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

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***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 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 coherency between their verbal explanation and mathematical representation.**

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

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, 2, 3]. Students' active engagement brings a meaningful understanding along with it [4, 5] and it promotes interest and motivation in science learning [6, 7]. Active learning occurs when students engage and take responsibility for their own learning [8]. Research has proved [9, 10] that hands-on learning environments increase students' understanding, motivation to learn science, the use of scientific terminology, and creative thinking.

Other studies [11,12] examined the best way of promoting active learning and they concluded that visual representations improve students' conceptual understanding and engagement. Furthermore, studies argue 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 such as vector representation, color-coding, and numerical values. However, while some research has claimed that virtual simulations are effective to support students' conceptual understanding of abstract concepts [16], others argued that it might not be effective to help understanding of certain concepts [17].

Physical manipulatives and simulations can be combined using visuo-haptic simulations that 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 a force feedback. The user feels the force on their hand while using the simulation (see an example in Figure III.2). Haptic-based experiences 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, 21, 22, 23, 24, 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 cubes 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?

Our results indicate that even though students received friction instruction just before pre-test, they still had many conceptual difficulties about the friction force between different objects with varying mass and size and surfaces with different friction coefficients. After completing the visuo-haptic simulation, most students revised their model of friction while some students maintained their initial non-normative ideas.

II. Friction experiment

We have developed a physical experiment (see Figure II.1) and a visuo-haptic simulation. 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 have the same size but different weight (Cube 2 is twice as heavy as Cube 1). Cube 3 is half the size of Cubes 1 and 2, and Cube 3 is 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 three different surfaces (smooth, medium, and rough). These surfaces had correlating coefficients of frictions (low, medium, and high). Surfaces used in the experiment are cardboard (smooth-low friction), fabric (medium, smooth-medium friction), and foam (rough, high friction). The amount of force required by the user to slide objects on each surface depends on the surface and the mass of the object.

During the experimental part students were asked to verbally predict the result of four scenarios. Scenarios are:

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 environment: the surfaces and cubes. They manually manipulated each cube and slid them on each surface. At the end of the recognition phase, users became familiar with Cubes 1 and 2 and the cardboard surface as the elements to be used for scenarios 1 and 2. Users identified Cubes 2 and 3 and the fabric surface as the elements needed to test scenarios 3 and 4. Finally, they recognized weight, measures, softness and roughness by visually observing and using their sense of touching.

Our analysis revealed three important results commonly brought up by students. First, participants had a higher level of engagement and motivation during the interaction with the physical manipulative. Second, participants had difficulties in the interpretation of the tactile feedback and confused density with weight and softness with smoothness. Students claimed that Cube 3 is heavier than 2 because it is denser (no heavier). They also indicated that foam is smooth because it is a soft material. Third, students concluded that Cubes 2 and 3 require different amount of force to be slid the same distance due the different surface areas.

III. VISUO-HAPTIC EXPERIMENT

The objective of the visuo-haptic simulation was to replicate the physical experiment from Section II, but also take advantage of the additional affordances of the computer to provide feedback that is impossible in real settings, 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 real world.

The design process and implementation of the features of the simulation followed a user-centered design based on the affordances of the physical manipulative tools to learn statics concepts and the affordances of visuo-haptic simulations as learning environments. Details about the design process of the simulation can be found in [Authors, 2017]. 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. FigureIII.1 and III.2 show a screenshot of the visuo-haptic simulation and the user working with the Falcon Haptic device. The user pushes the box 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 the 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)

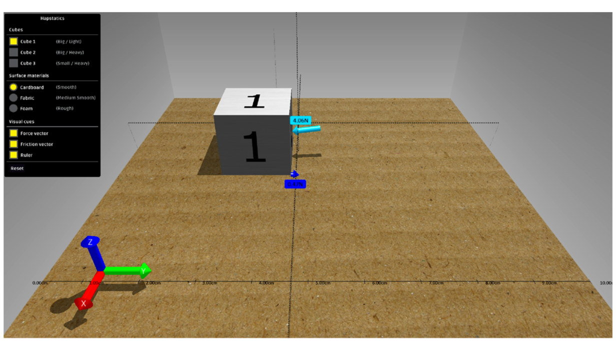


Figure III. 1: Visuo-haptic simulation shows the coordinate system, the 3D cross-hair cursor, and the applied force

The user could 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 is possible only by using the haptic device.

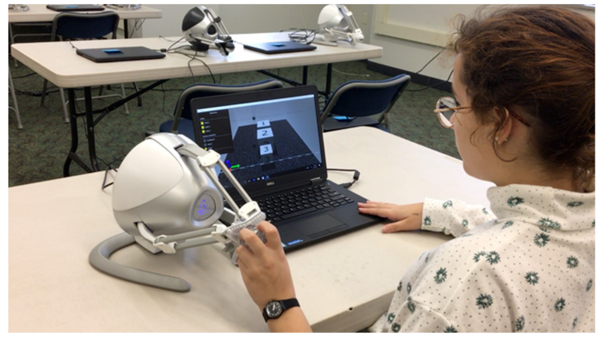


Figure III.2 User manipulates with the haptic device and the system provides visual and tactile feedback.

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.

The participants could replicate the practical experimental settings. We made sure the simulation followed used realistic parameter values and the user engaged with the simulation by using the same parameter in both the real and the virtual environments.

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. Arrows length corresponded to the force exerted by the participant and the surface (longer arrow implies larger force). The label is the magnitude of force exerted (numerical value).

IV. LEARNING MATERIALS DESIGN

The main purpose of the educational innovations is promoting efficient leaning and understanding of given information for all learners. Within a constructivist framework, students are encouraged to critically think, analyze, experience, revise and build knowledge piece by piece. White and Gunstone [29] proposed three phases to closely investigate learning and understanding. They stated these three phases as 'prediction' where students are expected to predict the possible result of given situation, 'observation' where students actually see and experience what happen, and 'explanation' where they compare and contrast their prediction and observation. In the large-scale study, we adopted the three-phase concept [29].

The sequence of the learning activity started with the recall phase. In this stage, learners are encouraged to remember their prior knowledge, which they presumably acquired in previous course(s). The next two stages were prediction phase and experimentation and observation phase. Observation and experimentation phase was followed by reflection phase where students had a chance to apply their learning to solve/answer isomorphic conceptual and simple calculation questions.

The last phase is called confirmation, which is similar to the explanation phase proposed by [29]. Additionally, in this phase, students compared their experience of visuo-haptic simulation with visual cues, which were available to them only when they completed their reflection. These five phases were designed as guidance for learners.

V. Methodology

A. Pretest & Posttest Design

The visuo-haptic project was conducted as a 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.

Given the constructivist nature of the learning environment, we designed the research materials based on qualitative studies where it is possible to identify more underlying reasons and insights into the particular case. Hence, pre-and posttests were designed to encourage learners to elaborate their opinion, reasoning and conceptual understanding of static friction. The abstract nature of forces (static friction, normal force, gravitational force, etc.) brings along many conceptual difficulties and non-normative understanding for many students [26, 27, 31].

We started to look over previous research, which present common conceptual difficulties that have been utilized by students. After identifying common difficulties and matching up with learning objectives, we have tried to frame possible questions by aligning with friction questions in the static concept inventory (SCI) [26].

The pretest consisted of declarative and procedural questions. For this paper, we analyzed four declarative and one procedural questions. Declarative questions followed the description of Section II., which are four what-if scenarios using cubes with different sizes and mass on different surfaces with different correlating coefficients of frictions.

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 is 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.

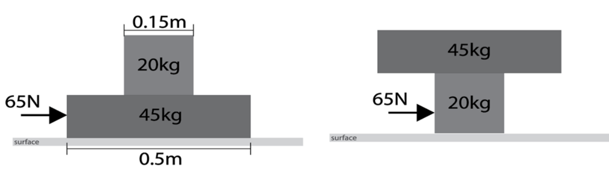


Figure V.1 Procedural question

Alignment on scenarios 3 and 4 where the same mass but different size cubes are located on rough and smooth surface, with this procedural question help to determine whether students could construct a coherent understanding between verbal explanations and mathematical representations.

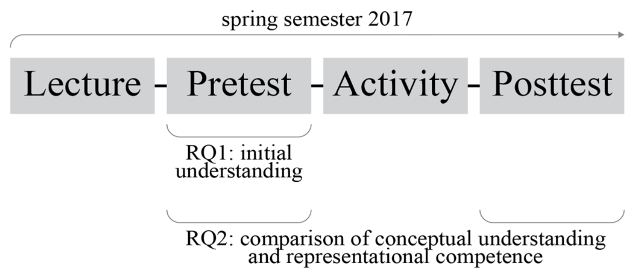
B. Subjects

24 participants of this study were students of engineering technology in 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.

Out of the 24 students, 21 had taken one or more courses in statics in high school and for 12 students the Applied Statics course was their first physics course at the undergraduate level.

C. Procedures and Data Collection Method

Our procedure (see FigureV.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 attend either, a lecture one day before or three days before the experiment. The content of the lecture is 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.

The activity took place during a lab section of the course and it started with an introduction about haptic technology. After the introduction, all students engaged with a haptic simulation about buoyancy as a pre-training session to get accustomed to the haptic feedback. Pre-training sessions help students bypass the "gee-whiz" phase of working with haptic systems and minimize 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 laboratory activity about friction consisted of three parts: recall, prediction and experimentation, and observation. Students did not use the simulation during recalling and prediction phases. They wrote down what they knew about friction forces and predictions for given settings. Once finished, students launched the simulation and the phase of experimentation and observation started. In this phase, students engaged with the visuo-haptic simulation in four parts: recognition, Configuration 1, Configuration 2, and

Configuration 3. During the recognition of the materials the participants weighted, observed, and felt the friction of each surface and the characteristics of the cubes. Figure V.3A shows a screenshot of the visuo-haptic simulation while Cube 2 is weighted. Figure V.3B shows the interaction with the haptic device: students first grabbed the cube positioning the cursor on the top and pulled up.

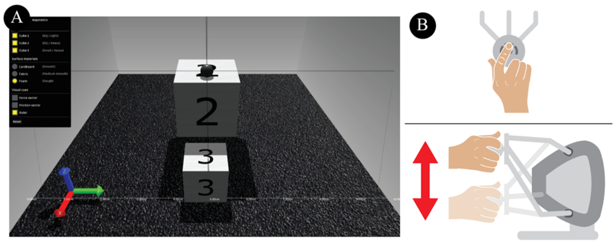


Figure V.3 Weighting the virtual object by using haptic device.

During the Configuration 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 configuration, the participants pushed Cube 2 on cardboard, fabric, and foam. Students again recorded their observations and compared with Configuration 1. During the Configuration 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 answer our first research question (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 treatment and categorized them under a common theme.

To answer our second research question, we used a phenomenological approach to examine each student's experiences and perceptions [34] after engaging with the visuo-haptic simulation. In this part of analysis, we looked at the changes in student's explanation of the phenomena before and after their experience with 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 questions that asked about the force required to push objects that have same sizes 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's 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, are bigger for Cube 2 because of the bigger mass.

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 is 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 are in equilibrium. That idea demonstrates an incomplete understanding even tough they complete a static lesson before the study.

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

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

Students ideas	Frequency
Heavy 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 bigger size 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

Students' verbal explanations in pretest questions are given below as examples to present students' normative and non-normative concepts.

Heavy objects are exposed to bigger friction force.

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

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.

Student S3 indicated that cube 1 has 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.

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).

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, both did not mention 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

Some students illustrated an understanding that the force applied 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 smaller size object would be half that for bigger size objects. Student's reasoning indicated that size-friction force relation is a challenging concept for most 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.

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

Another significant conceptual challenge for students was the relation between surface area and friction force. Many students fell into the misconception that bigger contact area makes it harder to move the objects. One of the reasons for this conceptual fallacy might be their experience in daily life. The bigger surface area is quite important for some phenomena such as maintaining less pressure or narrow tires for practical bikes. It might be also confusing for individuals to differentiate that heavy objects (most cases) tend to have bigger surface area, and they are difficult to move because of their mass not the surface area.

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 compare answers on each of the questions in pretest and posttest (Figure VI.1). Second, we examined verbal consistency by analyzing type of language used by students to describe phenomena of scenarios 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 on pretest and posttest.

Participant's answers on each scenario were categorized as complete, incomplete, incorrect, and irrelevant or no answer. A complete answer is accepted when students predicted the scenario correctly and included all variables. For example:

S10. Cube 1 will move faster than the cube 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 answers are 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

In this case, the reason of why pushing Cube 2 is more difficult was missed (i.e., heavier, due it mass). 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.

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 answer 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 and again in their answers. The figure also presents that after engaging with the visuo-haptic simulation students overcame their conceptual challenges about contact area-friction force relation. The number of students who realized the size does not affect friction force if the masses are equal increased in post-test. Furthermore, more students were able to show that with mathematical calculation (see figure VI.4).

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

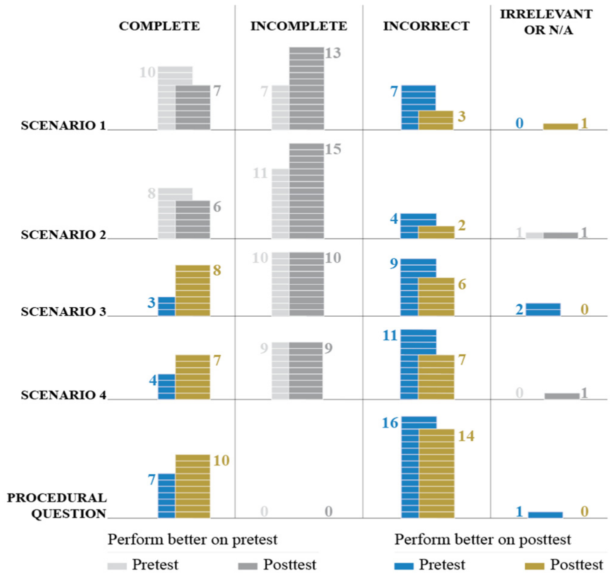


Figure VI.1 Comparison of results pretest vs posttest

Participants used three ways to describe the effect of the cube when a force is applied: using force terminology, speed and distance. Figure VI.2 compares the frequency of the effects in each scenario.

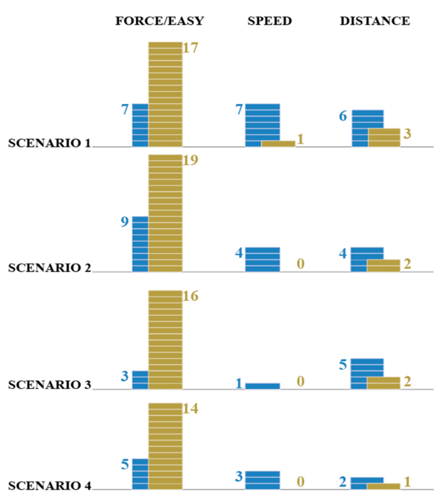


Figure VI.2 Comparison of results in pretest - posttest

Students used force terminology when the answer was based on the force required to slide the cube. This category includes adjectives 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…

To be able to examine if students could support their verbal explanation with 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 is 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 provide an incomplete answer on the other scenario, that participant's answers belongs inconsistency answer. Procedural question was classified on correct or incorrect. Figure VI.3 shows the results of verbal and mathematical consistency in pretest and posttest.

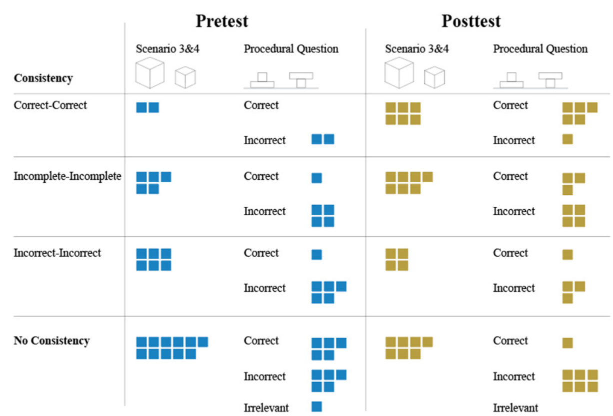


Figure VI.3 verbal and mathematical consistency results

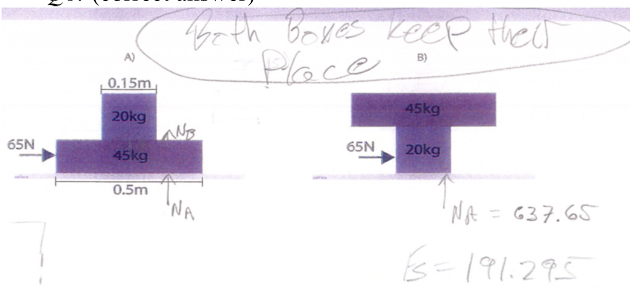
As it is shown in Figure VI.3, posttest showed more verbal consistency for scenarios 3 and 4. Students had more complete and incomplete answers in the posttest than they had in the pretest. Fewer students were identified in the incorrect-incorrect category in the posttest. Additionally, the number of inconsistencies in verbal-verbal and verbal-math representations decreased in the posttest.

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

Below, S23's pre- and post-test verbal and mathematical representation is given as an example of change in consistency in students' understanding. In 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, participant shifted to the category of correct-correct verbal consistency for scenario 3 and 4 and correct answer category for the procedural question.

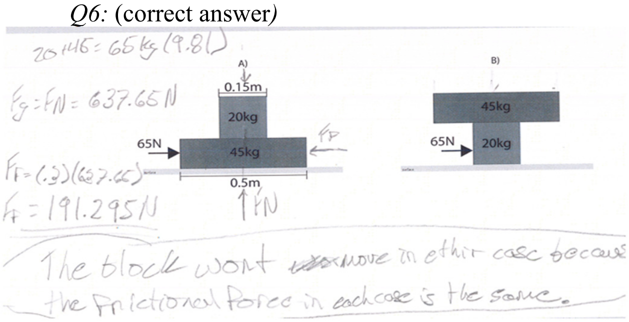
Pre-test:

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)



Post-test:

Q3: Both cube 3 and 2 would take the same force to move them because they weight 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)



Although mathematical representation was scientifically accurate, student S23's verbal responses were incomplete and incorrect before he engaged with visuo-haptic simulation. His post-test answers indicated that simulation helped him to changed 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 have different coefficient of friction and cubes have 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. Our results confirm Magana and Balachandran [24]'s study where they showed increment in conceptual students' understanding about electricity and magnetism by using haptic simulation.

The results of this study for the first research question confirmed many current researches, which attempted to reveal misconceptions [26, 27, 36, 37, 39]. Especially, our results confirmed the findings that presented in Steif's [35] One of the common theme arose from pretest answers of the engineering students who completed formal static instruction was friction force is always equal to normal force times the coefficient of friction even for the objects which are in equilibrium. This result shows similarity with the results that has been found in Steif and Dantzler [26] and Steif and Dollar' study [27]. Other faulty concepts brought up by students were friction is negligible for smooth surfaces and it is almost impossible to move objects on rough surfaces. Students tent to make those assumptions naturally before they actually made observations on both surfaces by pushing the cubes.

Although most students conceptualized static friction force is bigger for the heavier objects, they did not specify this detail in their verbal explanations. That means, students who gave correct answer for the question that ask comparison of 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 compare 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 these 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 visuo-haptic simulations, student's frequent non-normative ideas about friction of two different size 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 visuo-haptic simulation helped some students to review and revise their understanding while some students held on 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 in students verbal explanations and mathematical representations. We detected less verbal coherence in the pretest than after use of visuo-haptic simulation. We find this result quite correlated with Marsh's [40] findings about the relationship between verbal and math achievement. Students who had incomplete or incorrect verbal explanation tend to give wrong math representation to the similar question. Moreover, 5 students perform a correct-correct verbal consistency and answered correct 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 use to apply different situation, however, visuo-haptic simulation promotes increasing in conceptual understanding by being a good cognitive mediator.

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