Identifying Affordances of Physical Manipulative Tools for the Design of Visuo-haptic Simulations

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Abstract

Although the research on manipulatives reveals positive outcomes as compared to written or 2-D pictorial representations, the relative value of physical manipulatives, specifically, is mixed. In this paper, we hypothesize that computer-based haptic simulations have important advantages that are not available in a purely physical environment. We have performed several experiments in the study of the statics domain, identified the affordances of a physical manipulative setup, and proposed a way to adapt affordances from physical environments to the design of visuo-haptic simulations. Statics instruction is particularly well-suited because, in many cases, the rules of statics cannot be seen, but are readily available in the virtual environment. Our guiding research question was: "*To what extent can affordances of physical manipulatives be built into visuo-haptic simulations?* We have designed an experiment where students moved objects with different friction on different surfaces. Our study comprised seven students who were prompted with "what-if" scenarios where they first predicted what they thought might happen, and then tested their predictions by using a physical manipulative setup. We characterized students' interactions using Gaver's (1991) classification of affordances. Our results suggest a higher level of student engagement and motivation when using the physical manipulative setup. However, they also show greater confusion about: 1) density vs. weight, 2) mass vs. surface area, and 3) softness vs. smoothness. The findings were used to adapt and improve the design of visuo-haptic simulations to teach the concept of friction.

Introduction

Designing educational tools to develop conceptual understanding is a complex procedure. Educational tools need to bring together technological, educational, scientific, and social information into a single design solution. Therefore, incorporation of new learning tools in education should be a rational process guided by research. Early focus on the learners during the design of educational tools can facilitate deep thinking about concepts, operations, and relations instead of merely problems associated with usability considerations.

Learning innovations include the adaptation of tools used in non-educational contexts for learning purposes. In the early 2000s, researchers started to explore haptic devices in educational contexts (Section 1.3). The aim of this study is to explore the affordances of Physical Manipulative Tools (PMT) and use this understanding to inform the design of visuo-haptic simulations intended to help students learn statics concepts. We hypothesize that haptic devices can leverage benefits of PMT and overcome its limitations to improve learning experiences with statics concepts simulations.

Teaching and learning statics

We focus on the topic of statics, a branch of mechanics that studies forces and is one of the key elements in engineering design (Steif & Dantzler, 2005; Steif et al., 2010). Hundreds of thousands of students take at least one statics course each year around the world. A deep conceptual understanding of statics is critical for learning in post-requisite courses such as dynamics or machine design, where students apply the knowledge to new situations and contexts (Bransford, Brown, & Cocking, 2000).

Although statics is one of the most fundamental courses in engineering (Steif, 2004), it is hard to teach and learn due its abstract nature (Dede, Salzman, Loftin & Sprague, 1999; Reiner, 1999; Steif & Dantzler, 2005; Steif et al., 2010;). Common misconceptions in statics have been identified by Steif (2004), such as students' inability to identify acting forces, specific components of a system, as well as resulting behaviors from interacting parts. Steif (2004) further identified that location and directionality of force, force balance, and equilibrium statements are the most enduring misconceptions among students (Newcomer & Steif, 2008; Steif et al., 2010).

One of the key challenges in understanding and visualizing statics is the lack of effective integration of conceptual learning and representational competence (Steif & McCombs, 2006). Research suggests that the use of conceptual knowledge, inquiry strategies as well as graphical representations, are effective in formulating learning solutions (Novick, 1990; Brereton, 2004; Chi, 2011). To bridge the gap between conceptual understanding and representation, statics instruction has evolved and followed many of the modern trends: greater use of active learning, introduction of video-based lectures and animations (Fang, 2012), use of computer simulations (Zacharia & Olympiou, 2011), use of physical props and demonstrations in class (Miller, Lasry, Chu, & Mazur, 2013), and use of manipulatives in structured learning activities for students (Mejia, Goodridge, Call, & Wood, 2016). Although simulations are known to be efficient tools to improve students' learning and perception, we are not aware of any framework that combines visual and haptic simulations to improve students' learning of statics concepts. To assist with the design of visuo-haptic simulations, we analyze the affordances of physical manipulative tools and use these to inform our design of a visuo-haptic simulation.

Use of simulations and physical manipulative tools in teaching/learning environments

Laboratories and visual computer simulations have been found to be effective in helping students understand abstract concepts (Zacharia & Olympiou, 2011). However, it has been suggested that visual simulations alone may not be fully supportive for some students learning these concepts (Chi, 2008). In addition, most of the currently available simulations focus on the sense of sight and hearing, and very little on the sense of touch, which is one of the most common ways for people to interact with physical objects (Thurfjell, McLaughlin, Mattsson & Lammertse, 2002; Han & Black, 2011). Moreover, the availability of laboratories and equipment necessary to carry out physical experiments has been limited (Zacharia & Olympiou, 2011).

Physical manipulatives allow students to engage in active learning and to explore properties of objects, which is an effective way of learning abstract science concepts (Glasson, 1989; Vesilind

& Jones, 1996). For this study, we identified the affordances of physical manipulative tools and use them to design a visuo-haptic simulation.

Use of haptic devices for teaching and learning

Haptic devices are computer-assisted devices that provide the sense of touch through physical contact between the computer and the user. The user manipulates a 3-D cursor, usually in a form of sphere with buttons, and three independent stepper motors provide force feedback. The force is updated at high frequency (about 1kHz) and is fully under the control of the underlying simulator. Various haptic devices exist with varying precision, dynamic range of provided forces, and designs. Nowadays, haptics technologies are finding their way into the realm of education as learning tools to provide hands-on experiences (Minogue & Jones, 2006). Research on the use of haptic devices to help students improve their understanding of abstract concepts related to physical phenomena has been done in different fields such as mechanics, heat and temperature, as well as electricity and magnetism. Okamura et al. (2002) demonstrated that the use of haptic devices improves understanding of dynamic systems, modeling, and control by allowing students to feel viscous damping, stiffness, and inertia. Williams et al. (2003, 2007) showed the benefits of using haptics-augmented software activities supported by HTML tutorials to teach simple machines in elementary school. Sanchez et al. (2013) explored the cognitive implications as well as cognitive load management of students while interacting with haptics simulations. Researchers identified that when presenting visualization and haptic feedback together students may experience cognitive overload.

Other works introduce visuo-haptic computer simulations that allow users to feel the physical properties of objects such as hardness and weight for educational and training purposes. Jones et al. (2006) found that the haptic feedback provided a more immersive learning environment that not only improved engagement but also influenced the way in which the students constructed their understanding about viruses and nanoscale science concepts. Morris et al. (2007) showed that students more effectively memorize force patterns when those patterns were presented in visual and haptic format, rather than via either modality alone. Despite the recent progress and growing evidence of the benefit of haptics as an educative tool, the application of haptics in the field of statics remains largely unexplored.

Theoretical foundation

We use the three-affordance framework of Gaver (1991) in this study. Gaver’s definition of object affordances focuses on the interaction between technologies and the people. Objects affordances are attributes of both the object and the actor (Gaver, 1991).

The three affordances are: 1) false affordances, 2) hidden affordances, and 3) perceptible affordances (see Figure 1). *False affordances* have no real function; people may mistakenly try to act, but there is no affordance that supports that action. *Hidden affordances* are possibilities for action, but are not perceived by the actor. Both false and hidden affordances lead to mistakes in technology use. *Perceptible affordances* are when actors perform an action upon the affordance, in other words, there is a link between perception and action.

In our study, we identify perceptible, false and hidden affordances of physical manipulative tools. Once identified, we propose a way to adapt perceptible affordances to visuo-haptic environments, and overcome false and hidden affordances.

Perceptual information		Affordance: NO	Affordance: YES
	YES	False affordance	Perceptible affordance
	NO	Correct Rejection	Hidden affordance

Figure 1. Classification of affordances by Gaver (1991)

Methods

Our qualitative study focuses on the design of visuo-haptic simulations to teach statics concepts. To inform the design process of visuo-haptic simulations, we investigate the affordances of physical manipulative as tools to support cognition, and the guiding question is:

> *To what extent can affordances of physical manipulatives be built into visuo-haptic simulations?*

After the identification of the affordances, we propose a visuo-haptic simulation that adapts perceptible affordances and overcomes false and hidden affordances.

Scenarios and materials

We have developed four scenarios written by using a “what-if” setup, where a student must predict and explain the result of each situation and test it using the physical manipulative tool (PMT). The scenarios are:

a) Imagine that you have two cubes both made of the same material, which is smooth, and have the same sizes. The first cube is lighter. What if you push cube 1 on a very smooth surface from point A to B? What if you push cube 2 on a very smooth surface from point A to B?
b) What if you repeat the procedures in the previous case, but instead of moving the cubes on a very smooth surface, now start pushing them on a surface that is not as smooth as the previous case (medium smooth)?
c) Now, you have additional cube 3, which has the same weight as cube 2, but is half-size. What if you push cube 2 on a very smooth surface and then you push cube 3 on the same very smooth surface? What would happen?
d) What if you repeat the steps from the previous case, but instead of moving the cubes on a very smooth surface, move them on a surface that is not as smooth as in the previous case (medium smooth).

We intentionally avoid using technical words (e.g., force, friction, friction coefficient) when stating scenarios to reduce cognitive load and help participants to use and make connections between concepts. Misconceptions and use of technical words from participant's answers were analyzed in this study. The PMT has four elements: three cubes and one sliding surface (Figure 2). The cubes are made of plastic material and have the following parameters: Cube 1: 7.5cm, 0.08lb; Cube 2: 7.5cm, 0.1lb; Cube 3: 5cm, 0.1lb.

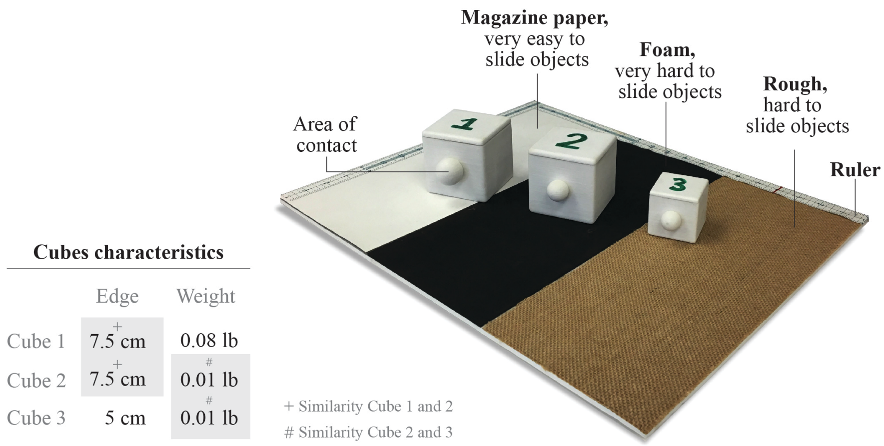

Figure 2. Physical manipulative tool elements

The contact area (Figure 2) is where students are supposed to touch the cubes in order to push them on the surface as it avoids rotating or tipping over. Furthermore, it is similar to the handle of the haptic device.

The flat surface where the cubes are moved is of size 21 x 14 in and it is made of thick foam covered by three different materials (7x14in for each): magazine paper, foam, and fabric. Magazine paper is the material where cubes can slide most easily (lower friction coefficient), followed by fabric (medium friction coefficient), and foam (highest friction coefficient).
A metric-scale ruler is placed along the perimeter of the whole flat surface to provide a visual cue to measure displacement distance.

Table 1 shows a description of the differences between scenarios, what we expect from learners (reasoning process), and the list of materials for each scenario which we expect participants to use to test their predictions.

Table 1. Scenario, scenario characteristics, reasoning process, and used materials

Scenario	Scenario characteristics	Reasoning process	Materials students use
A	Cubes of the same material and dimensions. Different weight Sliding surface: smooth	We expect learners know and can recognize how mass affects sliding. We expect them to recognize paper has the smoothest surface.	Cube 1 and Cube 2. Surface: Magazine paper

B	Cubes of the same material and dimensions Different weight Sliding surface: rough	We expect learners know and can recognize how the rough surface affects both cubes motions equally. We expect them to recognize the foam has the roughest surface.	Cube 1 and Cube 2. Surface: Foam
C	Cubes made of the same material and same weight Different dimensions, Sliding surface: smooth	We expect learners know and can recognize mass does affect friction force but dimensions do not. We expect them to recognize paper has the smoothest surface.	Cube 2 and Cube 3. Surface: Magazine paper.
D	Cubes made of the same material and weight. Different dimensions Sliding surface: rough	We expect learners know and can recognize how the rough surface affects both cubes equally, no matter the dimensions. We expect the recognition of the foam as rough.	Cube 2 and Cube 3. Surface: Foam

Participants

The participants in this study were undergraduate students, aged over 18, who had already taken different engineering and physics courses by the time the study was conducted. During the study, participants were required to complete a think aloud process and explain their reasoning throughout each scenario. The role of researchers was mainly taking notes and prompting participants to give more details about their thought process. Participation in this study was completely voluntary. The data collection was carried out during Spring 2017 at different places around a mid-west University campus. Participants in the study consisted of three females and four males. Three participants were majoring in technology, two in biology and two in physics. All participants took physics courses in high school and/or in college. All strongly agreed on the importance of understanding physics.

Procedure and data collection method

The study (see Figure 3) had five sequential parts: background questionnaire, verbal explanations of each scenario, recognition of the PMT, prediction test using PMT, and exit feedback.

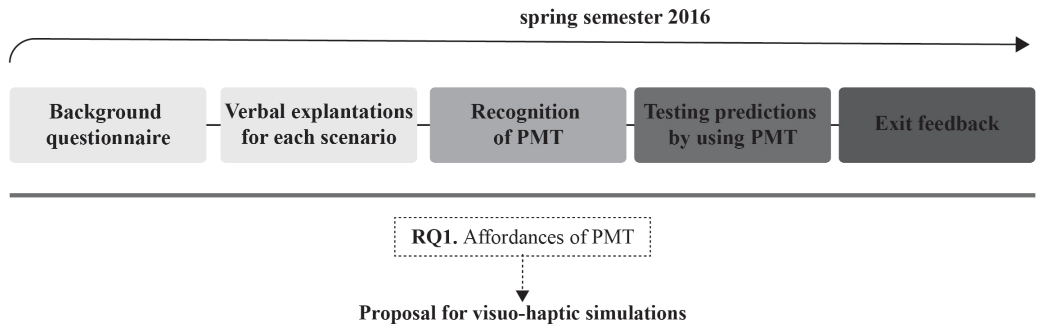

Figure 3. Method overview

Background questionnaire

A background questionnaire made up of a combination of short answer and Likert type questions was used to gather information about participants' previous experience and knowledge related to statics concepts. The questions included name, gender, major, academic level, age and number of physics courses taken in college and high school. Students were also asked about what motivated them to learn physics and what their perceptions about their understanding of physics concepts were.

Verbal explanations for each scenario

Researchers presented the scenarios to participants one at a time and participants made their predictions verbally. The result of the prediction phase for each scenario is important because the participants had a chance to run a thought experiment combining their previous knowledge with their subjective reasoning to explain the "what-if" statements (e.g., they push a heavy and a light object on different surfaces which have different friction coefficients). Students' responses were recorded by researchers. The collected data were: solutions for each scenario, the use of technical details and use of real-life examples to explain/reinforce the result prediction.

Recognition of the PMT

The physical manipulative tool was introduced to participants and they had a chance to investigate the differences among cubes by holding, observing, weighting by hand, and touching them as well as the three different surfaces (Figure 2). At the end of the recognition process, researchers asked participants: a) what is the difference between cubes? b) what is the difference between the textures on the surface? Students were expected to feel the weight difference among cube 1-3 and feel the difference of texture between materials.

Testing predictions by using PMT

After identifying the materials in the recognition stage, participants manipulated the physical tools. Based on their observations, participants confirmed or changed their predictions made during the verbal explanations phase by using PMT. Figure 4 shows the sequential steps during the test of predictions by using PMT phase.

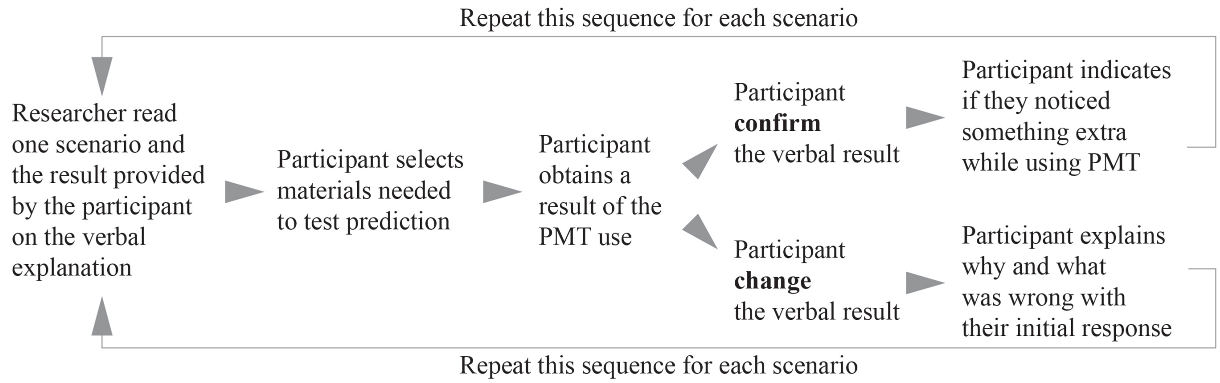

Figure 4. Sequence of the testing predictions by using PMT

Participants explained what they felt/observed using the PMT, and based on their observation-they were asked to confirm or change their answers from the prediction phase. If a participant wanted to change her/his prediction, s/he were asked to elaborate what was wrong with the previous response and why they think their new idea is better.

Exit feedback

The exit feedback allowed learners to share their final thoughts, comments, and suggestions related to the technology or materials. The participants emphasized the issues that they considered important to address for improving this study as well as the future studies. Some explanatory questions such as what aspects they liked about each scenario (e.g., how confident they felt now about the topic of friction between two objects) were addressed in the exit feedback survey. Students also rated perceptions of their own understanding by using Likert's scale questions (strongly disagree, disagree, neutral, agree, and strongly agree).

Data analysis method

We used knowledge elicitation (Bainbridge & Sanderson, 2005) to process data from the verbal/think-aloud protocols. We first transcribed students' verbal explanations and then used verbal protocol analysis which facilitated us to make inferences about problem solving process.

Results

All participants easily recognized the difference in weight between Cube 1 and 2 as well as their similarity in dimensions. However, all participants had problems determining whether Cube 2 and 3 weighed the same. Also, they chose magazine paper as the smoothest surface and the fabric as the roughest surface.

We tested four scenarios for this study. Scenario A was sliding two objects with the same size but different weights on a smooth surface. Scenario B was similar to Scenario A, but sliding the objects on a rough surface. Scenario C included sliding two objects with the same weight but different sizes on a smooth area. Scenario D was similar to Scenario C but included sliding the objects on a rough surface. Table 2 that shows quotes responses per scenario during the verbal explanations and use of the PMT.

Table 2. Scenarios, correct, partially correct and incorrect result using verbal explanations and PMT

Scenario	Correct result using verbal explanations	Partially correct result using verbal explanations	Incorrect result using verbal explanations	Correct result using PMT	Partially correct result using PMT	Incorrect result using PMT
A	“The lighter object is going to slide more distance” P1	*“Objects will be moved at different speeds” P4 * the participant does not indicate which of the two objects will be faster		“Objects moved less than on the smooth surface and the difference between objects is smaller (just 0.5in)” P2	“The lighter object moved more”. P2	
B	“The lighter object is still going to slide more distance than the heavy object” P2	*“Objects will be move at different speeds but slower than on a smooth surface” P4 * the participant does not indicate what object will be faster		“Nothing, happened what I said, the lighter object will get further” P1	*Objects moved less than on the smooth surface and the difference between objects is smaller (just 0.5in) *objects are affected equally	“Cubes moved the same, I don’t know why, just a bit more the lighter cube, I guess the rough surface affects more the lighter cube.” P3
C	“Objects are going to move the same because mass is the same” P1	*“Objects are going to move the same because there is no friction” P4 * there is a small amount of friction	“The small object is going to slide more because the surface area is smaller” P3		The small cube moved less, I think size is affecting.” P2	

D	"Still the same, objects have the same mass" P1	"Small object will be faster but not as fast as if it is sliding on a smooth area." P3	"Nothing- objects moved the same" P1	"Small cube is moving more, and that is because it has less contact surface." P4

Figure 5 shows the results of each scenario in the verbal explanations and the physical manipulative tool. Furthermore, it indicates if the participants confirmed or changed their verbal explanation after used the PMT.

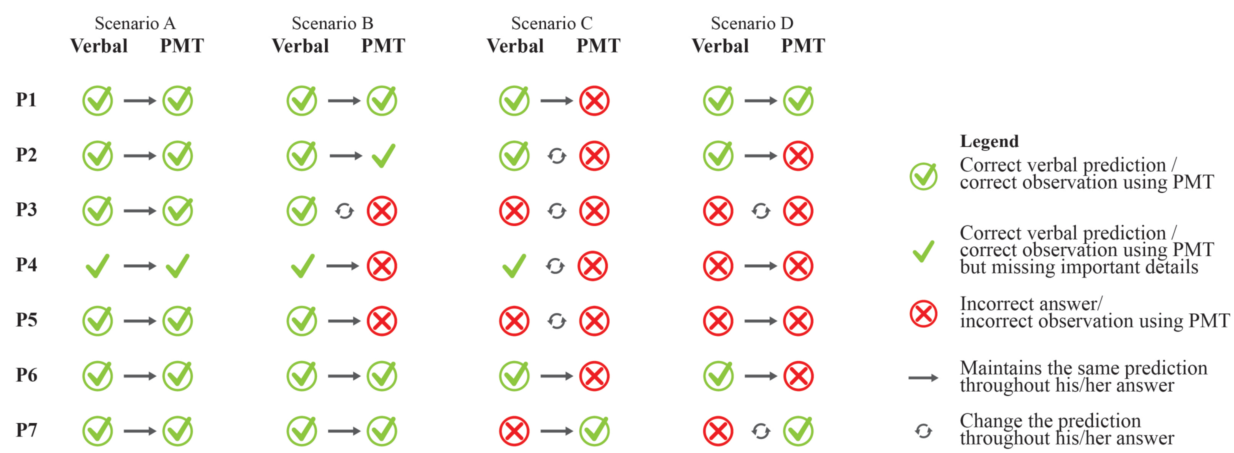

Figure 5. Results of each scenario.

Scenario A: As shown in Figure 6, the participants had more verbal answers in Scenario A and the PMT helped them to reinforce this idea. No changes on the first verbal prediction were made by participants after using the PMT. Participant 4 answered partially correct, but missed important information in the answer. (see Table 2).

For _Scenario B_, all students' predictions were correct (just participant 4 did not include important details), but three out of seven students gave an incorrect response after engaging with the PMT. Two participants maintained their predictions as their final response, even though the physical experiment showed another result. One participant changed his correct answer to incorrect one as result of his PMT engagement.

Scenario C presented more problems than Scenarios A and B. Three of the students' predictions were correct and one partially correct. Three students predicted the results of Scenario C incorrectly and just one of them was able to change his answer to the correct one after using the PMT. Four out of seven participants changed their responses to an incorrect one based on their observations while using the PMT. Participant 7 predicted the result incorrectly on the verbal explanation phase and revised the result to a correct one after using the PMT, but the participant reported that he did not feel confident with the result. He argued that more information was needed in order for him to confirm his response, and he decided to keep his initial thought.

In *Scenario D*, just three students' predictions were correct, while four of them were incorrect. After using the PMT, two students changed their correct reasoning to an incorrect one and one changed his/her incorrect response to a correct one. One participant changed his/her response even though s/he obtained a wrong idea from the PMT. The other participants argued that problems in the experiment made the results look different.

The results for each scenario were confirmed or changed based on the PMT results. Figure 6 shows the number of times that participants changed or kept their results from their verbal prediction to their experience based on the PMT results as correct, partially correct or incorrect.

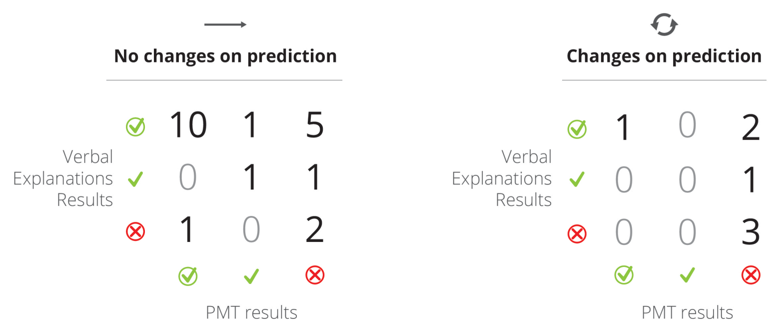

Figure 6. Number of times each case is presented on the results

In most cases, participants kept the responses the same from the prediction phase through their engagement with PMT (16x) even though the PMT observation showed a different outcome (4x). On three occasions, participants changed their verbal prediction from correct or partially correct to incorrect because the PMT showed another outcome. Five times students' responses were incorrect in both, prediction and PMT results, and it seems that in none of the cases PMT helped participants to change from wrong verbal prediction to a correct response.

Participants refused to change their verbal predictions based on the results of PMT. They concluded that the incorrect result was because they needed to conduct more experiments and they did not have enough evidence to change their response and/or they were not able to tell if they were applying more force to the heavy objects since they could not adjust the force they were applying to push objects.

At the end of the verbal prediction phase, researchers asked the participants what smooth surface or rough surface they imagined when they were making their prediction. Table 3 shows their answers and what real model they used for the prediction using PMT.

Table 3. Participant, what they imagined for verbal explanations and objects used while using PMT

Scenario	What they imagined for verbal explanations	Objects used while using PMT

	Moving objects	Smooth surface	Rough surface	Smooth surface	Rough surface
P1	Desk pen holder	Desk	Carpet	Cardboard	Magazine paper
P2	Cubes	Kitchen Table	Tablemat	Cardboard	Magazine paper
P3	Cell phone	Desk	Wood	Cardboard	Magazine paper
P4	Spheres	Bowling surface	Textured bowling surface	Cardboard	Magazine paper
P5	Spheres	Bowling surface	Tree bark	Cardboard	Magazine paper
P6	Boxes	Table	Sand paper	Cardboard	Magazine paper
P7	Cubes	Ice/metal	Table (Soft but rough when viewed under a microscope)	Cardboard	Magazine paper

As shown in Table 3, participants thought about objects that can be easily manipulated by hands and that they had experienced before. Smooth surfaces were always represented without textured surfaces and rough surfaces with textured surfaces. None of the participants predicted the foam as rough surface and used it to test friction force for any of the scenarios.

Summary of Affordances of PMT

In this section, we classify the affordances of the use of PMT in perceptible and false. No hidden affordances were found.

In the recognition stage, three perceptible affordances and two false affordances were recognized. Perceptible affordances were: (1) students' ability to recognize dimensional differences between large cubes and small cubes, (2) students' ability to recognize differences in weight between cubes with the same dimensions, and (3) students' ability to recognize smooth and rough surfaces. False affordances are: (1) students' ability to recognize that Cube 2 and 3 had the same weight and (2) students' ability to recognize friction properties of the materials. Also, in the recognition stage, we identified that participants weighed the objects with their hands, as well as pushed the objects forward using one finger.

Results showed three perceptible affordances and three false affordances in the experimentation stage with the PMT. Perceptible affordances included: (1) no explanation about how to use the tools were required, participants felt motivated while using PMT, (2) participants could feel and make conclusions based on the experience, and (3) the use of PMT helped participants to deeply reflect about the result. False affordances included: (1) rotation of the cubes impeded sliding the cubes easily, (2) participants were not able to recognize how much force they applied, and (3) the interaction with the PMT reinforced a misconception that the contact area has an impact on friction.

Details of how to overcome false affordances and adapt perceptible affordances are explained more in detail section 6 and section 7.

Discussion

Results obtained from this study showed that students carry several misconceptions about friction concepts. Misconceptions found are: (1) density vs. weight, (2) mass vs. surface area, and (3) softness vs. smoothness. The results are aligned with Steif's (2004) findings and support the premise that statics is a hard topic to teach and learn due to its abstract nature.

Participants confused weight with density. During the recognition of PMT phase, participants had problems to recognize cube 2 and cube 3 had the same weight. Cube 3 has the same weight as Cube 2; but since Cube 3 is smaller (and therefore denser), that led individuals to think that cube 3 is heavier. These results are aligned with Smith, Snir and Grosslight'ds (1992) that indicates students have misconceptions about density and weight even after instruction.

Results show that participants believed the area of the contact surface influences friction (scenarios C and D). Similar to Besson et al. (2007), our study found that students' understanding of friction and contact area was incomplete even after a sequence of experiments. As opposed to Lazonder and Ehrenhard (2014)'s study where students were able to correct their misconceptions by using physical manipulatives, our participants ended up stating incorrect results and explanations after they completed their observations with physical manipulative tools.

Our study identified that students confuse texture with friction. That is, students thought that when the surface was smooth (e.g., the foam) the friction force was going to be smaller; however, from the three surfaces, the foam was the surface with the highest friction. We were not able to identify other studies that have reported this possible misconception.

The results also showed that the PMT did not help students to change their incorrect predictions; in fact, it caused further confusion for the students whose prior knowledge was not complete. On the one hand, students who already understood the concept of friction recalled that information and they were able to predict results correctly. Also, those who did not know the rules regarding friction force could not predict correctly or changed their ideas to correct ones after engaging with the PMT. These findings are aligned with prior studies that claimed that the PMT is not a sufficient tool itself to improve physics content knowledge (Triona & Klahr, 2003; Zacharia, and Olympiou, 2011).

Identifying false affordances that leads to misconceptions and perceptible affordances of PMT, can help to inform the design of visuo-haptics simulations that considers the learner as the center of the design process. For instance, a perceptible affordance of the PMT we identified was that the sense of touch helps participants to explain and reflect about their reasoning of each scenario. We also identified that interacting with manipulatives increased the level of motivation and engagement within the activity.

Limitations from Learners' Interaction with the PMT

The main limitation identified of the PMT was the lack of measurement capabilities that could help students to perceive the differences in weight and size among cubes and the forces applied to move the objects across the surfaces. The PMT could be improved by providing visual cues that measure the force applied and weight.

Regarding with the cubes, participants did not use the knobs that were intended to move the cubes. The knobs seemed to impede the natural manipulation of the objects. Second, the cubes rotated while the participants were sliding the cubes. The rotational motion is a topic of dynamics, which includes more complex rules and is generally taught after statics. Therefore, this motion has the potential to result in confusion or additional cognitive load. Third, when participants wanted to feel the objects' attributes and the force that they applied on the objects, they preferred to close their eyes to focus on the sense of touch.

Our physical manipulative tool informed the design of visuo-haptic simulations. Our proposal considered limitations and affordances of PMT and propose a way to adapt affordances and overcome limitations in visuo-haptics simulations environments. Haptic simulations with a realistic scenario and user-friendly interface could help keep students' motivation high, while learning concepts in statics.

Implications for Visuo-haptic Simulation Design

The design of the visuo-haptic simulation aimed to leverage perceptible affordances and address false affordances identified through the PMT. In addition, results obtained from this experiment informed the design process of the visuo-haptic simulations. In this section, we propose a way to adapt perceptible affordances and overcome false affordances with visuo-haptic simulations. We hypothesize that this adaptation could help the learning process, but further studies in this field are needed.

Affordances adaptation.

Differences between Cube 1 and Cube 2 in size and weight are easy to recognize in the PMT. Cube 3 should be half size of Cube 1 and 2. Smooth surface should not contain texture and rough surface should be highly textured. Visuo-haptic simulations should maintain these differences as easy to perceive as in the PMT.

A pre-training session is required for the use of visuo-haptic simulations. Haptic devices are new in most of the learning environment. This no familiarity with the devices indicates that a pre-training session is required. Affordances of participants feeling motivated and deeply reflecting will be analyzed in future studies.

Implications of false affordances in the recognition stage

The first false affordance identified in the recognition stage, was that participants who engaged with the PMT had problems determining whether Cubes 2 and 3 had the same weight. This problem can be associated with a density misconception explained in detail in the discussion. This erroneous and doubtful result may be due to the subjective measurement where the cubes were weighted by hand. Participants generally held the cubes in their upward-facing palms to weight them. We propose in future experiments weight measurement by hanging the cubes by a string wrapped around the participants' wrists. By not placing the Cube in the palm of the hand, the weight will not be distributed in the surface area of the hand and will be concentrated in one single point. Figure 7A shows how participants weighted the cubes in our experiment and Figure 7B shows how we suggest to make the weight recognition.

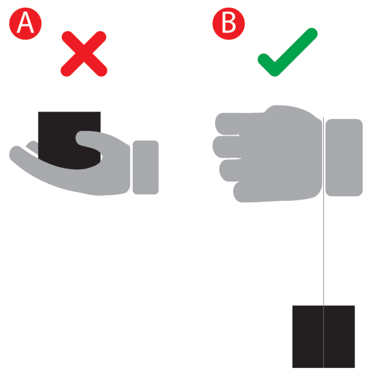

Figure 7. Measuring weight

For the haptic simulations, we enabled an option to grab cubes which can help learners to feel the difference between both cubes. The weight measure could be done with one cube at a time by using just one hand holding the haptic force feedback sensor.

The second false affordance of the recognition stage was that smooth-surface materials were perceived with lower friction. In this case foam, the smoothest material in the surface had the higher friction coefficient. However, foam was perceived as intermediate friction surface between the magazine paper and the fabric. A way to overcome this misconception in the haptic simulation is to conduct a pre-training step before the study of friction, where participants slide cubes on the three different materials. Visual cues and explicit information about the materials and cubes are required to keep participants' concentration on the statics problems instead of on the materials used to address the problems.

Implications of false affordances in the testing prediction stage

Rotation of cubes while participant's pushes the cubes indicates that force was not applied to the center of mass. Visuo-haptic simulations can constrain physical phenomena so students can benefit from the learning experience. For instance, cubes can be programmed to apply the pushing force on the center of mass, avoiding rotation.

Visual cues can help to magnify force applied to a Cube. The combination of visual cues along with force feedback has the potential to promote conceptual understanding. For instance, when an individual applies force to push a cube, the magnitude and direction of applied force accompanied the objects can appear on the screen. The visual cue arrow size could increase and decrease depending on the force exerted. These visual cues can help to address misconceptions such as the direction of forces, and the notion that contact area affects friction force.

Table 4 summarizes the affordances and implications for the visuo-haptic simulation by showing the elements to be implemented and the objective of each one.

Table 4. Elements to be implemented on the visuo-haptic simulation and the objective

Design Element	Goal and Intended Affordance
Objects to be push: cubes	Use objects that are familiar to learners
Small cube should be half the size of larger cubes	Easily recognize differences of sizes among cubes
Light cube should be half the weight of heavy cubes	Easily recognize differences of weight among cubes
To be able to hold the cubes	Tactile measure of the different weights of the cubes
Avoid the rotation of the cubes when they are pushed	Apply the force through the center of mass
Use of texture in surfaces	Easily recognize smooth (non-textured) from rough materials (high-textured)
Visual cues	Magnitude and direction of the force: to visualize explicit information about the physic phenomena Ruler: To measure displacement distance (ruler)
Tactile cues	Provide the possibility to feel forces acting in the simulation
Realistic scenario	Match the simulation with the learner's mental models
Pre-training session	Learn about the use of haptic devices Feel surfaces Keep learner's motivation while interact with visuo-haptic simulation

Visuo-haptic simulation proposal

We implemented the visuo-haptic simulation in C++ using the Chai3D, OpenGL, and GLSL, and we used Falcon Novint® to provide haptic force feedback. The system was executed on a desktop computer with Intel i7 CPU clocked @ 3.7GHz, 32GB of memory, and NVIDIA Titan Z graphics card. Figure 8 presents a screenshot of the visuo-haptic simulation.

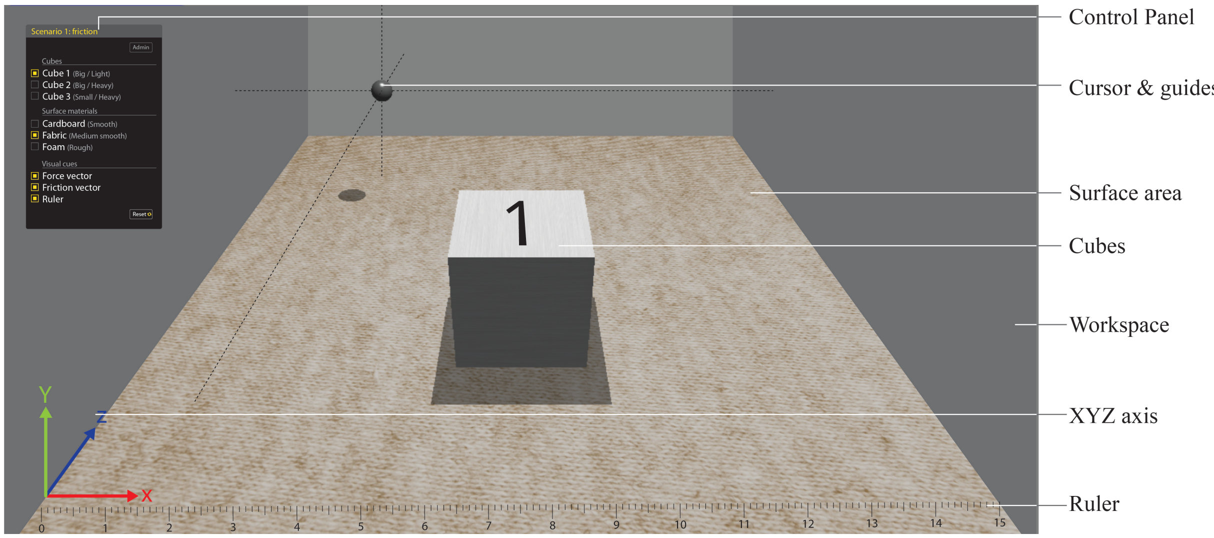

Figure 8. Screenshot of our visuo-haptic simulation

The visuo-haptic simulation has seven elements. Four elements were transferred from the PMT to the visuo-haptic simulation. These elements were workspace, a ruler to measure displacement, surface area with three different materials and different cubes. New elements include XYZ axis, a control panel to change scenarios, and a probe cursor with 3-D visual guides. The workspace area and XYZ axis provide visual cues and helps the navigation in the 3-D space. Moreover, the 3-D probe and the cubes have shadows. Shadows visually indicate the position of an element. The ruler helps to measure displacement of a cube when it is pushed. The control panel allows participants to select appropriate combinations of cubed and surfaces to perform the experiment (Figure 9).

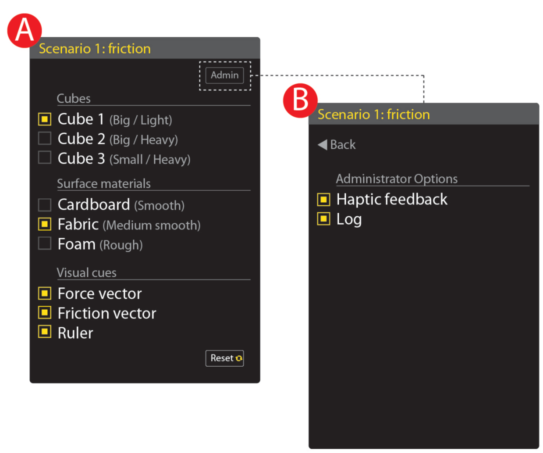

Figure 9. Control panel

Additional dynamic visual cues include a force vector, friction vector and a ruler that can be enabled or disabled. Vectors are represented by a magnitude label and an arrow that increases or decreases size and color depending on the force applied by the user. Figure 14 shows a comparison between the arrows when a user pushes Cube 1 on foam (Screenshot A), which represents a rough surface and on cardboard (Screenshot B) which represents the smooth surface.

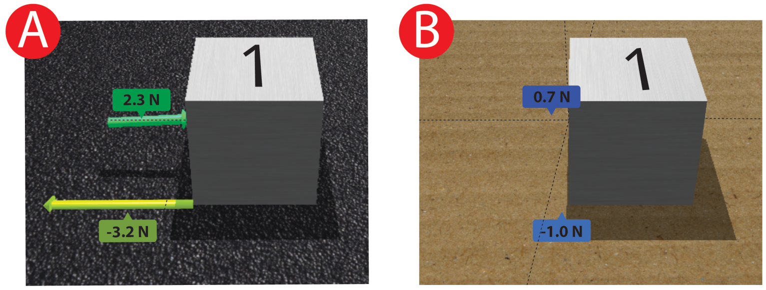

Figure 14. Comparison between forces

Summary and Future Work

The purpose of this study was to determine the affordances of physical manipulatives and to propose visuo-haptic simulations to adapt perceptible affordances and overcome false affordances in statics. We believe that the seamless combination of tactile feedback and visual feedback have the potential to help students engage deeply in the learning process, which could result in increased conceptual understanding. Our future work will explore this hypothesis as well as the kinds of interactions and their sequencing that can maximize their learning processes.

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