moving faster than cube 1. (answer of question 1, pretest, student ID24: V → V + H	**1.** Correct use of the easier/hard variable **2.** Correct use of the force variable **3.** Correct use of the speed variable
Correct and incomplete	Students correctly answered the questions. Students included only one variable (i.e., speed, applied force, friction) in their answers. Answers in this category received two points	Both cubes would move based on the applied force (answer of question 1, pretest, student ID7: V → V + H)	**1.** Correct use of the applied force variable
Incorrect and correct	Students used variables in both, correct and incorrect ways in the same answer. Answers in this category received one point	Cube 2 (big) and cube 3 (small) would have the same resistance due to inertia but cube 3 would have half the resistance due to friction as cube 2 (answer of question 1, pretest, student ID19: H → V + H)	**1.** Correct use of the inertia variable **2.** Incorrect use of the friction variable
Incorrect	Students incorrectly answered the questions. Students used one or more variables in an incorrect way. Answers in this category received zero points	Cube 3 (smaller) would move faster. (answer of question 3, pretest, student ID7: H → V + H)	**1.** Incorrect use of the speed variable
Not applicable	No variables were identified from the answer	Would be the same (answer of question 4, pretest, student ID13: H → V + H	No variables

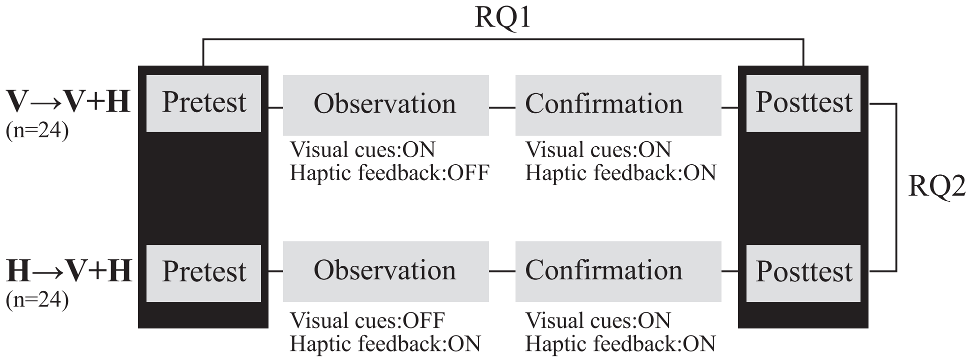

FIGURE 6 Research questions and statistical analysis

moderate effect size when $0.40 < |d| < 0.65$; weak to moderate effect size when $0.2 < |d| < 0.4$; and a weak effect size when $|d| < 0.2$ [65].

5.8.1 | Trustworthiness, reliability, and validity considerations

The learning materials used in this study, the worksheets and the VH simulation, were designed using a learner-centered approach. The questions used in this study are based on the misconceptions previously reported on the SCI by Steif and Dantzler [75] and studies indicating that students hold misconceptions about friction even after instruction [6,74]. The questions were prepared and revised by experts in the field of engineering and physics education. The questions were piloted in a previous study using a physical manipulative tool to design a VH simulation to teach friction [91]. We calculated the Cronbach's α to evaluate the internal consistency of the questions regarding the role of the friction force and the role of the object size. The internal consistency of the role of the friction force was 0.71. The internal consistency of the role of the object size was 0.6. Both values are considered to be in the acceptable range. The VH simulation was designed by a group of experts in different fields, such as engineering education, physics education, computer graphics, and user-interface design. The simulation was tested in different stages of the design process to avoid usability problems.

Three trained graders classified the students' answers. Each researcher performed an independent analysis of the entire data set. Two researchers evaluated each question separately. One researcher evaluated the consistency between questions 1 and 2 together and question 3 and 4 together. Differences in criteria were resolved during in-person meetings. Differences in the criteria were mainly due to the grammar or handwriting of the students. Cohen's κ was used to evaluate inter-rater agreement for answers classification. In all cases, the coefficient exceeded 0.7 and we concluded that the inter-rater agreement was acceptable [52].

Before running the t tests, an assumptions analysis was conducted. We used the QQ-plot and the Shapiro–Wilk test for normality. The Levenes' test was used to check the data variances. Results showed the normality assumption and the constant variances were met ($p < 0.05$).

6 | RESULTS

Our results are presented in two main sections corresponding to each research question: Section 6.1 shows results from the first research question regarding the effect of using VH simulations for improving conceptual understanding of friction concepts. Section 6.2 answers the second research question about how the order of the visual and haptic feedback affected the conceptual understanding of friction concept.

6.1 | Effect of the use of the VH simulation for improving conceptual learning of friction concepts

This section is divided into two subsections that address research question one. The first subsection explores the role of friction force (via object mass), while the second probes the role of object size. In both cases, we evaluated the VH simulation as a tool to promote learning.

6.1.1 | Role of the friction force

Results from two sliding scenarios in the VH simulation are presented in Table 3. We examined participant pre- and post-test data from scenarios 1 and 2 in which the sliding bodies have the same size, but different mass. Each answer was placed into one of five categories following the process of data analysis described in Section 5.8.

TABLE 3 Percentage of answers in the pre- and posttest on items related to the role of friction force

	Pretest performance (%)					Posttest performance (%)				
Scenario	**CC**	**CN**	**CI**	**I**	**NA**	**CC**	**CN**	**CI**	**I**	**NA**
S1	52.1	10.4	22.9	8.3	6.3	60.4	29.2	2.1	4.2	4.2
S2	62.5	12.5	6.3	14.6	4.2	70.8	10.4	10.4	2.1	6.3

Abbreviations: CC, correct and complete; CI, correct and incorrect; CN, correct but incomplete; I, incorrect; NA, not applicable; S1, scenario 1; S2, scenario 2.

The percentage of answers (Table 3) in correct categories (CC and CN) aggregated across the sample increased from pre- to posttest (positive results). The incorrect categories (CI, I, and NA) decreased from pre- to posttest. The CI category was included in both previously mentioned calculations of the percentages since both contained CI statements. The percentage of answers in the correct and the complete (CC) category increased from pre- to posttest for both questions. The percentage of answers in correct but incomplete (CN) category increased in the posttest for scenario 1 but decreased for scenario 2. The percentage of CI answers decreased from pre- to posttest for both scenarios. The percentage of incorrect answers (I) decreased from pre- to posttest in both scenarios. The percentage of NA answers increased for the first scenario by 2.1% and decreased by 2.1% for the second scenario.

The last step in the analysis consisted of identifying if the learning effects were statistically significant. A score was assigned to each answer based on the categorization of the answers. The maximum of points that a single student could obtain in this group was six (two questions, three points each). Table 4 shows the results for the inferential statistical analysis.

Results show an increment in conceptual knowledge from pretest to posttest regarding the role of the friction force. The embodied learning environment facilitated students to improve their conceptual knowledge. The value of $|d| = 0.31$ suggests a weak to moderate effect size of the VH simulation in conceptual knowledge of the role of the friction force.

6.1.2 | Role of the object size

The assessment questions focused on conceptual learning regarding the role of the object size were captured with scenario 3, scenario 4, and the PQs 1 and 2. The open-ended scenarios 3 and 4 regarded sliding a large cube and a small cube on a low friction surface (scenario 3) and then on a high friction surface (scenario 4). In PQ 1, participants predicted the outcome of moving a cube with a large contact area, if an applied force were to be exerted on the center of mass. The PQ 2 had participants predict the outcome of moving two attached objects, in two different configurations. For more detail about scenarios, see Section 5.7. Table 5 summarizes the percentage of answers in each category per scenario.

The CC category increased the frequency of answers from pre- to posttest. The percentage of answers in the pretest was between 15% and 58%. The percentage of answers in the posttest was between 42% and the 63%. The frequency of answers in the CN and CI categories decreased in the posttest. The frequency of incorrect answers decreased for scenario 3 by 21%.

The maximum points a student could obtain from all scenarios (S1–S4) and PQs (P1 and P2) were 12 (four questions, three points each). Table 6 presents the comparison of the total scores in the pre- and posttest.

Results show that there is a significant difference between the pre- and posttest results for questions assessing the role of the size of the cube (scenarios 3 and 4 and the PQs 1 and 2). Thus, we conclude that embodied learning experience increased students' conceptual learning of the role of the object size in friction concepts. The value of $|d| = 0.61$ suggests a moderate effect size of the instructional materials on helping students identify the role of the object size.

6.2 | Treatment effects

We performed three additional analyses to determine whether one of the treatment groups was better than the other one, that is, visual to visual + haptic ($V \rightarrow V + H$) versus haptic to visual + haptic ($H \rightarrow V + H$). The first analysis compared pretest scores for each treatment group before instruction to determine if groups started at

TABLE 4 Overall learning gains on the role of the friction coefficient of the friction force

Pretest		Posttest			Paired t test			
Mean	**Standard deviation**	**Mean**	**Standard deviation**	**Δ**	t	**df**	p **value**	**Effect size**
4.21 (70.17%)	1.53 (25.5%)	4.85 (80.83%)	1.58 (26.33%)	0.64 (10.6%)	−2.13	47	0.038	0.31

TABLE 5 Percentage of answers in the pre- and posttest on items related to the role of object size

	Pretest performance (%)					Posttest performance (%)				
Questions	CC	CN	CI	I	NA	CC	CN	CI	I	NA
S3	20.8	18.8	6.3	33.3	20.8	58.3	18.8	2.1	12.5	8.3
S4	22.9	12.5	18.8	35.4	10.4	45.8	12.5	6.3	27.1	8.3
P1	58.3	14.6	*	20.8	6.3	62.5	4.2	*	31.3	2.1
P2	14.6	6.3	*	56.3	22.9	41.7	6.3	*	52.1	0

Abbreviations: CC, correct and complete; CN, correct but incomplete; CI, correct and incorrect; I, incorrect; NA, not applicable; P1, procedural question 1; P2, procedural question 2; S3, scenario 3; S4, scenario 4.
*In procedural questions students did not combine correct with incorrect statements, incorrect calculations lead to incorrect answers.

the same level of understanding. The second analysis compared pretest versus posttest results independently to determine the extent to which participants from each group increased their conceptual understanding after instruction. The third analysis compared learning gains between treatment groups to identify if one of the treatments had an advantage over the other one.

6.2.1 | Role of the friction coefficient in the friction force

The same analysis of the role of the friction coefficient is presented for each group. Table 7 summarizes the percentage of answers per scenario and by group.

Table 7 shows that both treatment groups had similar results in the pretest. Overall, the frequency of students that provided correct answers increased in the posttest and the number of students that provided an incorrect answer decreased in the posttest, showing that the VH simulation might have positively influenced students' answers.

6.2.2 | Role of the object size in the friction force

The role of the object size is analyzed in the same way as in the previous section. Table 8 shows the categorization results for the pre- and posttest answers.

Results depicted on Table 8 show positive changes from pre- to posttest regarding the role of the object size per treatment group, except for P1 in the $V \rightarrow V + H$ group, where the number of correct answers decreased by 16.7% in the posttest. Each treatment group also presents positive and negative learning improvements.

6.2.3 | Comparison between treatment groups before instruction

This section compares the overall results (for all scenarios and PQs) obtained after comparing the two treatment groups on the pretest measures. We performed a two-tailed sample t test to compare the initial conceptual understanding for both groups. There was a significant difference in the pretest scores between the $V \rightarrow V + H$ group ($M = 8.12$, $SD = 2.82$) and the pretest scores for the $H \rightarrow V + H$ group ($M = 9.87$, $SD = 2.67$); $t\ (45.8) = -2.21$, $p < .05$, indicating that pretest scores were not comparable by groups.

6.2.4 | Comparison of learning gains by treatment group

We compared the pretest versus posttest scores for both groups independently to identify benefits on participants' learning. The maximum score that a student could obtain in any of these tests was 18 points (six questions and three points maximum for each question). Table 9 presents the summary of the comparison of the overall score between pre- and posttest for the $V \rightarrow V + H$ and the $H \rightarrow V + H$ groups separately.

Table 9 shows that there was a significant difference between the pretest ($M = 8.12$, $SD = 2.82$) and the posttest ($M = 11.88$, $SD = 3.49$) scores; $t\ (23) = 4.66$, $p < .001$ for the $V \rightarrow V + H$ group. The value of $|d| = 0.95$ suggests a strong effect on the learning increase for this group. Results from Table 9 also show that there was a significant difference between the pretest ($M = 9.87$, $SD = 2.67$) and the posttest ($M = 12.17$, $SD = 4.66$) scores; $t\ (23) = 2.51$, $p < .05$ for the $H \rightarrow V + H$ group. The value of $|d| = 0.51$ suggests a moderate effect on the learning increase for this group.

TABLE 6 Overall learning gains on the role of the object size

Pretest		Posttest		Paired *t* test			
Mean	Standard deviation	Mean	Standard deviation	*t*	df	*p* value	Effect size
4.79 (39.92%)	2.61 (21.75%)	7.17 (59.75%)	3.62 (30.16%)	−4.21	47	0.0001	0.61

TABLE 7 Percentage of answers in the pre- and post-test on items related to the role of the friction coefficient in the friction force per treatment group

		Pretest (%)					Posttest (%)				
S	Groups	CC	CN	CI	I	NA	CC	CN	CI	I	NA
S1	V → V + H	50.0	8.3	25.0	8.3	8.3	62.5	25.0	0	8.3	4.2
	H → V + H	54.2	12.5	20.8	8.3	4.2	58.3	33.3	4.2	0	4.2
S2	V → V + H	62.5	8.3	8.3	16.7	4.2	62.5	16.7	12.5	4.2	4.2
	H → V + H	62.5	16.7	4.2	12.5	4.2	79.2	4.2	8.3	0	8.3

Abbreviations: CC, correct and complete; CN, correct but incomplete; CI, correct and incorrect; H → V + H, haptic to visual + haptic group; I, incorrect; NA, not applicable; V → V + H, visual to visual+haptic group.

6.2.5 | Comparison of learning gains between treatment groups

We performed a learning gain analysis (i.e., posttest-pretest scores) to identify if the sequence of modality presentation had an effect (Table 10). Our results suggest that there was not a significant difference in learning gains when comparing the effects of the V → V + H condition ($M = 3.75$, $SD = 3.96$) with the effects of the H → V + H condition ($M = 2.29$, $SD = 4.47$); t (45, 3) = 1.197, $p > .24$. Therefore, the learning gains for the both treatment groups were comparable.

7 | DISCUSSION AND IMPLICATIONS FOR TEACHING AND LEARNING

In this study we examined how two different configurations of a VH simulation affected students' understanding of the concept of friction, and whether the order of visual and haptic feedback (V → V + H vs. H → V + H) influenced students' conceptual learning and representational competence. The following sections address each research question separately.

7.1 | Improving conceptual learning via VH simulations

Previous literature which studied students' learning with embodied learning experiences demonstrated a positive effect on conceptual learning [42,46,60]. Even though the argument about adding haptic feedback to visual manipulation is not better than having visual manipulation alone [34,55,60], the results from previous studies conducted by our research team showed that haptic feedback has great potential to improve student learning of force-related concepts [49,91]. Therefore, with this study we wanted to identify ways to maximize the effects of haptic feedback as a learning medium following a sequenced approach. Our initial hypothesis was that haptic technology combined with visual cues could facilitate learners to improve their understanding of mechanics concepts and be able to correct their non-normative ideas of friction concepts via embodied experiences supported with a VH interface. Regarding the first research question, two mechanics concepts that appeared to be most challenging for the understanding of friction were considered for this study: the role of roughness between a surface and a block, and the role of the

TABLE 8 Number of students on each category per questions on the role of the size of the object per treatment group

		Pretest performance (%)					Posttest performance (%)				
Question	Groups	CC	CN	CI	I	NA	CC	CN	CI	I	NA
S3	V → V + H	12.5	12.5	0	41.7	33.3	66.7	16.7	0	4.2	12.5
	H → V + H	29.2	25.0	12.5	25.0	8.3	50.0	20.8	4.2	20.8	4.2
S4	V → V + H	12.5	12.5	25.0	37.5	12.5	41.7	12.5	8.3	29.2	8.3
	H → V + H	33.3	12.5	12.5	33.3	8.3	50.0	12.5	4.2	25.0	8.3
P1	V → V + H	54.2	25.0	*	16.4	8.3	58.3	4.2	*	33.3	4.2
	H → V + H	62.5	8.3	*	25.0	4.2	66.7	4.2	*	29.2	0
P2	V → V + H	12.4	8.3	*	54.2	25.0	41.7	8.3	*	50.0	0
	H → V + H	16.7	4.2	*	58.3	20.8	41.7	4.2	*	54.2	0

Abbreviations: CC, correct and complete; CN, correct but incomplete; CI, correct and incorrect; H → V + H, haptic to visual + haptic group; I, incorrect; NA, not applicable; V → V + H, visual to visual + haptic group.
*In procedural questions students did not combine correct with incorrect statements, incorrect calculations leads to incorrect answers.

TABLE 9 Comparison between pretest versus posttest scores for both groups

	Pretest		Posttest		Paired t test			
Groups	Mean	Standard deviation	Mean	Standard deviation	t	df	p value	Effect size
V → V + H	8.12 (45.1%)	2.82 (15.6%)	11.88 (66%)	3.49 (19.38%)	−4.64	23	<.001	0.95
H → V + H	9.87 (54.83%)	2.67 (14.83%)	12.17 (67.61%)	4.66 (25.8%)	−2.51	23	.019	0.51

contact area between them. Previous studies revealed that students often struggle to identify the factors that affect friction force [74]. Although students are often able to calculate friction forces, they mostly fail to explain what their calculation reveals about how friction originates between two surfaces. In this study, we developed a VH simulation to facilitate students' conceptual understanding about how the phenomena happens between cubes, which have different masses and surface areas and surfaces that have different coefficients of friction.

The evidence provided in the results section, the categorization of students' answers, and the inferential analysis allowed us to make two main conclusions. First, considering the frequency of the correct categories (CC and CN) and the overall score, the comparison of pre- and posttest scores shows that there is a gain in the conceptual knowledge about the role of friction force. This can be seen in Table 3, where the number of students with correct answers increased in the posttest and in the comparison of means in the pre- and posttest for all students.

We independently analyzed pre- and posttest changes per scenario to understand what type of questions related to force feedback facilitated better comprehension of friction concepts. These analyses (Tables 3 and 5), indicated that as expected both treatments, V → V + H group and H → V + H, transitioned toward CC ideas. While all students increased their CC answers, and CN answers for scenario 1, they increased their CC answers, but decreased their CN answers for scenario 2. Moreover, there is a leap in the number of CC between the pre- and posttests for scenarios 3 and 4 while the number of CN remained the same. These results show similarity with Han and Black [28], Shaikh et al. [70], and Magana et al., [49] studies reported that embodied haptic experiences may facilitate learning physics concepts via building a solid cognitive foundation.

Although previous research has reported the value added of presenting information in multiple modalities (e.g., Jones and Magana [35], Magana et al. [49], Neri, et al. [58], Zacharia [94,95], Zacharia and Constantinou [96]), there is an opening for future work to determine the optimal ways to integrate VH simulation into the curriculum [55,95]. Similarly, there is also a need to identify the best combination of both modalities (V → V + H and H → V + H) [49,91]. However, a great number of studies have mainly focused on two questions: (a) does the use of virtual representations help improve students' conceptual understanding? [65,80,92,93] and (b) does adding haptic feedback into virtual simulations result in higher learning than using virtual simulations alone? [39,95,97]. In this study, we took a different perspective as proposed by Magana et al. [46,47,49], and sequenced the visual and haptic modalities but sequenced them in different orders.

We focused on a sequenced approach because a recent study identified that a sequenced approach resulted in higher learning gains in conceptual understanding of an abstract science concept than a combined approach [49]. Our results from this study indicate that students who received friction concepts in class before the study had many incomplete and incorrect statements. However, after engaging with embodied experiences via sequenced VH interactions (combination of touch sensor and visual cues), they increased the percentage of correct and complete statements. These results show similarities with previous studies conducted by Jones et al. [36] Magana and Balachandran [46], Magana et al. [49], Hallman et al. [25], and Reiner [63].

7.2 | The effect of sequencing of modalities

Results from the inferential analysis allowed us to make two important conclusions regarding the second research

TABLE 10 Learning gains comparison

V → V + H learning gains		H → V + H learning gains		Two-tailed t test		
Mean	Standard deviation	Mean	Standard deviation	t	df	p value
3.75 (20.83%)	3.96 (22%)	2.29 (12.72%)	4.47 (24.83%)	1.1969	45.345	0.2376

question: first, the VH simulation helped to improve the conceptual learning of basic concepts involved in friction forces and, second, that the order of the modalities did not reflect a significant variation in conceptual learning in this study. The second conclusion is supported by the results of the comparison of the posttest and learning gains in both treatment groups. Similar to the first research question, participants' conceptual understanding of the role of the friction surface was analyzed separately for both treatment groups. The analyses showed that the VH simulation improved participants' learning almost in the same manner for both sequences, in agreement with the findings of Magana et al. [49]. Similar results were found for the understanding of the role of the object size in solving PQs. Students in $V \rightarrow V + H$ group gave fewer correct answers to PQ 1 in the posttest, while students in $H \rightarrow V + H$ group gave more answers that were incorrect in the posttest for PQ 2.

Zacharia [95] looked deeply at 12 studies that used haptic and visual manipulatives as learning mediums with students from middle school to graduate levels. Among these studies, nine of them concluded that the haptic condition helped students to understand science concepts better [7–9,25,28,36,55,62,69]. We extended these results by identifying what type of haptic condition would increase students' meaningful learning of friction concepts. For this purpose, we analyzed students' learning process in haptic group (haptic to haptic + visual) versus students' learning process in visual group (visual to haptic + visual). Our results suggest that although both groups students increased their conceptual learning, students in the $V \rightarrow V + H$ group benefitted from the VH simulation better (strong effect size) than students in $H \rightarrow V + H$ group (moderate effect size) did. However, the overall gain between pre- and posttest for both groups was found to be similar, even though students in the $H \rightarrow V + H$ group performed better in the pretest. This result could mean that the order of introducing haptic feedback and visual cues does not affect students' conceptual learning of friction concepts.

In summary, we have integrated technology via sequenced visual and kinesthetic feedback into a learning experience about an abstract physics concept. We believe that due to the embodied learning design, our participants constructed new information with the proper harmony between visual and touch modalities and engaged in intentional bodily interactions by combining touch modality and virtual modality affordances. This process was facilitated by the principles of embodied learning as proposed by Abrahamson and Lindgren [1], along with a five-phase procedure (i.e., recall, prediction, observation, reflection, and confirmation), inspired by White and Gunstone [88]. Our findings indicate that students who engaged with the VH simulation and learning guidance improved their conceptual learning and representations on a relatively difficult and abstract physics concept. While our participants started with many incomplete and incorrect ideas about the behavior of friction forces between cubes with different masses and sizes, on the one hand, and surfaces with different friction coefficients, on the other, they showed an increase in their understanding toward more complete and correct explanations of the concept. Similar findings were reported by Minogue and Borland [54] regarding the concept of buoyancy.

7.3 | Implications for teaching and learning with haptic technology

The goal of much educational research is to find out how to improve teaching and learning processes [2,45,81,87]. Various methods and educational tools have been developed and tested to increase students' performance in science courses. One common feature of many of those innovative efforts is that it has focused on the media used to present and represent science concepts. Studies have shown that different representations and media can significantly affect students' performance [41]. Different media such as computer simulations, visualizations by using animations, pictures, symbols or graphs, and many more models have been identified as being useful to help construct abstract models in students' minds. We designed our instructional units and VH simulations under the guidance of embodied cognition theory. Our primary goal was to reduce cognitive load by offering students different learning media, which may have facilitated the understanding of more complex and abstract concepts [59].

According to embodied cognition theory, conceptual learning occurs when active, dynamic, and physical involvement happens between body and environment [95]. Science learning can then occur in a more meaningful way, can last longer, can provide deeper understanding, and can support transitions to other science concepts [28]. More abstract concepts could be understood via well-grounded structural components of intuitive and abstract knowledge [63,95]. Han and Black [28], on the other hand, asserted that before any formal instruction, using tangible manipulatives offers learners a foundation for their learning and enables them to construct a cognitive base for more comprehensive understanding. Adding haptic feedback in addition to visual representation can enable students to experience a real-life interaction of forces [56]. For example, via haptic devices, any imperceptible force (too small to feel) could be turned into more tangible form by magnifying the physical values. Therefore, users have the convenience of manipulating objects and feeling their interaction using the force feedback.

8 | LIMITATIONS, CONCLUSION, AND FUTURE WORK

This study used interactive learning materials (i.e., VH simulation), guidance (i.e., instructional worksheets), and prompt feedback (visual cues or/and touch feedback) to examine the best conditions for students' learning of friction concepts using haptics. Regardless of our efforts to optimize the learning materials, our study has some limitations. First was the inability to provide self-paced learning experiences for the students and the students with a slow learning pace may have fallen behind. A second limitation may have been related to previous exposure to learning from haptic technology. Although we accommodated a pretraining session, it may still not have been enough for students to fully develop the skill needed to interpret the force feedback, associate it with real force, and be able to detect nuances in the force feedback from the device. Our future work will also include extended exposure to haptic-enabled learning experiences throughout an entire semester. Another constraint was the physical capability of the haptic device. The device used in this study was limited to a 10 Newton force feedback. This may have been too subtle for small changes to be detected. A final limitation was the inability to control the makeup of the lab groups, which may have contributed to the differences observed in the pretests.

While our analyses demonstrated that VH simulation did make a significant difference in students' conceptual learning and facilitated their predictive conceptual explanation toward more CC ideas, we could not find any significant difference between the treatment groups on students' performance, although students in the H → V + H group performed slightly better in terms of conceptual learning. Findings from our study also suggest that students struggled to answer PQs even though they solved similar questions during their course lecture. After being exposed to the VH learning experience regarding the sequencing of modalities, again students in the H → V + H group responded to these PQs slightly better than students in the V → V + H, although the V → V + H group obtained a larger average learning gain than the H → V + H group. This result could be because the V → V + H group scores were lower than the scores of the H → V + H in the pretest.

Although there seem to be no significant differences between the treatments, there is still room for more comprehensive analyses in different contexts and different settings.

One of them includes an investigation of the conditions under which visual and haptic feedback can result in deeper conceptual and procedural learning of difficult concepts in STEM. For instance, we may perform a deeper qualitative analysis to identify evidence of conceptual change by teasing out nuances in students' language change. Specifically, analysis of the exact terminology used by students could help us to determine if students changed their understanding to a different ontological category [14] after the VH intervention. Other future work could investigate the impact of VH simulations on students' long-term retention of concepts learned.

ACKNOWLEDGMENTS

This study was supported in part by the U.S. National Science Foundation under the award #EEC1606396 and the Purdue University Provost Instructional Innovation Grant. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Science Foundation or Purdue University.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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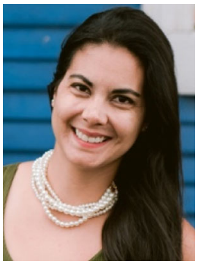

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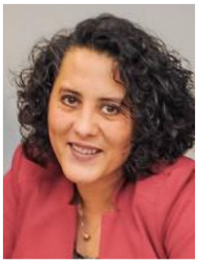

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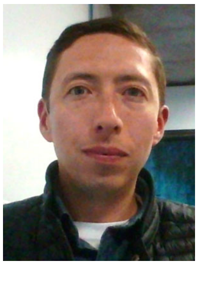

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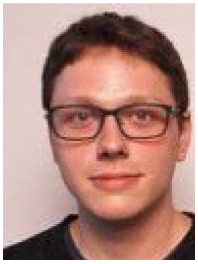

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How to cite this article: Yuksel T, Walsh Y, Magana AJ, et al. Visuohaptic experiments: Exploring the effects of visual and haptic feedback on students' learning of friction concepts. *Comput Appl Eng Educ.* 2019;1–26. https://doi.org/10.1002/cae.22157

APPENDIX A: EXAMPLE OF RUBRIC ITEMS AND CATEGORIZATION

Scenario	Category	Subcategory	Rubric item (what student indicates)
S1	Correct and related with statics items	Friction force statements	Lighter cube means less friction (heavy cube means more friction)
			Friction force acts on Lighter 1 is less than it acts on Heavier 2
		Applied force statements	Light cube requires less force (heavy cube requires more force)
			Light cube is easier to push/move (heavy cube is harder to push/ move)
		Weight statements	Explicitly identify that mass difference is important to calculate friction (heavy cube requires higher force)
		Sliding surface statements	Cubes will eventually stop because cubes' surface are not perfectly smooth
			Cubes requires a small force to start sliding on smooth surface
	Correct but not related with statics items	Cube's distance-displacement-distance	Light cube travels/moves farther (heavy travels less)
			Displacement (distance) among cubes is different
		Cube's motion	Light cube is faster (heavy cube is slower)
			Cubes move at different speeds depending on their masses
		Energy/work to move	Cubes have different kinetic energies
			Different kinetic friction (hard to start moving and then gets easier to move)
	Incorrect items	Weight statements	Different masses do not affect friction
		Friction statements	Friction affects both cubes equally
		Surface (smooth) statements	On frictionless surface heavier cube moves further due to momentum
			After cubes start moving, no force require to continue movement on smooth surface
		Applied force statements	Both cube require no force to move
			Both cubes requires the same force to move (only if the correct assumptions do not apply)
		Cube's distance-displacement	Heavy cube travels/moves farther (light travels less)
			Lighter cube stops sooner than the heavy cube
		Cube's motion	Light cube accelerates slower (heavy cube accelerate faster)
			Both cubes move with the same speed
	Irrelevant items		Cubes would bounce
			The cube would be the same
S2	Correct and related with statics items	Friction force statements	Lighter cube means less friction (heavy cube means more friction)
			FBD: correct friction force representation
		Applied force statements	Light cube requires less force (heavy cube requires more force)
			Light cube is easier to push/move (heavy cube is harder to push/ move)
		Weight statements	Explicitly identify that mass difference is important to calculate friction (heavy cube requires higher force)
		Sliding surface statements	(Compares with S1). Even harder to push both cubes
			(Compares with S1). More force is required for both cubes
	Correct but not related with statics items	Cube's distance-displacement-direction	Light cube travels/moves farther (heavy travels less)
			Light cube stops later (heavy cube stops sooner) (referring to distance)
		Cube's motion	Light cube moves faster than heavy cube

(Continues)

TABLE (Continued)

Scenario	Category	Subcategory	Rubric item (what student indicates)
			Light cube requires less force to move at constant speed (heavy cube requires more force)
		Energy/work to move	Light cube requires less work to move (heavy cube requires more work to move)
			(Compares with S1). Requires more effort for both cubes
	Incorrect items	Weight statement	Different masses do not affect friction
		Friction statements	Friction affects both cubes equally
			$f = \mu mg = ma$ and $a = \mu g$
		Surface (roughness) statements	Rough surface has more friction
			On rough surface, cubes may not move at all
		Applied force statements	Both cubes require the same force to move
			Heavy cube is harder to move, but after it starts moving, it moves smoother than light cube
		Cube's distance-displacement	Both cubes moving at the same speed
			If both cubes move at the same speed, then the resultant force on both cube should be zero
	Irrelevant items		The difference is smaller
			The same results occur
S3	Correct and related with statics items	Friction force statements	Friction force is equal for both cubes
			$F_f = NF_n$
		Applied force statements	Both cubes requires the same force
			Equally hard/easy to push both cubes
		Weight statements	Mass are equal—same weight (explicit reason for no differences)
		Sliding surface statements	Inertia is the same for both cubes. Same force to overcome
			On smooth surface both cubes are easy to push
		Size	Size does not play a role
	Correct but not related with statics items	Cube's distance-displacement-direction	Same distance/travel for both cubes
			Same direction for both cubes
		Cube's motion	Same drag for both cubes
			Same speed for both cubes
		Energy to move	Same amount of work is required to move both cubes
		Cube's features	Small cube is denser
	Incorrect items	Friction statements	Small cube experiences half/less resistance
		Applied force statements	Both cubes require the same amount of force but applied to different areas
			No external force needed to continue movement
		Cube's distance-displacement	Small cube travels/moves farther (big travels less)
		Cube's motion	Small cube is faster (big cube is slower)
			Small cube accelerates faster (big cube accelerate slower)
			Cube 2 accelerates faster than cube 1 b/c $a1 < a2$
		Energy to move	Small cube takes less initial energy than big cube.
		Size	Different size/area/surface different (more or less) applied force
			Different size/area/surface different (more or less) Friction force

(Continues)

TABLE (Continued)

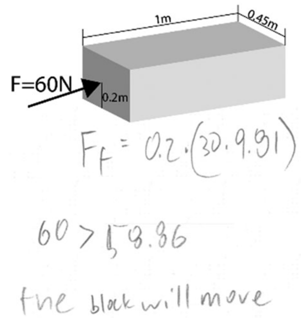
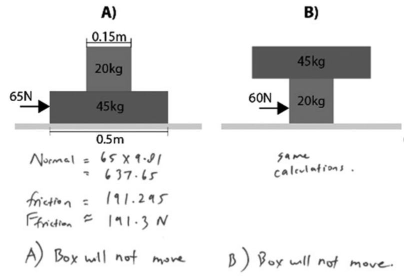
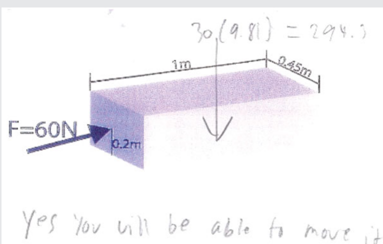
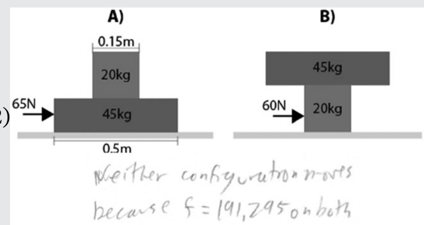
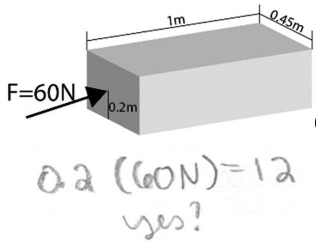
Scenario	Category	Subcategory	Rubric item (what student indicates)
		Others	Same as described in scenario 1(a)
	Irrelevant items		Both cube move and then slow down when you stop pushing.
			inertia is not related with friction
S4	Correct and related with statics items	Friction force statements	The friction force is equal for both cubes
			Static and kinetic friction (hard start and then soft move)
		Applied force statements	Both cubes requires the same force
			Both cubes are equally hard/easy to push both cubes
		Weight statements	The mass are equal—same weight (explicit reason for no differences)
		Sliding surface statements	The inertia is the same for both cubes. Same force to overcome
			On smooth surface both cubes are easy to push
		Size	Indicated that Size does not play a role
	Correct but not related with statics items	Cube's distance-displacement-direction	Same distance/travel for both cubes
			Cubes stop at the same time
		Cube's motion	Both cubes move at the same speed
			Both cubes accelerates the same
		Energy to move	Same amount of work is required to move both cubes
			Both cubes have the same momentum
		Cube's features	Small cube is denser
	Incorrect items	Friction statements	Small cube experiences half/less resistance
		Applied force statements	Both cubes require the same amount of force but applied to different areas
			Small cube requires less force (big cube requires more force)
		Cube's distance-displacement	Small cube travels/moves farther (big travels less)
		Cube's motion	Small cube is faster (big cube is slower)
			Cube 2 accelerates faster than cube 1 b/c $A1 < A2$
		Energy to move	Small cube takes less initial energy than big cube.
		Size	Different size/area/surface different (more or less) applied force
			Cube 3 is like cube 1 b/c it has less contact area than cube 2
		Others	Same as described in scenario 1(a)
			No differences between cubes (no explicit reason why they are different)
	Irrelevant items		Both cube move and then slow down when you stop pushing
			Inertia is not related with friction

APPENDIX B: PARTICIPANTS' ANSWERS FOR THE PREDICTIVE CONCEPTUAL QUESTIONS, IDENTIFIED STATEMENTS AND SELECTED ITEMS OF THE RUBRIC, CATEGORIZATION OF THE ANSWER, AND EXPLANATION OF THE CATEGORIZATION

Participants' answers for the conceptual question	Identified statements and selected items of the rubric	Categorization of the answer	Explanation of the categorization
Both cubes should move about the same distance because of the equal weights (ID22, Scenario 3, Pretest, haptic to visual + haptic treatment group)	(1) Both cubes should move about the same distance (*CORRECT: both cubes travel or move same distance*)(2) … because of the equal weights *(CORRECT: mass are equal or cubes have the same weight (explicitly indicates this reason)*	Correct and complete (CC)	The participant demonstrates good understanding about the friction concept in the answer and shows enough evidence to support it
It starts to move when I push it and gets faster. No difference between Cube 3 and Cube 2. (ID30, Scenario 3, Pretest, haptic to visual + haptic treatment group)	(1) It starts to move when I push it and gets faster. *(NA: It starts to move when I push it and gets faster.)*(2) No difference between Cube 3 and Cube 2 *(CORRECT: both cubes behave the same)*	Correct but incomplete (CN)	The participant demonstrates good understanding about the friction concept in the answer but does not show enough evidence to support it
For cube 3, when you push it on the smooth surface, the same amount of force would be used for cube 2 but the friction would be different in how cube 3 is smaller than cube 2. (ID11, Scenario 3, Pretest, haptic to visual + haptic treatment group)	(1) The same amount of force would be used for cube 2 (*CORRECT: both cubes require the same force*).(2) …but the friction would be different in how cube 3 is smaller than cube 2 (*INCORRECT: differences is area means different friction force*)	Correct and incorrect (CI)	The participant does not demonstrate good understanding about the friction concept and combines CI statements in the answer
Because cube 2 has more surface area than cube 3 contacting the floor, it is going to take more force to move it (ID10, Scenario 3, Pretest, haptic to visual + haptic treatment group)	(1) Because cube 2 has more surface area than cube 3 contacting the floor, it is going to take more force to move it (*INCORRECT: because of the different size, area or surface means more or less applied force for cube 2*)	Incorrect (I)	The participant does not demonstrate good understanding about the friction concept and provide just incorrect statements in the answer
The cubes should move in the same manner (ID22, scenario 3, Pretest, visual to visual + haptic treatment group)	(1) The cubes should move in the same manner *(NA: no differences between cubes, i.e., no explicit reason why they are different)*	NA	The participant does not demonstrate good understanding about friction concepts. The student provided an answer with statements that cannot be categorized due lack of context or ambiguous language

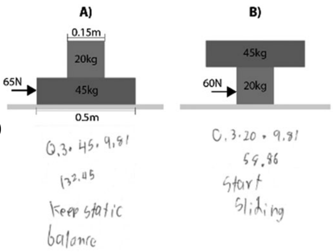
The classification of a given answer did not only depend on the number of items checked in the rubric (Table 2), but it also depended on the kind of evidence provided by the participant. For example, participant ID30 answered using two statements, one correct which is a scientifically acceptable answer to the question (*No difference between Cube 3 and Cube 2*) and one NA which is not related to the answer of the question (*It starts to move when I push it and gets faster*). Participant ID22 answered the same question by using two statements too, both correct. ID22 is an example of CC answer while ID30 correct but incomplete answer.

APPENDIX C: ANSWERS FOR THE PROCEDURAL QUESTIONS, IDENTIFIED STATEMENTS AND SELECTED ITEMS OF THE RUBRIC, CATEGORIZATION OF THE ANSWERS AND EXPLANATION OF THE CATEGORIZATION

Participants' answers for both procedural questions	Identified statements and selected items of the rubric	Categorization of the answer	Explanation of the categorization
 (ID22, Procedural question 1, Posttest, visual→visual+haptic treatment group).-  (ID17, Procedural question 2, Posttest, visual→visual+haptic treatment group).	(1) CORRECT: Correct calculation and explanation: The applied force is bigger than friction force. Hence, the block moves. (2A) CORRECT: Correct calculation and answer: the block not will move (procedural question 1) 2B) CORRECT: Correct answer: the block will not move (procedural question 2)	Correct and complete (CC)	The participant demonstrates good mathematical understanding and skills to solve the problem and interpretation of the result (correct conceptual answer).
 (ID8, Pretest, haptic→visual+haptic treatment Group 2)  (ID29, Pretest, haptic→visual+haptic treatment group)	1) INCOMPLETE: Incomplete calculation or no calculations 2A) CORRECT: Correct answer: the block will move	Correct but incomplete (CN)	The participant does not demonstrate any mathematical understanding and skills to solve the problem and the conceptual answer is correct.
 (ID24, Pretest, haptic→visual+haptic treatment Group	1) INCORRECT: CALCULATIONS 2) INCORRECT ANSWER: answer is incorrect or hard to interpret.	Incorrect (I)	The participant does not demonstrate good mathematical understanding and skills to solve the problem and the conceptual answer is incorrect.

(Continues)

TABLE (Continued)

Participants' answers for both procedural questions	Identified statements and selected items of the rubric	Categorization of the answer	Explanation of the categorization
2)  (ID30, Posttest, visual→visual+haptic treatment group)			
No answer	No items/ no answer	NA	The participant leaves the question in blank