Exploration of Affordances of Visuo-Haptic Simulations to Learn the Concept of Friction

Tugba Yuksel
Department of Curriculum and Instruction and Department of Physics and Astronomy
Purdue University
West Lafayette, Indiana 47907
Email: tyuksel@purdue.edu

Yoselyn Walsh
Department of Computer and Information Technology
Purdue University
West Lafayette, Indiana 47907
Email: ywalsh@purdue.edu

Vojtech Krs
Department of Computer Graphics Technology
Purdue University
West Lafayette, Indiana 47907
Email: vkrs@purdue.edu

Bedrich Benes
Department of Computer Graphics Technology
Purdue University
West Lafayette, Indiana 47907
bbenes@purdue.edu

Ida B. Ngambeki
Department of Computer and Information Technology
Purdue University
West Lafayette, Indiana 47907
ingambek@purdue.edu

Edward J. Berger
School of Engineering Education
Purdue University
West Lafayette, Indiana 47907
bergere@purdue.edu

Alejandra J. Magana
Department of Computer and Information Technology and School of Engineering Education
Purdue University
West Lafayette, Indiana 47907
admagana@purdue.edu

***Abstract*— We explored the affordances of using visuo-haptic simulations to improve conceptual understanding and representational competence of the concept of friction. Visuo-haptic simulations are computer-based simulations that encode mathematical and physical models of certain phenomena and provide visual and tactile feedback. Users can see the simulation and feel the friction with their hand by using a special device connected to a computer. We hypothesized that visual and haptic feedback together can help students to improve learning of friction. We recruited 24 engineering technology students with a previous experience in at least one physics course, and we examined their reasoning and understanding about statics concepts *before* and *after* engaging with visuo-haptic simulations. Our instructional approach included four steps: 1) lecture about friction, 2) pretest, 3) laboratory session, and 4) posttest. The laboratory session consisted of a pre-training session, guided learning materials based on a constructivist framework, and use of the friction visuo-haptic simulation. We report students' prior conceptions of statics concepts, ways in which they interacted and reasoned with each of the different pedagogical tools, and compared reasoning processes, explanations and learning gains. Our results suggest that the visuo-haptic simulation helped students refine their explanations and increased the coherence between their verbal explanation and mathematical representation.**

Keywords—affordances; visuo-haptic simulation; physical manuulatives; conceptual understanding; learning; visual learning

I. Introduction

Constructivist theorists who have studied different approaches to increase students' performance in science and engineering courses have argued that learning occurs best by doing [1-3]. Students' active engagement brings meaningful understanding [4, 5] and at the same time promotes interest and motivation in science learning [6-8]. Previous research has suggested [9,10] that hands-on learning environments can increase students' understanding, motivation to learn science, the use of scientific terminology, and creative thinking. In addition, studies [11,12] have concluded that visual representations improve students' conceptual understanding and engagement. Specifically, studies that have focused on the use of manipulatives for learning have argued that even though physical manipulatives have touch and active involvement factors, virtual experiments are at least equally useful as physical manipulatives [13]. Virtual experiments in educational settings provide accuracy, easy manipulation [14,15], and extra virtual support (e.g., vector representation, color-coding, and numerical values). However, while some research has claimed virtual simulations are effective to support students' conceptual understanding of abstract concepts [16], others have argued that simulations might not be effective as much as physical manipulatives to help understanding of certain concepts, which requires more affordances such as tactile [16,17].

Physical manipulatives and simulations can be combined using visuo-haptic simulations, which are computer-based simulations that use a computer model of certain phenomenon and provide both visual and tactile feedback. The computer is connected to the haptic device providing 3D point probe and force feedback. The user feels the force on their hand while using the simulation an example of which appear later in the paper. Haptic-based experiences can facilitate meaningful learning by combining both virtual and touch feedback perspectives. Haptic technology has been used in many different fields from medical training [18] to assisting visually impaired individuals [19]. Recent efforts using haptic devices in educational settings have demonstrated that learners could improve their understanding of scientific concepts and particularly abstract phenomena by having both hands-on experience [20-25] and virtual cues at the same time.

In this paper, we focus on the concept of friction that is one of the key elements of engineering design [26, 27]. Tens of thousands of students take at least one course in statics in engineering programs around the world each semester. Deep conceptual understanding of statics can strengthen more advanced concepts (i.e., fluids and dynamics), and can help to solve other engineering problems. We explore the affordances of visuo-haptic simulations to improve students' conceptual understanding of friction. In particular, we address the following research questions:

1) What are students' initial understanding and predictions of static friction force between different size and mass bodies and surfaces, which have different coefficients of static friction?

2) How does experiencing visuo-haptic simulations help to enhance students' conceptual understanding and representational competence of static friction?

II. FRICTION EXPERIMENT

We have developed a physical experiment (see Figure II.1) and a visuo-haptic simulation (section III) as part of our large-scale study. Physical experiments informed the design of the visuo-haptic simulation and allowed the comparison of affordances between two different tactile learning tools as a facilitator of conceptual development [28]. The friction experiment explored the effect of object mass and size on surfaces with different friction coefficients. We used three 3D printed cubes. Cubes 1 and 2 had the same size but different weight (Cube 2 is twice as heavy as Cube 1). Cube 3 was half the length side of Cubes 1 and 2, and Cube 3 was the same weight as Cube 2.

Figure II.1. Physical experiment used three cubes and three different surfaces.

The three cubes were used in conjunction with a board that was covered with three different surfaces (smooth, medium, and rough). These surfaces had correlating coefficients of friction (low, medium, and high). Surfaces used in the experiment were cardboard (smooth-low friction), fabric (medium, medium friction), and foam (rough, high friction). The amount of force required by the user to slide objects on each surface depended on the surface and the mass of the object.

During the experiment, students were asked to verbally predict the result of four scenarios. Scenarios were:

1. *What happens if you push two objects made from the same material and with the same size, but with different weights (one half the weight of the other) on a smooth surface?*
2. *What if you push the same objects on a rough surface?*
3. *What if, instead of having the previous objects, you push two objects with the same weight but different sizes (one is half the size of the other) on a smooth surface?*
4. *What if you push the previous objects on a rough surface?*

We did not use any technical words such as force, friction, coefficient of friction, etc. to prevent any possible loss of insights regarding students' ideas and related reasoning. Once the participants made predictions for each scenario, the physical manipulative was introduced. Participants first got familiar with the environment: the surfaces and cubes. They manually manipulated each cube and slid them on each surface. At the end of the recognition phase, students became familiar with Cubes 1 and 2 and the cardboard surfaces as the elements to be used for scenarios 1 and 2. Students identified Cubes 2 and 3 and the fabric surface as the elements needed to test scenarios 3 and 4. Finally, they recognized weight, physical dimensions, and roughness via both visual observation and touch.

III. VISUO-HAPTIC EXPERIMENT

The objective of the visuo-haptic simulation was to replicate the physical experiment from Section II, but also to take advantage of the additional affordances of the computer to provide feedback, such as arrows indicating forces, color-coding, etc. Moreover, we could disable certain features, such as the visual or the haptic feedback or 3D cross-hair cursor, which is impossible in the physical experiment. Details about the user-centered design process and implementation of the simulation can be found in detail in [28]. Below we provide only the most relevant information.

The visuo-haptic simulation was implemented in C++ using Chai3D, OpenGL, and GLSL. The system was tested on a laptop computer with Intel i7 CPU @ 2.2GHz, 16GB of memory, and Intel® Iris™ Graphics 540 card. The force feedback was generated by the Falcon Novint® device. Figures III.1 and III.2 show a screenshot of the visuo-haptic simulation and a user working with the Falcon Haptic device. The user pushes the cube in the simulation, and the arrow indicates the force. We used a 3D cross-hair cursor to indicate the position of the haptic cursor as well as shadows and walls bounding the simulation environment. The ruler, as in the physical manipulative tool, helped to measure displacement of the cube. (See also the video here: https://www.youtube.com/watch?v=71vQRRU-IU0)

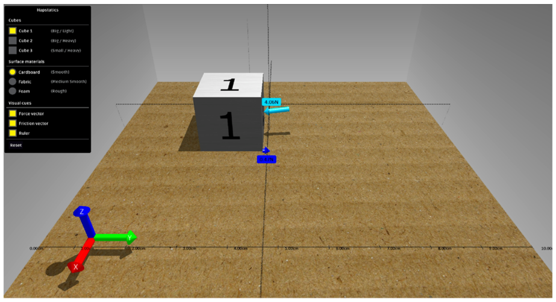


Figure III. 1: Visuo-haptic simulation shows the coordinate system, the 3D cross-hair cursor (black lines perpendicular to the axis of the coordinate system), and the applied force

The system allowed the user to use the mouse to set some options in the control panel (upper left part of Figure III. 1) that switched the cubes, surfaces, and turned on/off certain visual cues. Interaction with the cubes was possible only by using the haptic device. During the experiments, instructions on how and when to use were provided to the participants.

Three cubes can be added to the scene at the same time. The cubes follow the description from Section II; i.e., two with the same size but different mass and a third one, half the size and the same mass as the heavier cube. Figure III.2 shows a participant interacting with the visuo-haptic simulation with the three cubes in the scene on the rough surface.

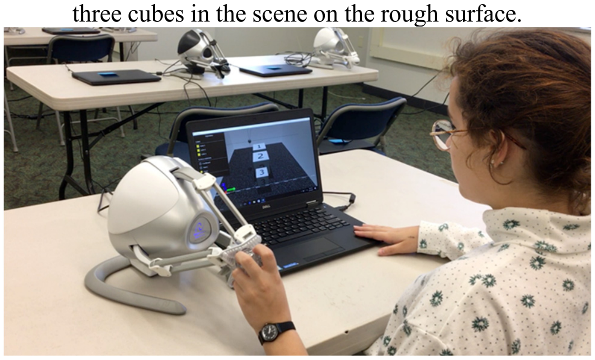


Figure III.2 User manipulates the haptic device and the system provides visual and tactile feedback.

The participants could replicate the practical experimental settings. We made sure the simulation followed realistic parameter values and that the user similarly engaged with the physical and the virtual environments. The haptic simulation was calibrated to match the physical experiment. In particular, we matched the physical limitations of the haptic device such as the dynamic range of the generated forces.

The visuo-haptic simulation used additional visual cues such as force vectors, a friction vector, and 3D coordinate axis. Force and friction vectors were represented with an arrow and a label (Figure III.1). Arrow length corresponded to the force exerted by the participant and the surface (longer arrow implied larger force). The label was the magnitude of force exerted (numerical value).

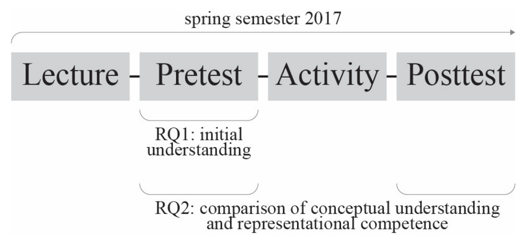
IV. PARTICIPANTS

Twenty-four participants of this study were engineering technology from a Midwest university in USA. The data were collected from the students who were enrolled on one laboratory session of an Applied Statics course during the spring 2017 semester. The course consisted of two lectures (one hour each) and one lab section (2 hours) per week. Participants were 20 males and 4 females. Among the participants, 21 had taken one or more courses, which introduced to them concepts in statics (e.g., force and motion) in high school and the Applied Statics course was the first undergraduate level physics course for 12 of the students.

V. PROCEDURES

A. Overview

Our procedure (see Figure V.2) consisted of four steps: 1) lecture, 2) pretest, 3) activity session, and 4) posttest. Research question one (see Section I) about initial understanding and predictions about statics concepts was answered by analyzing the pretest responses. Comparisons of the pretest and the posttest helped to answer research question two.



FigureV.2 Method overview

Students first received a lecture on friction prior to the experimental activity. Students attended either a lecture one day before of the laboratory session or three days before the experiment. The content of the lecture was the same for both sessions. To retain consistency, students received the same instruction from the course professor and took the pretest at the end of the lecture about friction. The pretest followed the structure described in Part A of Section V.

B. Pretest & Posttest Design

The visuo-haptic project was conducted as part of an ongoing design-based research (DBR) project. Design-based research enables researchers to understand how learning occurs in an innovative setting that can be engineered and designed by referring to learners' needs and conditions [30]. DBR involves a sequence of design revisions, iterative refinements, and implementation stages.

The data collection consisted of qualitative questions. Qualitative questions allow us to identify student's underlying reasons and insights into the nature of friction forces. The abstract nature of forces in general (static friction, normal force, gravitational force, etc.) brings along many conceptual difficulties and non-normative understandings for many students [26, 27, 31], because forces cannot be 'seen' in a visual sense. Questions were designed based on the statics concept inventory (SCI) [26] and aligned with our learning objectives.

The pretest consisted of declarative and procedural questions. For this paper, we analyzed four declarative and one procedural questions. For declarative questions we used the same scenarios stated in Section II, which were four what-if scenarios using cubes with different sizes and mass on different surfaces with different correlating coefficients of frictions. In the analysis, we looked at students' responses to descriptive questions to monitor changes in their conceptual understanding.

The procedural question consisted of two uniform boxes attached and positioned on their long side and short side (Figure V.1 left and right) on a surface where the coefficient of static friction was 0.3. The question was: what would happen with the boxes on each scenario: slide or keep static balance, if a force of 65N was applied on the bottom box. Students were required to draw free body diagrams, and do the calculations.

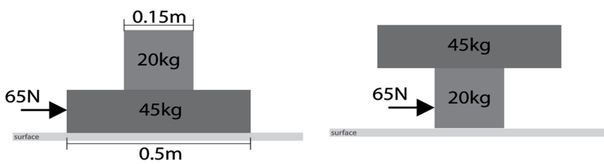


Figure V.1 Procedural question

Alignment of scenarios 3 and 4 had the same mass but different size cubes located on rough and smooth surface. The procedural question helped to determine whether students could construct a coherent understanding between verbal explanations and mathematical representations.

C. Activity Design

The activity took place during a lab section of the course. First students received an introduction about haptic technology, followed by a pre-training session. Participants engaged with a haptic simulation about buoyancy as a pre-training session to get accustomed to the haptic feedback. Pre-training sessions helped students bypass the "gee-whiz" phase of working with haptic systems and minimized any consequent effects on data collection. Students recorded their observations and related notes on a worksheet. The pre-training session finished with conceptual questions about buoyancy.

The activity was designed using a four-phase framework, inspired by White and Gunstone's [29] three-phase approach, for the experimental protocol:

1. recall: participants were encouraged to remember their prior knowledge about friction, as learned in a previous physics course.
2. prediction: participants predicted the outcome of a given scenario or experiment.
3. observation: participants made an experimental observation (physical or virtual) about the given scenario.
4. confirmation: participants compared and contrasted their predictions and observations, including further review of visuo-haptic simulation results with and without various visual cues.

Students did not use the simulation during recall and prediction phases, but instead documented their prior knowledge about friction forces and their predictions for the given scenarios.

Once finished, students launched the simulation and observation phase of the experiment began. In this phase, students engaged with the visuo-haptic simulation in four parts, starting with a recognition stage in which they examined the (virtual) cubes and explored in an unstructured way the surface friction. The observation then proceeded with three different friction scenarios involved various combinations of cubes and surfaces. Figure V.3A shows a screenshot of the visuo-haptic simulation where Cube 2 is being manipulated. Figure V.3B shows the interaction with the haptic device: students first grabbed the cube positioning the cursor on the top of it and pulled it up.

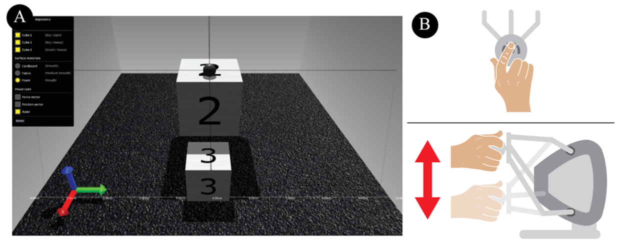


Figure V.3 Manipulating the virtual object by using haptic device.

In scenario 1, the participants pushed Cube 1 on cardboard (low friction), the fabric (medium friction) and then foam (high friction). Students recorded their observations about what they felt and saw. For the second scenario, the participants pushed Cube 2 on cardboard, fabric, and foam. Participants again recorded their observations and compared with scenario 1. During scenario 3, the participants pushed Cube 3 on cardboard, the fabric and then foam and recorded observations about what they felt and saw in comparison with Configurations 1 and 2.

D. Data Analysis

To approach our research questions (Section I), we used an open coding strategy, which allowed us to develop working codes and categories to classify students' common ideas about friction [32, 33]. We identified all scientifically accurate and inaccurate concepts brought up by students before the experiment and categorized them under a common theme.

To answer our second research question, after engaging with the visuo-haptic simulation, we looked at the changes in students' explanations of the phenomena before and after their experience with the visuo-haptic simulation as well as coherence in their responses.

VI. Results

A. Research Question 1:Students' initial understanding and predictions of static friction force

The analysis of individual responses for the pretest questions that asked about the force required to push objects having the same size and different mass on smooth and rough surfaces (scenarios 1 and 2) indicated that Cube 1 (small mass object) is easier to push as compared to Cube 2 (greater mass object). It was, however, at times particularly difficult to interpret if students were aware of mass' role in friction force since they did not mention it in their answers. Some students supported their ideas by referring to momentum or energy concepts, which they thought were bigger for Cube 2 because of the bigger mass. In their words: "If both cubes are moving at the same speed, the main differences are going to be the kinetic energy of each object due to the equation $KE=1/2mv^2$ (S20)" or "If it is frictionless, the heavier block will move faster due to the momentum" (S18)

The most challenging concept was the surface contact area size and friction force relation (scenarios 3 and 4). Many students believed that if the contact area is bigger, it is difficult to move the objects. In this case, cube 2 was more difficult to move than cube 3. Moreover, most students indicated that friction force is always equal to normal force times the coefficient of friction even for the objects which were in not sliding. This idea demonstrates students' incomplete understanding even though they completed a statics lesson before the study.

Table VI.1 shows students' common normative (correct) and non-normative (incorrect) ideas about friction against a smooth or rough surface, and cubes with same size and different mass (scenario 1 and 2) or different size and same mass (scenarios 3 and 4).

Table VI.1:
Students' Initial normative & non-normative Conceptions

Students' conceptions (pretest)	Counts
Heavier objects experience larger friction force (Normative)	14
Cube 2 is harder to push (no supportive argument) (Normative but incomplete)	13
Among same mass objects, the physically larger one is harder to push (more contact area) (Non-normative)	9
On a Smooth Surface, friction is same for all objects (Non-normative)	7
Same mass but different size objects require the same force to move (no supportive argument) (Normative but incomplete)	6
Smooth Surface = Frictionless Surface (Non-normative)	4
Same mass but different size objects require the same force to move because size does not matter (Normative)	4
Heavier objects move further because of their momentum (or energy) (Non-normative)	3
Among same mass objects, the smaller one is harder to push (more dense, or smaller contact area) (Non-normative)	2
Same mass but different size objects require the same force to move but friction they experience is different due to the size difference (Non-normative)	2
On a rough surface, heavier objects move faster (or Travel further) (Non-normative)	2
Surface smoothness or roughness does not affect friction (Non-normative)	1
Lighter objects require less force to move, but heavier objects move more easily after overcoming static friction (Non-normative)	1
Different masses experience the same friction force (Non-normative)	1
If the size of the objects are different, mass does not play a big role on friction (Non-normative)	1

A set of students' verbal explanations in pretest questions are given below as examples of their normative and non-normative conceptions.

Heavy objects are exposed to bigger friction force.

S3: Cube 1 will require less force due to it having a lower normal force $F=\mu f_n$ (Normative)

S10: Cube 1 will move faster than the heavier Cube 2 because less force is required to move a lighter object. Also, being lighter means less friction between the bottom of the cube and the surface. (Non-normative)

Student S3 indicated that cube 1 had lower mass and consequently lower gravitational force and wrote the friction force equation. He used the term "normal force" to refer to gravitational force. S10, on the other hand, talked about kinetic friction instead of static friction. He indicated an inverse relationship between friction and mass of the objects.

S18: If it is frictionless, the heavier block will move further due to momentum. (Non-normative)

S28: The cube would move forward sliding until friction caused the cube to stop, because the surfaces are not perfectly smooth. Cube 2 assuming it was pushed with the same amount of force would slide for a longer period because it will have a larger momentum (caused by a larger weight). (Non-normative)

Both students S18 and S28 indicated that heavier objects move further in comparison to lighter objects due to their large momentum. These students used their knowledge of linear momentum to explain friction forces. Although S28 was aware that friction force makes moving objects more difficult, neither participant mentioned that friction force between heavier objects and the surface would be more than it is between lighter objects and the surface.

S6: The Cube 2 and Cube 3 would have the same resistance due to inertia but cube 3 would have half the resistance due to friction as Cube 2. (Non-normative)

Some students incorrectly illustrated their understanding that the force applied for just starting to move an object is different than the friction force. For example, even though S6 showed an accurate understanding that the same mass objects' resistance to move would be the same; he thought friction force for the object with smaller contact area would be smaller. This participant's reasoning indicated that that surface area-friction force relation is a challenging concept for some students and sometimes it might be difficult to change.

S10: Because Cube 2 has more surface area than Cube 3 contacting the floor, it is going to take more force to move it. (Non-normative)

S19: Due to the increased surface area touching the smooth surface (the bottom), the larger cube would *have more friction acting on it than the smaller cube with less surface area. (Non-normative)*

B. *Research Question 2. How visuo-haptic simulations enhance conceptual understanding and representational competence of static friction*

To answer this research question, declarative and procedural questions were analyzed in the pretest and posttest. Three types of analyses were performed. First, we compared answers from each of the questions on the pretest and posttest assessments (Figure VI.1). Second, we examined verbal consistency by analyzing the language used by students to describe phenomena for each scenario in the pretest and posttest (Figure VI.2). Third, we analyzed verbal-mathematical consistency by comparing the responses of scenarios 3 and 4 (same mass, different size on smooth or rough surface) with the procedural questions on the pretest and posttest.

Participants' answers on each scenario were categorized as complete, incomplete, incorrect, irrelevant, or no answer. A complete answer was accepted when students predicted the scenario correctly and included all variables such as gravitational force and coefficient of friction of different surfaces. For example:

S10. Cube 1 will move faster than the heavier Cube 2 because less force is required to move a lighter object. Also, being lighter means less friction between the bottom of the cube and the surface. (Incomplete)

Incomplete answers were those where the participants correctly predicted the result of the scenario but missed important details.

S2. It would be more difficult to push Cube 2. (Incomplete)

In this case, the reason why pushing Cube 2 was more difficult was missed (i.e., heavier, due it mass). A wrong answer was when participants predicted incorrectly the scenario.

S11. Cube 1 would require the same force to move as Cube 2 because the force does not necessarily matter on a smooth surface. (Non-normative)

In the previous example, the student assumed that a smooth surface has no friction. As shown in Figure VI.1, for all scenarios, students revised their incorrect answers after visuo-haptic experience. However, for the first and second scenario, the number of complete answers decreased and the number of incomplete answers increased in the posttest. We believe that was because mass contribution to the friction force became very obvious for most students, so they did not mention that again in their answers. The figure also presents patterns suggesting that after engaging with the visuo-haptic simulation, many students overcame their conceptual challenges about contact area-friction force relation since the number of incorrect answer to scenario 3 decreased. The number of students who realized that the size of the cubes does not affect friction force if the masses are equal increased in the posttest. Furthermore, more students were able to show their understanding with a mathematical calculation (see Figure VI.4).

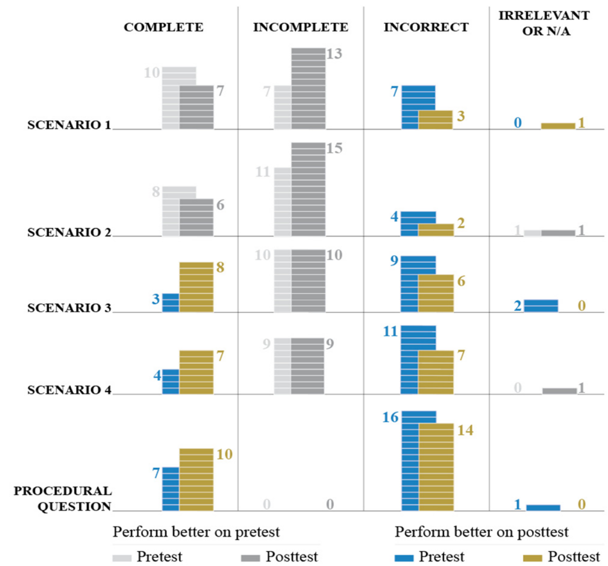


Figure VI.1 Comparison of results pretest vs posttest

Figure VI.1 shows a comparison of results in pre-and post-test for each scenario.

Participants used three ways to describe the effect of the cube when a force is applied: using force, speed and distance terminology. Students used force terminology when the answer was based on the force required to slide the cube. This category includes adjectives such as easy and difficult.

S2. It would be more difficult to push cube 2.

S17. The same amount of force would be required to push each cube

Students used speed when they refer to how fast or slow the cube travels.

S21. Cube 1 moves faster, because less friction while cube 2 moves slower.

Some students also mentioned distance when they refer to how far the cube is when the force is applied.

S28. Both cubes would move the same distance as the other…

Figure VI.2 compares the frequency of using the terms such as force, speed and distance in each scenario.

To be able to examine if students could support their verbal explanation with a mathematical representation or vice versa, we analyzed the verbal and mathematical consistency in pretest and posttest. We believe that an accurate consistency between verbal explanations and verbal-mathematical representations are a significant indicator of a sufficient conceptual understanding. For that purpose, we analyzed scenario 3 and 4 with the procedural question. In both cases, the misconception of surface area affecting the friction properties was addressed; first by words, and then by the drawing. For example, if a participant correctly answered both scenarios, that answer belongs to the correct-correct category. If a participant incorrectly predicted one of the scenarios and provided an incomplete answer on the other scenario, that participant's answers belonged to the inconsistency category. The procedural question was classified as correct or incorrect.

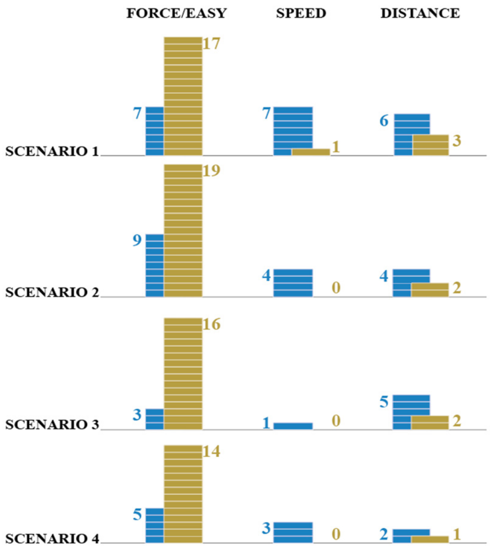


Figure VI.2 Comparison of results in pretest - posttest

Posttest analysis showed more verbal-verbal consistency for scenarios 3 and 4, which asked the same concepts from a different angle. We considered there was consistency when students responded to both questions correctly. Students had more complete and incomplete answers in the posttest than they did in the pretest. Fewer students were identified in the incorrect-incorrect category in the posttest. Additionally, the number of inconsistencies in verbal-verbal and verbal-math representations decreased in the posttest.

Correct procedural answers were more frequent in posttest (n=10) than in pretest (n=7). Students with correct and incomplete verbal consistency were able to perform correctly on the procedural question in the posttest than in the pretest. Figure VI.3 shows the results of verbal and mathematical consistency in pretest and posttest.

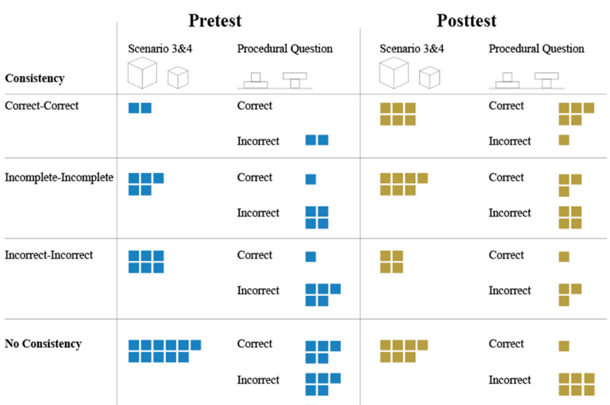


Figure VI.3 verbal and mathematical consistency results

Below, S23's pre- and post-test verbal and mathematical representation is given as an example of change in consistency in students' understanding. In the pretest the participant belonged to the *no verbal consistency* category for scenario 3 and 4 and *correct answer category* in the procedural question. In the posttest, the participant shifted to the category of correct-correct verbal consistency for scenario 3 and 4 and correct answer category for the procedural question.

Pre-test:

> *Q3: Again both cubes would take the same amount of force to move* (correct answer)
> *Q4: Cube 2 would be harder to move because greater area touching the rough surface* (incorrect answer)
> *Q6:* (correct answer)

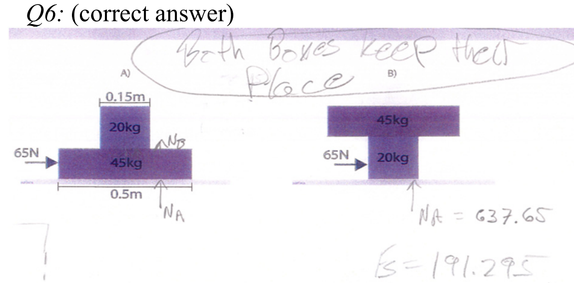


Figure VII.4 Student 23's pretest response to Q6

Post-test:

> *Q3: Both cube 3 and 2 would take the same force to move them because they weight [sic] the same.* (correct answer)
> *Q4: The same result as part c* [question 3]. *They both would require the same force to move. This force would just be greater* (correct answer)
> *Q6:* (correct answer*)*

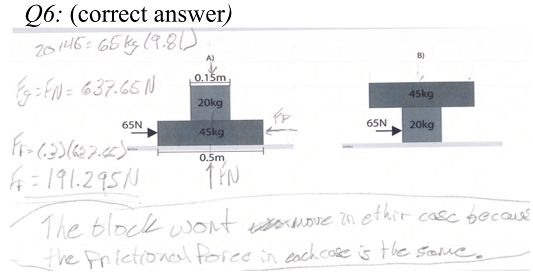


Figure VII.5 Student S23's posttest response to Q6

Although the mathematical representation was scientifically accurate, student S23's verbal responses were incomplete and incorrect before he engaged with the visuo-haptic simulation. His post-test answers indicated that the simulation helped him to change his verbal explanation and have consistency between verbal-verbal and verbal-mathematical representations.

VII. Discussion

This study aimed to 1) explore student initial conceptual understanding of friction force between surfaces having different coefficient of friction and cubes having different masses and sizes, and 2) identify how engagement with visuo-haptic simulation affects students' conceptual representation and understanding of static friction. Students performed better in general after engaging with the visuo-haptic simulation than in the pretest, as evidenced by students use of more accurate terminology in the posttest and an increase in the number of correct answers regarding the consistency between their verbal-verbal explanations and verbal-mathematical representations. Our results are therefore aligned with Magana and Balachandran [24]'s study where they showed increment in students' conceptual understanding about electricity and magnetism by using haptic simulation.

The results of this study for the first research question are consistent with many current research studies, which have attempted to reveal misconceptions in statics [26], [27], [36], [37], [39]. Especially, our results are aligned with the findings presented in Steif's [35]. One of the common themes that arose from pretest answers of the students who completed the formal statics instruction was that friction force is always equal to normal force times the coefficient of friction even for the objects which are not sliding. This result shows similarity with the results previously found in Steif and Dantzler [26] and Steif and Dollar' studies [27]. Another frequently encountered assumption brought up by students were that friction is negligible for smooth surfaces and it requires more force to move objects on rough surfaces. Students tended to make this assumption naturally before they actually made observations on both surfaces by pushing the cubes. We believe that these kinds of assumptions could be attributed to the way statics concepts are differently taught in high school physics and engineering. For instance, in some physics problems, some surfaces (e.g. ice) are assumed to be frictionless for simplification purpose. In reality, unless it is specifically indicated, all surfaces more or less have coefficient of friction, even glass on glass have coefficient of friction ~0.94. In contrast, in engineering, friction is considered as negligible for smooth surfaces.

Specifically, in physics force and motion are taught together, while in engineering statics and dynamics are taught separately. As it can be observed from students' responses on the pretest (Table VI.1), some of students' explanations confluence dynamics and statics concepts in their explanations, such as using the technical definition of momentum to explain the forces required to start sliding a box on different surfaces. Again, we believe this could be attributed to the way statics concepts are taught differently in physics and engineering.

Although most students conceptualized that static friction is bigger for the heavier objects, they did not specify this detail in their verbal explanations. That means, students who gave a correct answer for the question that asked them to compare the force required to move light and heavy objects, they did not elaborate their answers by providing their reasoning. However, we identified an increment in the number of students who correctly and in detail compared forces in posttest.

Some students identified the friction force during the motion of the cubes by using the terms "slowing down faster", "go faster/slower" and "go further" in the pretest, similar to Halloun and Hestenes's [37] findings. These students most likely used this terminology based on their knowledge of one-dimensional motion under a constant force.

Similar to Smith, Snir and Grosslight's findings [38] with sixth and seventh graders, students had confusion to differentiate between mass and density of the objects. Before engagement with the visuo-haptic simulation, students' frequent non-normative ideas about friction of two different sizes but same mass objects on smooth or rough surfaces were either: (i) bigger cube requires more force to move than smaller cube because of the bigger contact area, or (ii) smaller cube requires more force to move than bigger cube because of its density. However, the posttest responses revealed that the visuo-haptic simulation appeared to help some students to review and revise their understanding while some students held their original model of friction dependence on contact area, which is aligned with Besson et al.'s findings [39].

In this study we also examined the consistency of students' verbal explanations and mathematical representations. We detected less verbal coherence in the pretest than after the use of the visuo-haptic simulation. We find this result quite aligned with Marsh's [40] findings about the relationship between verbal and mathematical achievement. Students who had incomplete or incorrect verbal explanations tended to give incorrect mathematical representation to similar questions. Moreover, 5 students performed a correct-correct verbal consistency and answered correctly the procedural question. No students performed correctly in all categories in the pretest. In general, the findings of this research confirm the premise that the concepts of statics are very challenging for learners to completely understand and to apply in different situations. However, the use of visuo-haptic simulations has some promise to increase conceptual understanding by being a good cognitive mediator.

VIII. CONCLUSION & FUTURE WORK

This paper discusses affordances of visuo-haptic simulations (combination of force feedback and visual cues) supported with guided learning materials in undergraduate engineering students' conceptual understanding of friction concept. The overall results suggest that students performed better in terms of explanation and use of accurate terminology after the implementation. Additionally, as indicator of meaningful understanding, there seemed to be more coherencies in students' answers to procedural questions.

As the large-scale research continues, we will work to improve our learning materials and visuo-haptic simulation to address the limitations or user challenges that we might have faced during the implementation. Additionally, our research group is currently working on developing two other visuo-haptic simulations and supported learning materials in two other statics concepts (truss and pulleys). At this point our primary goals are 1) exploring affordances and constrains of visuo-haptic simulations across different statics concepts, 2) comparing the conceptual understanding after receiving only visual feedback versus haptic and visual feedback.

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