IMPROVING CONCEPTUAL UNDERSTANDING OF STATICS CONCEPTS THROUGH TACTILE FEEDBACK TOOLS

by

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I dedicate this dissertation to my little girl, Jime, for being the strength I always need and the light that guides me to be a better person.

To my mom and dad, for teaching me to dream big and giving me wings to fly.

To my brothers, for always supporting us and giving us so much love.

To my family in West Lafayette, for joining us on this journey and making it beautiful.

To Vito, for the many sleepless nights by my side.

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LIST OF ABBREVIATIONS

CC	Conceptual change
CDS	Complex Dynamic Systems
CFa	Correct Applied force
CFf	Correct Friction force
CHE	Correct Hard or easy
CO	Correct Other
CS	Correct Speed
CTD	Correct Traveled distance
CQ1	Conceptual question 1. Role of the object's weight in friction
CQ2	Conceptual question 2. Role of the object's size in friction
DCT	Dual Code Theory
DoF	Degrees of Freedom
ECT	Embodied cognition theories
Fa	Applied force
FBD	Free Body Diagram
FCI	Force Concept Inventory
Ff	Frictional force
Fg	Gravitational force
fMRI	Functional magnetic resonance imaging
Fn	Normal force
H	Haptic feedback
H+V	Haptic feedback + enhanced visual feedback
IFa	Incorrect Applied force
IFf	Incorrect Friction force
IHE	Incorrect Hard or easy
IO	Incorrect Other
IS	Incorrect Speed
ITD	Incorrect Traveled distance

LTM	Long-term memory
PMT	Physical manipulative tool
SCI	Statics concept inventory
STEM	Science, Technology, Engineering, and Mathematics
STM	Short-term memory
V	Enhanced visual feedback
VHS	Visuohaptic simulation
VMT	Virtual manipulative tool
VR	Virtual reality
WM	Working memory
XR	Mixed reality

GLOSSARY

Affordance – "The term affordance refers to the relationship between a physical object and a person (or for that matter, any interacting agent, whether animal or human, or even machines and robots). An affordance is a relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used" (Norman, 1988, p.11).

Body image – Body image is the conscious awareness of our own body, based on perceptions, attitudes, beliefs of our own body. Body image is about having perception or belief about our own body (Gallagher, 2005).

Body schema – is the unconscious performance of the body, based on sensorimotor capacities and perceptual monitoring to maintain the posture (Gallagher, 2005).

Cognition – "whatever it is we are doing to achieve our ends is what we mean by cognition" (Turner, 2016b, p.VI).

Embodied cognition – "The emerging viewpoint of embodied cognition holds that cognitive processes are deeply rooted in the body's interactions with the world." (M. Wilson, 2002, p.625).

Haptic devices – Active haptic devices are interfaces to computers or networks that exchange power (e.g., forces, vibrations, heat) through contact with some part of the user's body, following a programmed interactive algorithm (MacLean, 2008).

Mental imagery – "A mental image occurs when a representation of the type created during the initial phases of perception is present but the stimulus is not actually being perceived" (Kosslyn, 1994, p.4).

Mental model – Visuo-spatial representations of the argument that is constructed and evaluated (Johnson-Laird, 1983).

Physical manipulative – Physical manipulative tools (PMT) promotes learning by the manipulation of concrete objects in real-life to observe a phenomenon (Zacharia & Olympiou, 2011)

Virtual manipulative – Virtual manipulative promotes the observation of a phenomenon through interactive visualizations and materials projected by a computer-based simulation (Zacharia & Olympiou, 2011).

Visuohaptic simulation – Visuohaptic simulations are multimodal learning tools that enable learners to control a virtual environment through a haptic device (Hamza-Lup, Bogdan, Popovici, & Costea, 2019; Magana, Serrano, & Rebello, 2019; Yuksel et al., 2019)

ABSTRACT

Learning practices in education are constantly evolving to provide high-quality education. One of the trends used to provide high-quality education is incorporating technological tools to teach and learn STEM concepts. Implementing physical manipulative tools and virtual manipulative tools in STEM classrooms positively influenced conceptual learning. Furthermore, visuohaptic simulations are learning tools that combine physical and virtual manipulative affordances in a single learning experience. For investigating the value of visual and haptic feedback in virtual environments, we designed an embodied learning experience where learners used a hands-on tool for learning friction concepts. The theoretical framework of embodied learning guided the design of the learning tools and the research design. The learning tools were visuohaptic simulations and physical manipulative tool. Results suggested no influence in conceptual knowledge of the physical manipulative tool. On the opposite, results suggested a positive influence of the visuohaptic simulation on conceptual knowledge. Moreover, our studies suggested that learners exposed to enhanced visual feedback and haptic feedback used two different mechanisms for improving friction conceptual knowledge. When enhanced visual feedback was activated, learners read the cubes' forces from the computer screen for correcting their answer or reinforce their correct knowledge. When haptic feedback was activated, learners inferred about the cubes' forces from the haptic feedback for correcting their answer or reinforce their correct knowledge. In a sequenced approach of feedback of haptic to haptic + enhanced visual, learners obtained the benefits of the haptic and visual feedback for learning friction.

CHAPTER 1. INTRODUCTION

1.1 Statement of the problem

The world we live in and the world we are building requires knowledge in science, technology, engineering, and mathematics (STEM). Investment in STEM education has become an economic, political, and social factor for developing a country (U.S. Department of Education, 2016). The White House news reported in 2016 that Barack Obama's administration designated three billion dollars for the improvement of STEM education across the country. Improvements in STEM education relate to the increment in the capacity and number of programs in the country that provide students a high-quality education (e.g. National Research Council, 2012; Roy, 2018).

Along with the world necessity of STEM professionals, STEM educators face challenges in the classrooms related to content knowledge. The quality of STEM education is linked with content knowledge (National Research Council, 2012). Content knowledge is a group of concepts that learners acquired through instruction. The way content knowledge is delivered to learners is essential in the learning process due to its abstract nature, and many times, the ways that humans experience the concepts in their daily lives (e.g., forces, electricity).

Humans started developing explanations of a scientific phenomenon at the early stages of their lives and continued modifying it in adulthood (Gopnik, 2010; Kontra, Goldin-Meadow, & Beilock, 2012). Preconceptions, or explanations created before exposure to formal instruction, are usually fragmented and not aligned to the scientific view. However, scientific knowledge can be build based on those explanations (Vosniadou, 2013a). Researchers pointed out that STEM concepts' comprehension requires real-life experiences and multiple interactions with learning materials (Al Azawi, Albadi, Moghaddas, & Westlake, 2019; Höst, Schönborn, & Palmerius, 2013; Marshall & Young, 2006; Minstrell, 1984; Winn et al., 2006). Moreover, many scientific theories used today started when scientists manipulated objects. For instance, Michael Faraday experienced magnetic fields by manipulating objects in the environment. After many experiments, Faraday drew the electric fields as lines. Faraday's lines helped him understand the magnetic fields and explain to others the phenomenon. Today, Faraday's magnetic fields' representations are used as scaffolding methods for teaching (Holton, Brush, & Evans, 2001).

The abstract nature of the concepts relates to humans' possibility of visualizing and experiencing the concepts in daily activities (e.g., human experience the forces acting on an object by holding it). However, scientific explanations require understanding the microscopic level of the concept (e.g., how objects experience attractions from the center of the Earth). The use of technology enhances the learning experience by providing information not available for the human eye (Olympiou, Zacharia, & De Jong, 2013). Hence, to face educational, social, and economic challenges, STEM education continually transforms the curriculum, instruction, assessment, and integrating technology and engineering in classrooms (Guzzetti, 2000; Kennedy & Odell, 2014).

One promising trend in science education is the use of embodied cognition theories for designing learning experiences. Embodied cognition theories (ECT) states that cognitive processes occurred by coupling together the mind, environment, and the body (Barsalou, 1999; Lindgren & Johnson-Glenberg, 2013; Turner, 2016b). ECT relates sensorimotor experiences with the acquisition and mastering of knowledge and skills, and with the representation of events and concepts (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008; Glenberg, 2010; Meteyard, Bahrami, & Vigliocco, 2007). For instance, by re-experiencing the phenomenon in a guided activity, learners can construct scientific knowledge of the forces acting on an object while holding it. Hence, ECT theories for designing learning environments provide researchers and practitioners a structure to investigate how the learners' actions impacted the reasoning and thinking (Kontra et al., 2012).

Physical and virtual manipulative learning tools are investigated through the lens of ECT. Results suggests that physical and virtual manipulative are beneficial for learners in the comprehension of science topics and developing of procedural skills (e.g. Gire et al., 2010; Jang, Vitale, Jyung, & Black, 2017). The benefit of physical and virtual manipulative is that the environments provide learners with immersive experiences that increase engagement, while learners are exposed to the learning content, manipulating the learning material, and observing directly the phenomenon (de Jong, Linn, & Zacharia, 2013; Olympiou & Zacharia, 2012; Zacharia & Michael, 2016). Additionally, researchers identified that physical and virtual manipulative have unique affordances that impact learning in different ways. For instance, learners can touch objects with physical manipulative and obtain information about the material, weight, and size. With virtual manipulative, learners can observe the force magnitude and direction of the forces. Information obtained from the physical and virtual tools is required to explain how forces act in an object while holding it.

Technology advances allow combining physical and virtual environments into a single learning experience. For instance, Johnson-Glenberg, Birchfield, Tolentino, and Koziupa (2014) designed a mixed-reality environment (XR) for learning chemistry that requires the manipulation of physical objects to change the outcome provided by the virtual environment; Magana and Balachandran (2017) designed a visuohaptic simulation for learning electricity and magnetism. Learners controlled the virtual environment using a device that provided haptic feedback. Results from both studies suggested positive learning outcomes in the use of the learning tool for conceptual learning. However, research is unclear in key elements of how the use of the body contributes to the learning process of STEM concepts. Some of the unclear aspects are: (a) the impact of physical interactions, such as gestures, body movements in learning; and (b) the value of the haptic feedback in manipulating learning materials.

1.2 Relevance of this study

This work explores the value of the haptic and visual feedback for learning statics concepts. Statics is a branch of mechanics that studies forces. The study of forces is considered a key element of engineering design (Steif & Dantzler, 2005; Steif, Lobue, Fay, & Kara, 2010). Each year, thousands of students take a statics course as part of their curriculum (e.g., mechanical engineering students). However, exposure to content knowledge is in many cases incomplete or inaccurate after instruction (Dollar & Steif, 2005, 2006; Newcomer & Steif, 2008; Streveler, Brown, Herman, & Montfort, 2015; Streveler, Litzinger, Miller, & Steif, 2008).

The abstract nature of statics and the simultaneous reactions makes statics concepts hard to teach and learn (Dede, Salzman, Loftin, & Sprague, 1999; Perkins et al., 2006; Reiner, 1999; Steif & Dantzler, 2005; Steif et al., 2010). For instance, people cannot see what or how forces act upon stationary and in-movement bodies (Steif & Dollar, 2003). Furthermore, learners provide statics explanations as a sequence of steps instead of a phenomenon with multiple simultaneous reactions. Explanations of science concepts in steps are considered scientifically inaccurate because it focuses on macroscopic information, and beginning and end stages of the phenomena (Chi, 2013; Kurnaz & Ekşi, 2015). Learning tools that provide embodied experiences in enhanced virtual environments (e.g., visuohaptic simulations) can promote the comprehension of the statics concepts from the scientific perspective because it can show the abstract information (e.g., forces acting on the objects) and the process of how to obtain the information (e.g., action and reaction forces). (Höst et al., 2013).

This study's relevance for the learners is that embodied learning promotes the learning of forces in its natural way, enhancing aspects of the scientific point of view for promoting comprehension of the phenomenon. For research, this study's relevance is in the analysis of the use of embodied learning tools. Analysis of how learners used the learning tools linked with the learning outcome may help identify the value of the body actions and the value of the haptic feedback as cognitive mediators for learning statics.

1.3 Research questions and hypothesis

The goal of the research is to contribute to the knowledge of embodied cognition and STEM education. The study identifies the value of haptic feedback as a cognitive mediator in virtual environments for learning. The guiding research question for meeting this goal is: *what is the value of visual and haptic feedback in a virtual environment?* Two experiments helped to answer the guiding research question. All the studies focused on two main elements of friction concepts, the role of the object weight, and the role of the object size in friction.

The first study focused on the comparison of the tactile feedback in the visuohaptic simulations (VHS) vs. physical manipulatives (PMT). The research questions of the first study are:

1. What are the differences in student's explanations of friction concepts (i.e., role of the object's weight in friction, and role of the object's size in friction) between interacting with a physical manipulative tool (PMT) and a visuohaptic simulation (VHS)?
   H_{o1}: PMT and the different VHS configurations provide the same learning advantages to students (PMT = VHS).
   H_{a1}: PMT and the different VHS configurations provide different learning advantages to students (PMT $\neq$ VHS).

2. What is the influence of VHS's visual and haptic feedback on students' conceptual knowledge of the role of the objects' size in friction?
   H_{o2}: haptic and visual feedback influence the conceptual learning of friction similarly (H = V).
   H_{a2}: haptic and visual feedback influence the conceptual learning friction differently (H $\neq$ V).

The second study is qualitative and focused on the effect of combining visual and haptic feedback in a sequenced approach for learning friction. The guiding research question is *What are the differences in students' conceptual explanations before, during, and after interacting with a visuohaptic simulation in two different sequenced approaches such as visual to haptic + visual feedback* $(V \rightarrow H+V)$*, and haptic to haptic + visual* $(H \rightarrow H+V)$*?*

The sub-questions of the second study are:

1. What are the characteristics of student's explanations of friction-related conceptual questions?
2. What are the differences between the conditions of sequenced approaches $(V \rightarrow H+V$ vs. $H \rightarrow H+V)$ in student's explanations used to answer the friction-related conceptual questions at the different stages of the study (pretest, interaction 1, midtest, interaction 2, and posttest)?
3. What are the differences between the low-level, medium-level, and high-level performers on each condition of sequenced approaches $(V \rightarrow H+V$ vs. $H \rightarrow H+V)$ in student's' explanations used to answer the friction-related conceptual questions at the different stages of the study (pretest, interaction 1, midtest, interaction 2, and posttest)?

1.4 Assumptions

The dissertation has the following assumptions:

- Participants of this study answered all the assessment questions honestly.
- Participants answered the assessment questions based on their knowledge.
- Participants had prior experience in physics courses.
- Students voluntarily participated in the study.

- Students do not have any motor disability in their hands that impedes the use of tactile tools.
- Students' interactions (e.g., conversations) in the laboratory sections may affect the assessment answers.

1.5 Limitations

The dissertation has the following limitations:

- Participants of the study were enrolled in the introductory physics course in the technology program. The inferences of the study may be applicable to other students with similar characteristics. However, more studies are required for generalized the inferences.
- Participants of the study were male majority. The number of participants per study are based on the number of students registered in the course on the specific semester. The researcher had no control over the registration process.
- The study took place during the Spring 2017 and the Spring 2019. Changes in the engineering curriculum may affect future studies.
- The data analysis of gestures was performed by a non-US citizen. Gestures have social meanings that could be lost in the analysis.

1.6 Delimitations

The dissertation has the following delimitation:

- The only tactile learning tools explored in the study are the physical manipulative tools and the visuohaptic simulations. The study does not pretend to explore all tactile learning tools used for learning purposes.
- The haptic feedback was explored always in companion of visual feedback.

- The study does not focus on the learning process with tactile learning tools of people with an impairment (e.g., visual, motor).
- The topic used to explore the effect of the tactile learning tools in learning is friction. The inferences of the study may be applicable to other science topics with similar characteristics. However, more studies are required for generalized the inferences.
- The perspective of the embodied cognition influenced the study. Other perspectives may influence the results differently. The author recognizes the importance of other perspectives and the relevance for the findings.

1.7 Document Organization

This dissertation has ten chapters. Chapter 2 contains the literature review relevant to the studies, and Chapter 3 provides details of embodied cognition as a theoretical framework. Chapter 4 provides details about the learning materials used in the studies (i.e., physical manipulative tools, visuohaptic simulations, and worksheets). Chapter 5 presents the first study's details that compare the learning benefits of the physical manipulative tool vs. the visuohaptic simulations in different modalities of visual and haptic feedback. Chapter 6 presents the details of the second study that compares the students' explanations of friction concepts. Students in the second study used the visuohaptic simulations of two sequenced approaches of visual to haptic + visual, and haptic to haptic + visual. Chapter 7 summarizes the results of the studies. Chapter 8 presents the discussion of the results, and Chapter 9 presents the implications for teaching and learning, for the design for learning design, implications for the research in embodied learning. Chapter 10 presents the limitations and conclusions of the dissertation.

CHAPTER 2. LITERATURE REVIEW

Chapter 2 presents a summary of the literature relevant to using hands-on learning tools for science concepts. The first section (Section 2.1 to Section 2.3) focuses on conceptual knowledge in science, teaching science, and students' ideas in statics. Section 2.4 focuses on the use of physical and virtual manipulatives for learning. Section 2.5 focuses on using visuohaptic simulations for learning, and Section 2.6 focuses on visual and haptic feedback characteristics. Section 2.7 summarizes the chapter.

2.1 Conceptual knowledge in science

Acquiring knowledge is a complex process for humans. The process of acquiring knowledge (e.g., using the body, social interactions, and instruction) and the troublesome nature of knowledge plays an important role in developing content knowledge of science.

Scientific knowledge is considered troublesome knowledge. There are six forms of troublesome knowledge: ritual, inert, conceptually difficult, alien, tacit, and troublesome language (Meyer & Land, 2006). Ritual knowledge refers to the knowledge acquired by routine. For instance, solving a mathematical equation, not knowing why the variables are needed, is considered ritual knowledge. Inert knowledge is the knowledge that humans only call when it is needed. It is not used actively (e.g., recall a mathematical formula to solve a problem). Alien knowledge is counter-intuitive, intellectually absurd at face value (e.g., the idea that hot water freezes faster than cold water is counter-intuitive). Tacit knowledge remains in the practical consciousness and helps humans make predictions about a specific physic phenomenon based on their body experiences (Hallman, Paley, Han, & Black, 2009). Tacit knowledge is difficult to explain (e.g., language and body language). Troublesome language refers to epistemic problems and the use of metaphors. For example, the word gas is used as synonymous with a flammable substance (e.g., gas LPG, butane gas). The air is a gas that is not flammable, and we need it to live. The word gas is troublesome because of the language.

Science instruction may facilitate the transition from empirical and troublesome knowledge to scientifically accurate explanations of phenomena. Figure 2.1 is a graphical representation of conceptual change.

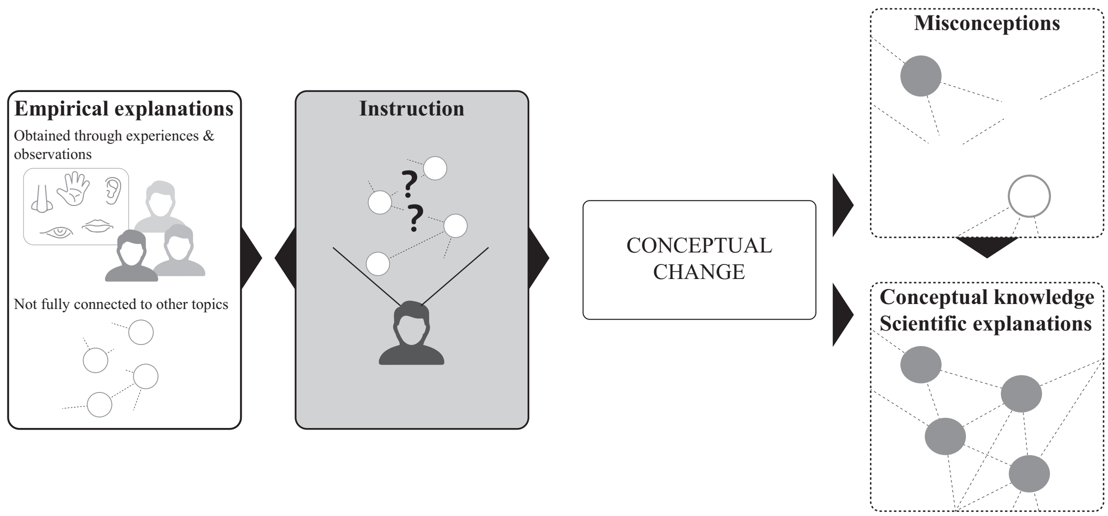

Figure 2.1. Overcoming threshold concepts (Meyer & Land, 2006).

Learners acquired empirical explanations based on daily experiences and observations at the early stages of their life (Halloun & Hestenes, 1985a). Moreover, children can construct their knowledge by conducting experiments, analyzing the results, and forming theories that explain their observations (Gopnik, 2010; Kontra et al., 2012). However, real-life experiences and observations do not fully explain a scientific concept. Empirical explanations are robust, difficult to modify, may not be aligned to the scientific knowledge, and the result of a system of belief that is hard to repair (Minstrell, 1984; Vosniadou, 2013a). Furthermore, incorrect empirical explanations may prevent the acquisition of the scientific view of phenomena (Streveler et al., 2015). The inclusion of empirical explanations in statics may result in higher achievements of students after instruction (Halloun & Hestenes, 1985a; Minstrell, 1984).

Instruction exposes learners to the scientific view of the concepts learned during childhood (e.g., statics, electricity). However, exposure to scientific content does not guarantee the acquisition of scientific conceptual knowledge. For instance, learners may understand the idea that forces explain why an object stops after being pushed but may believe that the forces acting on the object are a property of the object instead of an interaction that causes an effect to the object to be pushed in a certain direction (Brown & Hammer, 2013). Misconceptions are fragmented ideas after instructions (Vosniadou, 2013a). The transition to an accurate explanation of a phenomenon requires learners to change how they see a phenomenon. Conceptual change (CC) is the research that focuses on how conceptual knowledge improves after instruction (Vosniadou, 2013a).

2.1.1 Conceptual change

The conceptual change (CC) research focuses on revising the prior knowledge to add scientific information by reconstructing new conceptual representations through the cognitive process and sociocultural interactions (Hatano & Inagaki, 2003; Vosniadou, 2013a; Vosniadou & Ioannides, 1998). Brown and Hammer (2013) proposed using the Complex Dynamic Systems (CDS) perspective to evaluate a conceptual change in physics.

For CDS, the conceptual knowledge changes over time and depends on the context and prior knowledge. CDS' four main characteristics are non-linearity, intrinsic dynamism, emergence, and embeddedness (Brown & Hammer, 2013). Learning activities do not always increase knowledge in the students. There is no linear relationship between instruction and conceptual knowledge. Knowledge comes from different sources at different times, scales (Thelen & Smith, 2016). Explanations that students use are dynamic too. Depending on the context, an explanation for a concept can change (e.g., a verbal question can elicit a different explanation than a graphic question). Introducing new ideas or re-wiring ideas may produce the emergence of new patterns and connections between concepts. The conceptual knowledge of a specific topic can be embedded in a broader conceptual system. For instance, the friction force's conceptual knowledge may be embedded in the conceptual knowledge of statics. The size of the conceptual knowledge and the connections between concepts depend on the subject's expertise in the topic.

The CC research in physics has more than 30 years. Researchers have found multiple misconceptions and mixed results in the physics CC interventions. For instance, (Minstrell, 1984) reported being frustrated by the little effect in the CC of forces in the students after instruction (e.g., learners failed to recognize the normal force acting on stationary objects). Minstrell further designed learning activities where the students were required to consider their prior knowledge and feel the forces acting on static objects. After experiencing the forces, learners discussed the forces acting on stationary objects. The majority of students ($\approx$ 90%) included the normal force in their explanations of the forces acting on stationary objects. (Clement, 1993) also explored the students' preconceptions of static objects as barriers that cannot exert forces. Two hundred five students in high-school were assigned to a control group and an experimental group. Students in the experimental group were exposed to the analogy that a stationary book over a spring experience the same forces as a book over the table. The control group's learning gains were 28.2%, while the experimental group's learning gains were 54.6%.

2.2 Teaching science

Cimer (2007) summarized six principles for effective teaching science concepts: (a) consideration of students' prior knowledge, (b) encourage students to apply knowledge in different contexts, (c) encourage the participation of students in learning activities, (d) encourage student inquiry, (e) encourage cooperative learning, and (f) providing assessments and feedback.

Incorporating prior ideas in instruction is beneficial for both learners and instructors. To students' incorporation of prior knowledge in instruction allows learners to convert their ideas into hypotheses that can be tested. To instructors, acknowledgment of student's prior ideas allows for early focus on critical aspects of the instruction that may hinder students learning (Cimer, 2007).

Challenges in science education include that students may perceive scientific knowledge as isolated and incoherent (Gilbert, Bulte, & Pilot, 2011). Encouraging students to apply scientific knowledge in multiple contexts may help students solve everyday problems instead of isolating knowledge. Cimers' found that one effective way of integrating the classroom's teaching principles is by designing active learning activities. For instance, Steif and Dollar (2003) proposed a new approach for teaching statics concepts that combine techniques of isolation of concepts with active learning using physical manipulatives. Active learning activities promote participation in learning activities, which also contributes to learning.

The use of learning tools requires guidance to encourage learners to focus on specific elements of the phenomena and prompts for reflection (e.g. Mayer & Johnson, 2010). Guidance and feedback allow instructors to monitor students' performance. The amount of guidance and feedback provided to learners during instruction depends on the learners' characteristics (Johnson & Priest, 2014). For instance, low-performers benefited more from instruction when explanatory feedback is provided through the process of learning. Guidance may hinder learning for high-performers because the guidance information does not promote the generative cognitive process (Johnson & Priest, 2014; Kalyuga, 2014). The generative cognitive process occurs when learners make sense of the learning material and can integrate the new information with their prior knowledge (Johnson & Priest, 2014).

2.2.1 Teaching friction

Kurnaz and Ekşi (2015) investigated student's mental model of friction in high-schoolers (*n* = 215). Participants answered three open-ended questions regarding the concept of friction, why friction occurred, and the molecule's interactions between an object and a surface when an object is sliding from point A to point B. Researchers found that 60.93% of the mental models contained explanations that include scientific arguments (e.g., microscopic perspective) and non-scientific arguments (e.g., macroscopic perspective). Only 2.79% provided answers from the scientific point of view. Students in higher levels of high-school (e.g., twelve-graders) had a higher scientific knowledge of friction than students in the lower levels (nine-graders) Kurnaz and Ekşi (2015) concluded that participants acquired scientific knowledge of friction in high-school. Students moved from macroscopic explanations in nine-grade to scientific explanations in twelve-grade. Moreover, researchers concluded that teaching friction requires first to focus on macroscopic explanations (e.g., traveled distance of the object after being pushed) and then at microscopic levels (e.g., molecules adhesion).

Besson, Borghi, De Ambrosis, and Mascheretti (2007) designed a standard approach for designing experiments and models for teaching friction between solids. For their approach, Besson and colleagues considered students' prior ideas of friction, which includes the incorrect conception of friction force acting only on the object in motion and the interchangeable way that students used for normal force and weight. Besson and colleagues recommended for friction instruction to (a) talk about friction as an omnipresent set of phenomena required for most of the activities, (b) not talk about friction as a negative phenomenon (e.g., just opposing the movement), (c) highlight the importance of friction for the equilibrium after stress or motion, (e) use experiments where the objects in motion are in a vertical position rather than horizontal position, and (f) use structural models that describe aspects of the structure of the solid surfaces, and the physical processes producing friction. Furthermore, Besson and colleagues considered that models involving visual representations that do not show all the model's information allow students' reasoning, creation of interpretations, and predictions.

2.3 Student's ideas in statics

Halloun and Hestenes (1985a) made one of the first attempts to summarize and categorized students' ideas of statics concepts. Researchers called the incorrect student's statics ideas, the *"student's commonsense beliefs of statics"*. In this document, the concept of commonsense beliefs and misconceptions are synonymous because both are based on prior experience and are not aligned to the physics laws.

For categorized student's misconceptions in statics, researchers developed an instrument of thirty-six multiple-choice question (Halloun & Hestenes, 1985b). College students (n = 478) solved a multiple-choice diagnostic test at the beginning and the end of the semester. Twenty-two students also participated in a semi-structured interview to expand the findings of the quantitative study. Researchers classified the commonsense ideas into two main categories, the principle of motion and influences of motion.

The principles of motion were divided into five main ideas (a) description of motion, (b) moving and resting objects, (c) causes of motion, (d) action and reactions' forces, and (e) Newtons superposition principle. The description of motion included the not well-defined concepts of distance, velocity, and acceleration. For instance, 15% of the students in the posttest incorrectly believed that constant acceleration is the result of a constant force applied to the object.

The diagnostic test results suggested that students believed that every object remains at rest in the absence of a force. Students believed that the motion of an object started by an applied force or by gravity. In the absence of those forces, an object will stop moving. Furthermore, students mentioned that no forces were acting on an object resting on a table, the reason why the object is not moving. The misconception contradicted Newton's first law, which stated that an object in motion would remain in motion in the absence of force, constant speed, and direction unless a net force acts on it. During the interviews, all learners recalled Newton's law for describing the forces and motion of objects. However, in the written posttest, 20% of the participants indicated at least one question that objects slow down under no net force. Only 1% of the participants had the misconception across all the questions asking about objects' motion. Halloun and Hestenes (1985b) concluded that conceptual knowledge of statics is context dependable. Another finding of Halloun and Hestenes (1985b) is that students believed that a heavy object requires a higher force to transitioning to move than a light object, but once the motion started, less effort is required to maintain the motion.

The influences on motion were classified into five main ideas (a) the effect of the applied force, (b) the effect of the internal force, (c) the effect of the resistance force, (d) the effect of the obstacles, and (e) the effect of gravity. Students explained that the applied force caused-motion only if the force is higher than the weight of the object being moved. Students believed that increments in acceleration are due to increments in the applied force. To maintain an object in movement, an internal force in the direction of the movement is required. The internal force can be transmitted from one object to the other. However, the weight of the object is an intrinsic resistance of an object to the motion. Friction was also considered as an opposite resistance of motion. Obstacles in the object's motion path can stop an object, but obstacles do not exert forces. Furthermore, finally, students considered the force of gravity only when the object is falling. An object resting on a surface is not affected by any force.

The investigation of students' commonsense explanations of statics and the questions used for the investigation later built the Force Concept Inventory (FCI) by Hestenes, Wells, and Swackhamer (1992). The FCI is an instrument used for studies around the World to test the conceptual understanding of Newtonian Mechanics in high school and college-level students. Misconceptions found (e.g., the force of gravity only acts on falling objects) informed the student's conceptual understanding of forces and allowed incorporating the findings in instruction. For instance, based on the FCI findings, Dollar and Steif designed learning modules (Dollar & Steif, 2006), and hands-on activities for teaching statics (Dollar & Steif, 2005)

Steif (2004) explored the concepts of the FCI in the context of engineering education ($n = 245$). Steif found that engineering students had eleven main statics failures related to four clusters and four skills. Steif considered that statics' conceptual understanding and implementation skills are important for further courses and statics instructions. Skills are related to the representational competence of students (e.g., drawing the free-body diagrams). Figure 2.2. summarized the statics failures.

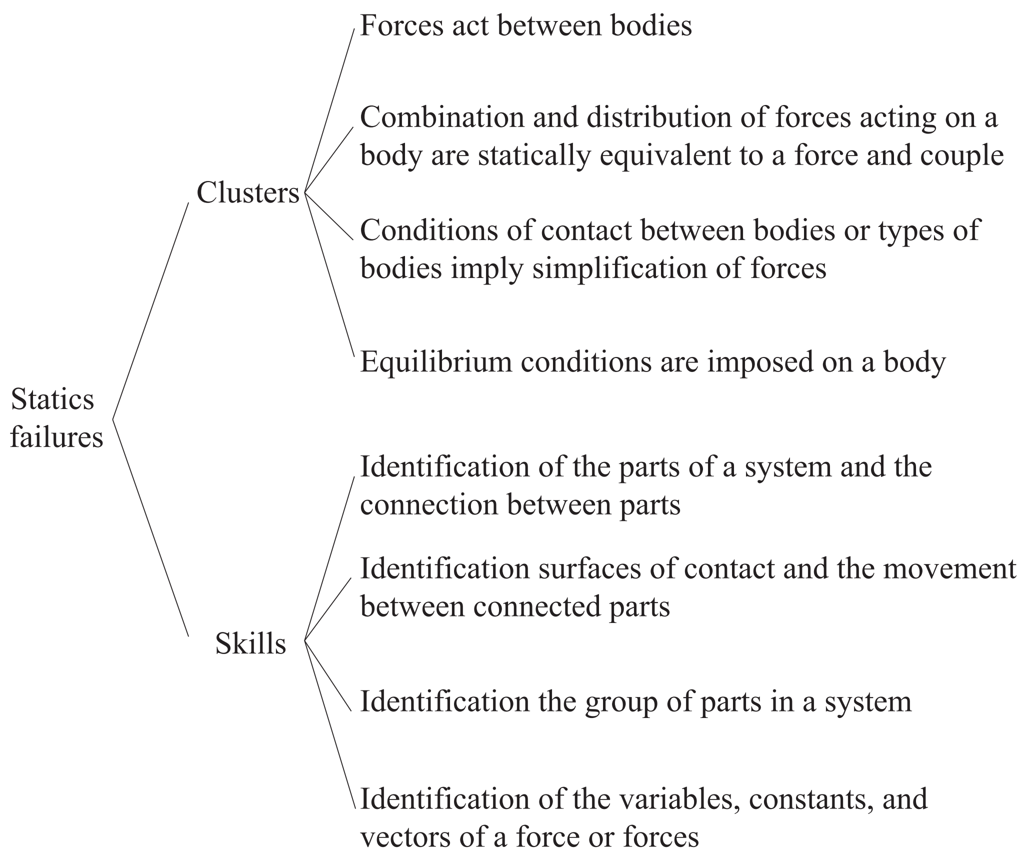

Figure 2.2. Statics failures by Steif (2004)

The clusters of student's failures are (a) forces act between bodies, (b) combinations and distributions of forces acting on a body are statically equivalent to a force and couple, (c) conditions of contact between bodies or types of bodies imply simplification of forces, and (d) equilibrium conditions are imposed on a body. The skills are (a) identification of the parts of a system and the connection between parts, (b) identify surfaces of contact and the movement between connected parts, (c) identify the group of parts in a system, and (d) be able to identify the variables, constants, and vectors of a force or forces.

Students failed to correctly identify or represent in the free body diagram (FBD) the forces acting between bodies. Students leaved a force off the FBD (Error 3), added a force that were not acting on the body (Error 5), and duplicated a force in the FBD (Error 5). When a force is not considered, or more forces are considered, the student usually failed to meet Newton's Third Law, which states that for every action, there is an equal and opposite reaction (Error 6).

In the second cluster, students did not realize that a single net force can be used to replace the multiple forces acting between two bodies in contact (Error 7). Also, students failed to identify that both objects are in contact when two objects exert forces (Error 8). The momentum of an object is the result of all the forces, not a force by itself (Error 11).

In the third cluster, objects in contact are also considered. Students failed to consider the friction force between objects or to neglect; in some cases, the friction (Error 9). In the fourth cluster, students failed to identify the equilibrium conditions imposed on a body by failing to identify the equilibrium object (Error 1), not considering all the parts of the object (Error 2), excluding forces acting on the body (Error 3), adding forces that are not acting on the body (Error 4, and Error 5), failing to account Newton's Third Law (Error 6), and failing to discern between forces and momentum (Error 10).

Steif and Dantzler (2005) later used the findings in Steif (2004) to build the Static Concept Inventory (SCI). SCI comprises twenty-seven questions, addressing free body diagrams, static equivalence, equilibrium, forces at connections, and friction. The SCI is currently used to identify statics misconceptions in engineering students and develop learning tools for teaching statics (Litzinger et al., 2010, e.g.).

2.4 Physical and virtual manipulatives for learning

Teaching and learning statics have evolved and followed many modern trends observable in other contexts, including physical manipulatives and virtual experiments (de Jong et al., 2013; Perkins et al., 2006; Steif & Dollar, 2003, e.g.). Physical manipulative (PM) and virtual manipulative (VM) are hands-on learning tools that promote active learning of science concepts (de Jong et al., 2013). Physical manipulative tools promotes learning by manipulating concrete objects in real-life to observe a phenomenon, while virtual manipulative promotes the observation of a phenomenon through interactive visualizations and materials projected by a computer-based simulation (Zacharia & Olympiou, 2011).

Results from empirical studies in the use of physical and virtual manipulative (PM and VM) suggested positive results in motivations and attitudes towards learning science and learning (de Jong et al., 2013; Satterthwait, 2010; Zacharia, 2015, e.g.). Zacharia and Michael (2016) summarized the reported affordances in the research of PM and VM environments that promote the learning of STEM concepts. According to Zacharia and Michael (2016), the shared affordances of the PM and VM are that they (a) expose students to science and experimentation skills, (b) allow the manipulation of the learning material, and (c) allow the direct observation of the phenomenon, (d) promote the participation of the students in instruction.

VM and PM support a deep understanding of concepts by allowing students to conduct experiments (Jara, Candelas, Puente, & Torres, 2011). Using VM and PM that considers student's prior knowledge in the design may allow students to have the opportunity to test their hypothesis and modify the context and variables affecting the results. Hence, VM and PM may promote students' inquiry in science and cooperative learning by encouraging discussion among peers. Furthermore, combining PM and VM in a single learning experience may enhance the learning in science (de Jong et al., 2013; Olympiou & Zacharia, 2012).

The affordances of PM environments are (a) allow learners to have a multi-sensory input (e.g., tactile input) during the manipulation of objects, (b) develop psychomotor skills, (c) allow learners to use the body for learning, and (d) do not limit the presence of error showing the science phenomenon as it is in nature. The multi-sensory input allows the information to flow actively in a two-way path between the learner and the tool (Fritz & Barner, 1999). First, students manipulate the tool to obtain information about the concept represented by the tool (e.g., manipulate two objects to compare the weight of the objects). Secondly, the tool provides an output based on the participant's input (e.g., the object's velocity increases when the applied force is provided to start the motion increases). Other information that students can obtain by manipulating an object is the object's characteristics (e.g., shape) and the material of the object (e.g., hardness) (McLinden & McCall, 2003).

VM environments, on the other hand, mostly provide visual output, and for the manipulation of the virtual environment, learners use their fingers and hand. With VM, learners interact with virtual environments that model a phenomenon (Zacharia & Michael, 2016). The use of VM can allow students to conduct experiments with a non-visible phenomenon (e.g., statics), encouraging them to explore abstract information from different representations to construct knowledge (de Jong et al., 2013). The affordances of the VM are: (a) allow the change in variables that are hard or impossible to modify in real life, (b) allow the use of multiple linked representations (e.g., diagrams, animations, formulas), (c) allow the analysis of the concepts beyond the normal perception (e.g., from the abstract perspective), (d) identify errors that can be minimized, (e) allow learners to experiment multiple times, (f) provide to learners feedback in real-time, (g) provide observable outcomes no matter the complexity of the concepts, and (h) expose students to a natural or scientific phenomenon, that under other circumstances (e.g., economic, social, safety) would not be possible (D'Angelo et al., 2014). Furthermore, Zacharia and Michael (2016) considered that VM surpasses any limitation that a PM can have.

VM often take the form of computer simulations, whose advantages for learning science concepts have been widely documented in the literature. Specifically, D'Angelo et al. (2014) used a metanalysis approach for summarizing the benefits of using computer simulations for learning. Results suggested that computer simulations had a strong effect size in learning and that compared with traditional methods, students exposed to simulations had a mean score of 23% higher than students not exposed to computer simulations. Furthermore, when students were exposed to simulations that take advantage of the visual feedback (e.g.., enhanced visual feedback showing model's information), or are based on pedagogical approaches (e.g., scaffolding), their performance increased at least 19% vs. conditions using a non-modified simulation. In another study, Dori and Belcher (2005) used simulations for teaching electromagnetism concepts and processes in large scale groups (117 students at a time). Participants exposed to the simulations had a failure rate in electromagnetism concepts of 5%, while the control group (e.g., exposed to lecture only) had a failure rate of 13%.

Comparing the use of PM and VM for learning, Skulmowski, Pradel, Kühnert, Brunnett, and Rey (2016) compared the effect in a spatial learning task in undergraduate students (n = 96) using PM or a VM for heart anatomy. The physical and the virtual tool showed all the labels contained the heart's names at once (permanent condition) or by a selection of specific parts (selective condition). Results suggested statistically significant differences in the retention of the heart part's names in favor of the students using the physical heart $[F(1,92) = 5.8, p = 0.018]$. For the physical tool, the permanent condition $(M = 6.00, SD = 2.64)$ performed better than the selective condition $(M = 5.62, SD = 2.57)$. For the simulation, the selective condition $(M = 5.96, SD = 2.42)$ performed better than the permanent condition $(M = 5.70, SD = 2.95)$.

Skulmowski et al. (2016) also compared the cognitive load of participants used the PM and the VM. Cognitive load is a construct of the load required by a learner to develop a task (Paas, Tuovinen, Tabbers, & Gerven, 2003). In the physical tool, students in the permanent condition experienced a lower overall cognitive load than the students in the selective condition. Contrary, in the simulation, the permanent condition's overall cognitive load was higher than for the selective condition. Regarding the germane load (e.g., how difficult was learning with the tool) results favored the physical tool $[F(1,92) = 8.08, p = 0.006]$.

Finkelstein et al. (2005) found different results comparing PM and VM for learning about circuits. Undergraduate students (*n*= 231) registered in an introductory physics class completed a laboratory session of circuits using a PM or a VM. Another group of students (*n*= 107) learned about friction lecture only (L). In the VM simulation, learners controlled the electrons to observe the propagation of the electric field. In the PM, learners manipulated resistors, wires, light bulbs, batteries, and measurement equipment for constructing a circuit and observe the electric field. Results suggested that participants exposed to the VM solved a challenge to build a circuit faster than those who used a PM and participants in the lecture only (VM $>$ PM $>$ L). Furthermore, in the reasoning task, students exposed to VM outperform students in the PM (p-value < 0.05).

2.5 Combining physical and virtual manipulative in visuohaptic simulations

Visuohaptic simulations are multimodal learning tools that enable learners to control a virtual environment through a haptic device (Hamza-Lup et al., 2019; Magana et al., 2019; Yuksel et al., 2019). The use of visuohaptic simulations (VHS) for learning science has been explored in different application domains. For instance,Yeom, Choi-Lundberg, Fluck, and Sale (2017) investigated the perception of usefulness and ease to use of visuohaptic simulations for learning gross anatomy. Undergraduate students (*n* = 89) explored different body organs (e.g., heart) for learning their structure and composition. Results suggested that participants rated the activity as useful $(M = 72\%, SD = 18\%)$, and easy to use $(M = 57\%, SD = 22\%)$.

In comparison with other learning methods, exposure of learners to VHS has shown mixed results. For instance, Amirkhani and Nahvi (2016) performed a study comparing the learning gains of students exposed to a VHS or a lecture for learning impedance control and fuzzy control. Amirkhani and Nahvi (2016) found that students exposed to VHS $(M = 76.6, SD = 12.04)$ performed statistically better in the posttest than students exposed to a lecture $(M = 62.12, SD = 18.37)$ at $t(28) = -2.42, p = 0.022$.

Comparing VHS with simulations (VM), results are not conclusive. Quantitative studies found that comparing the learning gains between students exposed to a VHS or a VM had no statistically significant differences. For instance, Park et al. (2010) performed an experiment in the electric field domain. Park and colleagues found statistically significant learning gains from pretest to posttest in students exposed to the VHS and the VM. Posttest score comparison between conditions found that students exposed to the VHS and VM equally benefited from the learning activity.

In another study, Magana et al. (2017) obtained similar results in the electric field domain. Learning gains analysis from pretest to posttest were statistically significantly different in both conditions (VHS and VM). The posttest score comparison between conditions was not statistically significantly different.

Magana et al. (2017) focused on the value of the haptic feedback in multimedia environments for learning electricity and magnetism concepts. Seventy-five undergraduate students completed the study consisting of three main steps: pretest, learning experience, and posttest. The learning experience consisted of a course designed under the guidance of multimedia principles to teach electricity and magnetism concepts. Additionally, after the multimedia course, twenty-five students interacted with the visuohaptic simulation, and twenty-five students interacted with the virtual simulation. Results suggested an increment in conceptual knowledge from pretest and posttest in all the conditions. Students who received the multimedia course and interacted with the visuohaptic simulation had a higher mean increment from protest to posttest (e.g., 27.45% higher than the multimedia course only 50.98% higher than the multimedia course + simulation condition). Also, for the three conditions, posttest scores were statistically significantly higher than the pretest scores $(p < 0.05)$. However, posttest scores were not statistically significantly different between conditions, $F(2,72) = 2.69, p = 0.75$. Magana and colleagues suggested that participants that interacted with the visuohaptic condition may experience cognitive overload due to the split attention effect. Participants were not able to connect the visual and haptic feedback with the electricity and magnetism topic. However, another possible explanation for the study's lack of power is that the participants increased their conceptual knowledge from pretest to posttest.

Wiebe, Minogue, Jones, Cowley, and Krebs (2009) compared the effects in learning about levers in thirty-three middle schoolers interacting with a simulation (*n* = 13) or a visuohaptic simulation (*n* = 20). Participants in the pretest and posttest answered thirteen questions. Questions were open-ended (e.g., use the space below to explain to a younger student what a lever is) and selecting an option (e.g., what type of lever is the one depicted in the image). During the interaction with the virtual environment, participants solved three lever exercises. For solving the exercise, learners manipulated the different variables affecting the lever (e.g., weight, distance). Answers of a portion of the participants on each condition (Simulation: *n* = 9, Visuohaptic: *n* = 17), were recorded and analyzed. The interaction phase analysis included the answers of the lever's exercises, the total fixation time in seconds, and the eye's gaze.

Results of the Wieber and colleague's study suggested higher scores in the posttest in nine out of thirteen items in both conditions. However, pretest-posttest item comparison showed no statistically significant differences on any item nor condition. The analysis of the performance during the interaction with the virtual environment resulted in differences among conditions. Students in the simulation condition $(M = 13.54, SD = 0.88)$ outperform students in the visuohaptic condition $(M = 11.85, SD = 1.18)$ in solving the exercises with the virtual environment, $U = 35.5, p < 0.05$. The analysis of total amount of fixation time on key elements of levers (e.g., load, force) suggested that students in the visuohaptic condition $(M = 10.09, SD = 4.88)$ spend more time in key elements of the simulation than the students in the simulation condition $(M = 5.53, SD = 4.07), X2 = 15.50, p = 0.048)$. The analysis of visual trends while solving the exercises showed similar patterns in participants from both conditions.

The third explanation of the results regards why students in the visuohaptic condition did not outperform students in the simulation condition. Researchers indicated that participants in the visuohaptic condition might experience a high cognitive load that hampered them to parse and integrate the visual and haptic information appropriately. High cognitive load could result from the novelty and nature of the haptic technology, which limited the exploration of the levers phenomena and increased the perceptual demands to processes the haptic feedback. Also, neuroscience research indicates that visual and haptic feedback is processed by the same areas of the brain (e.g. , Sathian 2005) suggesting that haptic feedback increased the cognitive demand of the participants.

Hallman et al. (2009) performed a study that showed positive results in favor of the visuohaptic simulation over the virtual manipulative (VHS > VM). In their study, twenty-eight graduate students interacting with a simulation (*n* = 14) or a visuohaptic simulation (*n* = 14) learned about gears. Participants in the pretest and posttest answered twenty Likert-scale questions addressing content, technical elements, and motivation. Posttest scores were higher in the content (by 0.07 points) and technical elements (by 0.08 points) for the visuohaptic group than in the simulation group. The ANCOVA analysis considering pretest scores as covariable, showed that posttest scores of the visuohaptic group $(M = 3.71, SD = 1.14)$ was statistically significantly higher than the posttest scores of the simulation group $(M = 2.79, SD = 1.12), F(1,27) = 4.28, p < 0.05$. The motivation score was higher in the simulation group than in the visuohaptic group (by 0.28 points). In short, results suggested that receiving haptic feedback for learning gears in virtual environments was beneficial; however, the students' motivation was higher in the simulation group than in the visuohaptic group. Researchers believed that the lack of familiarity with the haptic device influenced motivation perception.

Bivall, Ainsworth, and Tibell (2011) study focused on the added value of the haptic feedback in virtual environments for learning molecular interactions. Twenty postgraduate students registered in a molecular course voluntarily completed the study by using a simulation (VM, *n* = 10) or by using a visuohaptic simulation (VHS, *n* = 10). Participants answered the same assessment tool in the pretest and posttest. The assessment tool consisted of four short questions, ten open-ended questions of molecular interactions, and usability questions. Researchers used quantitative and qualitative approaches for the analysis of the pretest and posttest answers. The comparison of the short questions from pretest to posttest showed no statistically significant differences in either condition. The analysis of open-ended questions from pretest to posttest showed statistically significant differences in the visuohaptic group ($p = 0.03$), and non-statistically significant differences in the simulation group ($p > 0.05$).

Bivall and colleagues performed a semantic analysis of the open-ended questions by classifying the words used to answer the questions into five categories: chemical, steric, force, dynamic, energetic. Results showed that all categories in both conditions increased from pretest to posttest, suggesting that students provided more elaborated answers after the intervention. However, only the category of force in the visuohaptic group had a statistically significantly higher percentage in the posttest ($p < 0.001$). Results suggested the haptic feedback helped students learn more about the process of protein-ligand recognition and changed the way they reasoned about molecules to include more force-based explanations. Also, researchers concluded that haptic feedback might also have protected students from drawing erroneous conclusions about the process of protein-ligand recognition observed when students interacted with only the visual model. Regarding the usability questions, the main finding found by Bivall and colleagues is that participants in the visuohaptic group reported getting frustrated by the haptic feedback because it was perceived as a mistake of the simulation instead of feedback of the molecule's reactions.

In another qualitative study, Höst et al. (2013) interviewed four students while interacting with a visuohaptic simulation for learning electric fields and magnetism. The procedures followed two steps; first, participants completed the writing pretest, and secondly interacted with the visuohaptic simulation. Analysis of the participants' behaviors and verbal explanations suggested positive outcomes during the interaction with the visuohaptic simulation. Participants that provided an alternative conception of the electric and magnetism topic in the pretest improved their answer during the interaction with the visuohaptic simulation. Participants that provided a correct conception in the pretest reinforced their answer during the interaction with the visuohaptic simulation. Similarly, participants that provided an incomplete conception in the pretest acquired knowledge during the interaction with the visuohaptic simulation. Results suggested that visuohaptic simulations promote the learning of science concepts through haptic and visual feedback.

Visual and haptic feedback provided learners an immersive-virtual experience that enhanced the conceptual understanding of the phenomena. For instance, haptic and visual feedback facilitated learners' acquisition of new knowledge, otherwise hard to acquire due to the electricity and magnetism topic's abstract nature. Furthermore, Höst and colleagues found evidence to support (Reiner, 1999) 's claim, which suggested that tactile feedback retrieved and recruited tacit knowledge for learning science concepts.

Minogue and Borland (2016), in a pre-posttest study, investigated the role of the haptic feedback in students' buoyancy ideas. Participants were 40 undergraduate students in education majors: 22 received visual and haptic feedback, while 18 received only visual feedback. Using mixed methods to analyze students' answers, the researchers found learning gains between pretest and posttest but no differences in the learning gains between the two treatment groups. For the qualitative analysis, students answered a question regarding why objects sink. The analysis of adjectives, verbs, and nouns used in the students' answers showed that the force feedback influenced the student's conceptual answers. For instance, students receiving the haptic feedback used 15 times more the verb pushing and 13 more times the noun mass in the posttest than the students who only received visual feedback. The analysis of adjectives did not show differences between treatment groups.

Yuksel et al. (2019), investigated students' conceptual and procedural knowledge about the friction of 48 undergraduate students from a technology program. Students were assigned to a sequenced approach in the pre-post test study where students either started with enhanced visual information only or haptic feedback with minimal information and then transitioned to enhanced visual information and haptic feedback together. Conceptual questions asked focused on the role of the object's weight in friction and the role of the object's size in friction. Researchers found significant learning gains in both treatment groups from pretest to posttest $(p < 0.05)$ and effects sizes between 0.31 and 0.61. No statistically significant differences were found in the comparison of learning gains between the treatment groups. The authors concluded that visuohaptic simulations helped students build correct conceptual knowledge, but the visual and haptic feedback in the sequenced approach was inconclusive.

In our prior study Walsh, Magana, and Feng (2020), we expanded Yuksel et al. (2019) 's study by using mixed methods of data analysis. Similarly to Yuksel et al. (2019)' study, we found significant learning gains from pretest to posttest in students' scores. Qualitative data analysis methods were used to balance the lack of power results due to the sample size.

Student's answers in pretest and posttest were classified into four categories, correct and complete, correct, incorrect, and no answer. Correct and complete answers included two or more correct statements in the answers for answering a conceptual question. In correct answers, participants only used one correct statement for answering the conceptual questions, incorrect answers used one or more incorrect statements, and no answers included blank answers and off-topic answers. Results suggested that participants in the $H \rightarrow H+V$ condition outperformed the students in the $V \rightarrow H+V$ condition. The $H \rightarrow H+V$ had significant learning gains $(p = 0.0004)$ with a strong effect size. The $V \rightarrow H+V$ condition did not have significant learning gains $(p > 0.05)$. For the question regarding the objects' role in friction, the $H \rightarrow H+V$ condition showed 46.67% of improvements in students' answers from pretest to posttest. The $V \rightarrow H+V$ condition had 28.6% of improvements. The study concluded that the sequenced approach of $H \rightarrow H+V$ had a greater influence on conceptual knowledge than the $V \rightarrow H+V$ condition.

2.5.1 Summary of studies results

Table 2.1 presents a summary of the study's results.

Table 2.1. Summary of studies results

Study	Conditions	Main results
Skulmowski, Pradel, Kühnert, Brunnett, and Rey (2016) in learning heart anatomy	PM (permanent and selective) vs VM (permanent and selective)	Retention of names: PM > VM. Germane load: PM > VM.
Finkelstein et al. (2005) in learning circuits	Lecture vs PM vs VM	Time building a circuit: VM > PM > L. Reasoning task: VM > PM > L.
Zacharia (2007) in learning electric circuits	PM vs (PM + VM)	Learning gains: PM < PM + VM.
Olympiou and Zacharia, (2012) in learning electric circuits	PM vs VM vs (PM + VM)	Learning gains: PM + VM > VM and PM + VM > PM.
Amirkhani and Nahvi (2016) in learning Impedance control and fuzzy control	VHS vs. Lecture	Posttest scores: VHS > Lecture.

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Table 2.1 continued from previous page

Study	Conditions	Main results
Park et al. (2010) in learning electric fields	VHS vs VM	Learning gains: VHS = VM.
Magana et al. (2017) in learning electricity and magnetism	Multimedia environment (MM) vs MM + VM vs MM + VHS	Learning gains: MM + VHS > MM > MM + VM. Posttest scores: MM = MM + VM = MM + VHS.
Wiebe et al. (2009) in learning levers	VM vs VHS	No significant learning gains: VM + VHS. Interaction performance: VM > VHS. Fixation time of key elements of levers: VHS > VM. Visual pattern: VHS = VM.
Hallman et al. (2009) in learning gears	VM vs VHS	Content and technical elements of gears: VHS > VM. Motivation: VM > VHS Posttest scores: VHS > VM

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Table 2.1 continued from previous page

Study	Conditions	Main results
Bivall, Ainsworth, and Tibell (2011) in learning molecular interactions	VM vs. VHS	No significant learning gains in multiple-choice, VM + VHS. Open-ended questions scores were significantly different only for the VHS. Semantic analysis of words: use of force word VHS > VM.
Höst, et al. (2013) in learning electricity and magnetism	VHS (pretest vs. posttest, interviews)	Found correction of misconceptions, reinforcement of knowledge
Minogue and Borland (2006) in learnign buoyancy	VM vs. VHS	No significant learning gains Higher used of the word force VM <. VHS
Yuksel et al. (2019) in learning friction	VHS sequenced approaches $H \rightarrow H+V$, and $V \rightarrow H+V$	Significant learning gains: $H \rightarrow H+V = V \rightarrow H+V$ Posttest scores: $H \rightarrow H+V = V \rightarrow H+V$
Walsh, Feng, and Magana (2020) in learning friction	VHS sequenced approaches $H \rightarrow H+V$, and $V \rightarrow H+V$	Significant learning gains: $H \rightarrow H+V > V \rightarrow H+V$ Answers improvements: $H \rightarrow H+V > V \rightarrow H+V$

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Table 2.1 continued from previous page

Study	Conditions	Main results
Han and Black (2011) in simple machines	H (haptic feedback) vs K (kinesthetic feedback) vs VM	Recalling, retention, inference, transfer, comprehension: H > K > VM, and K = WM

2.6 Visual and tactile feedback

The visual and the auditory senses for learning have been widely explored in the educational field (e.g., simulations, animations, pictures, audio). Studies have demonstrated the importance of visual and auditory feedback for learning through different lenses such as Multimedia Learning theory by Mayer (2009), and the Dual Code Theory (DCT) by Paivio (1991). However, visual and auditory learning tools provide students a limited learning experience. The sense of touch is required to explore the World and construct knowledge about the environment (McLinden & McCall, 2003; Minogue & Jones, 2006). Touch helps to contextualize the information perceived and understand spatial concepts, classify impressions and collect more information, not available for just seeing or hearing, i.e., surface properties, the fragility of materials, weights, forces, stress, texture, and magnetism (McLinden & McCall, 2003).

The sight and the sense of touch in the form of kinesthesia are usually used together to perceive the environment. Visual perception is through the reflection of light on surfaces (Yantis, 2001). Kinesthetic information refers to the sense of force within muscles and tendons. Kinesthesia includes proprioception, which refers to the body position (O'Malley & Gupta, 2008). Despite the differences between the interactions with a sense of sight and touch, the researchers found evidence that humans recruit similar brain areas while interacting with visual and tactile information (Sathian, 2005). For instance, tactile perception recruits multiple visual cortical regions in a task-specific manner, e.g., the lateral occipital complex (LOC) is recruited during haptic object discrimination (Amedi, Jacobson, Hendler, Malach, & Zohary, 2002); the intrapariental sulcus (aIPS) is activated during a stimulus of tactile and visual rotations (Alivisatos & Petrides, 1997); the region of the extrastriate cortex of the brain is recruited for shape recognition and discrimination (Pietrini et al., 2004). However, the mechanism underlying such brain areas recruitment is uncertain (Sathian, 2005). Sathian suggested that mental imagery and other factors (e.g., location of the stimuli) can explain why it mediates visual cortical involvement in tactile perception.

Fritz and Barner (1999) compared the differences between visual and kinesthetic feedback to design data visualizations for people with visual impairments. From the interaction with the learner, the differences between the visual and kinesthetic feedback are (a) the physical mechanism to obtain the information, (b) information bandwidth, (c) the organs used for acquiring the information, (d) object exploration, (e) the information delivery to the learner, and (f) causality. For obtaining visual information, the retina interprets the vast amount of information provided by the light waves (106, 104 bits/sec). The muscles and spindles interpret a limited amount of information (20-30Hz) provided by the force, length, and velocity of the body movement for getting haptic information. Furthermore, the information needs to be enhanced to perceive certain haptic details (e.g., forces acting between specific molecules).

For receiving haptic feedback, the person needs to contact the environment, while for receiving visual information, contact is not required. The exploration of the objects may be easier using the vision than the sense of touch (e.g., determining the object's shape). Furthermore, visual information may be presented alone or with other information (e.g., audio, tactile), while the interpretation of haptic information is better with additional information (e.g., visual). The causality of the visual information is passive. The data flows from the environment to the learner. The haptic information's causality is active; the learner provides an input that modifies the output (e.g., the force used to push an object affects the objects' acceleration).

The scientific information is visible through the visual feedback and tangible to the haptic feedback (O'Malley & Gupta, 2008). Through enhanced visual feedback, learners see characteristics of the phenomenon not visible at naked-eye (e.g., forces, molecules composition). Through haptic feedback, learners explore shape, weight, hardness, material properties, texture (i.e., by vibrations).

Han and Black (2011) investigated the role of the haptic feedback in the conceptual understanding of simple machines in 118 middle-schoolers. The conditions of the experiment were, simulation (*VM*), kinesthetic feedback (*K*), and haptic feedback, which includes force + kinesthetic feedbacks (*H*). In the simulation condition, participants only received visual feedback. In the kinesthetic condition, participants received visual and kinesthetic feedback. In the force + kinesthetic condition, participants received visual, kinesthetic, and force feedback. Kinesthetic feedback is related to the movements of the arms for interacting with the haptic device. Force feedback is when participants felt it harder to move the haptic device.

The first part of the study's procedures included a pretest, training session, interaction with the virtual environment for learning gears, midtest, videos, and a posttest. The midtest evaluated the participant's ability to recall information from the simulation and the participant's ability to transfer simple machines' knowledge. The comparison of the midtest means scores in recalling and transfer suggested a better performance of the participants in haptic condition followed by the kinesthetic condition and the simulation $(H > K > VM)$. However, only the comparison of the recalling means between the haptic condition $(M = 3.93)$ and the simulation condition $(M = 3.23)$ were statistically significantly different $(p = 0.04)$.

The analysis of the midtest scores of the inference test suggested statistically significant differences between the conditions $(p > 0.04)$. After the midtest, participants watched videos explaining how a window winder and a salad spinner worked. The posttest assessed the participant's ability to recall information from examples used in the lecture and an inference task. For the questions related to the window winder example, results suggested a better performance of the participants in haptic condition followed by the kinesthetic condition and the simulation $(H > K > VM)$. Only the means scores of the

$H(M=4.98)$, and $VM(M=4.24)$ were statistically significantly different. For the questions related to the salad spinner, results suggested a better performance of the participants in haptic condition followed by the simulation and the kinesthetic condition $(H > VM > K)$. Only the means scores of the $H(M=4.95)$, and $K(M=4.0)$ were statistically significantly different. In the inference task, participants answered questions about gears. Results suggested a better performance of the participants in haptic condition followed by the kinesthetic condition and the simulation $(H > K > VM)$. Only the means scores of the $H(M=2.98)$, and $VM(M=2.05)$ were statistically significantly different.

In the second part of the study, a week later, participants completed a delayed posttest. The delayed posttest evaluated the participant's abilities to recall information from the simulation. Results suggested a better performance of the participants in haptic condition followed by the simulation condition and the kinesthetic condition $(H > VM > K)$. However, non-statistical differences in the student's scores were found.

In the third week of the study, participants read an instructional text and answered questions about inclined planes. Results suggested a better performance of the participants in haptic condition followed by the simulation condition and the kinesthetic condition $(H > VM > K)$. Only the means scores of the $H(M=5.18)$, and $K(M=4.15)$ were statistically significantly different.

In summary, Han and Black (2011) study found beneficial the haptic feedback in students' conceptual knowledge of simple machines. Participants receiving force and kinesthetic feedback outperformed in all the test (e.g., midtest, posttest, delayed posttest) the participants in the kinesthetic (*K)* and simulation conditions (*VM*). Researchers concluded that force and kinesthetic feedback provided a grounded experience to learners about simple machines that were beneficial in transfer, recall, and inference tasks. Providing only kinesthetic feedback did not provide an advantage to learners compared to providing only visual feedback $(K vs. VM)$, suggesting that kinesthetic feedback did not provide a grounded learning experience for learning simple machines.

2.6.1 Summary of the comparison of visual and tactile feedback

Table 2.2 presents a of the comparison of visual and tactile feedback.

Table 2.2. Differences between visual and tactile perception.

Characteristic	Visual	Kinesthetic
Interaction	Light/sound waves	Force, length, velocity
Organs	Retina/car drum	Muscles and spindles
Perceptual Organization	Spatially mapped	Body mapped
User-Tech	No contact require	Requires contact
Exploration	Easy	Hard
Devices used	Screens and objects	Haptic devices
Learners' actions	Observe, analyze, see	Push, pull, manipulate, feel
Delivery to learner	Alone & Accompanied	Accompanied
Science representation	Visible	Tangible
Causality	One-way, passive	Two-way, active
Information bandwidth	106, 104 (bits/sec)	20-30Hz

2.7 Chapter summary

The chapter provided evidence from prior research that indicated that acquiring science knowledge is challenging for teaching and learning. Specifically for statics, results from the Force Concept Inventory by Hestenes et al. (1992) and the Statics Concept Inventory by Steif (2004) suggested that students had problems identifying the forces acting on objects, the principle of action-reaction of forces, and equilibrium condition. Hence, the conceptual knowledge of friction concepts is considered incomplete and troublesome.

For providing high-quality science education, researchers had investigated different ways to promote the acquisition of scientific knowledge. One way is considering student's prior knowledge as a step for constructing scientific knowledge (e.g., Besson et al., 2007). During instruction, students confront prior knowledge or construct their scientific knowledge by including their empirical explanations. Moreover, literature from different fields (e.g., science education, conceptual knowledge) identified the importance of the investigation and inclusion of prior knowledge and empirical explanations in instruction as an effective practice in teaching and learning science,(Brown & Hammer, 2013; Halloun & Hestenes, 1985a; Kurnaz & Ekşi, 2015; Steif, 2004).

Another way to promote high-quality education in science is by implementing active learning activities in the classrooms (Mayer & Johnson, 2010). Moreover, the combination of active learning activities and methodological approaches that guides students towards the acquisition of science knowledge suggested positive learning outcomes (e.g., Yuksel et al., 2019)

The use of physical and virtual manipulatives as active learning tools suggested different advantages for learning science concepts (de Jong et al., 2013). The main advantage of physical manipulatives (PM) is that exposed students to content knowledge through objects manipulated by hands or the body. Virtual manipulatives (VM) provided the advantage of enhancing the information and eliminating a phenomena' abstract nature (e.g., showing molecular interaction). Studies comparing virtual and physical manipulative suggested learning benefits from both physical and virtual manipulatives (e.g., Finkelstein et al., 2005; Skulmowski et al., 2016). Moreover, Zacharia and Michael (2016) suggested that affordances of the PM and VM complemented each other to enhance the learning experience of electricity and magnetism concepts. However, there is no research investigating how learners acquired the knowledge through VM or manipulating the physical objects.

Visuohaptic simulations (VHS) are multimodal learning tools that combine the affordances of PM and VM tools. Learners manipulate a virtual environment with a haptic device (Hamza-Lup et al., 2019; Magana et al., 2019; Yuksel et al., 2019). Results from different studies suggested that visuohaptic simulations are beneficial for learning science concepts (e.g., Amirkhani & Nahvi, 2016; Magana et al., 2017).

For investigating the value of haptic feedback for learning science concepts, we found studies comparing VHS vs.VM, but we did not find studies comparing VHS vs. PM. Table 2.1 summarized all the results from the studies included in the document. Results from the comparison of VHS vs. VM are mixed. For instance, Wiebe et al. (2009) found no differences in the comparison of pretest and posttest scores (VHS = VM), but participants in the VM condition performed better in the stage of the study where learners interacted with the tool for answering the conceptual questions of levers (VM $>$ VHS). However, the fixation time in critical elements of the content knowledge was higher in students in the VHS condition (VHS $>$ VM).

Research focusing on the value of haptic and visual feedback in virtual environments suggested that haptic feedback and visual feedback provide different advantages in conceptual learning. For instance, Walsh et al. (2020) exposed learners to a sequenced of haptic and visual feedback approach. Results suggested that students exposed to haptic feedback first and then visual feedback $H \rightarrow H+V$had higher increments in the posttest scores than students exposed to visual feedback first and then haptic feedback $V \rightarrow H+V$. However, the advantages for learning, or the learners' mechanisms for acquiring content knowledge, are clear (e.g., how visual and haptic feedback promotes learning).

In summary, chapter 2 provided evidence of the need for investigating new teaching and learning methods for science concepts. Teaching and learning methods must incorporate the student's prior knowledge and past experiences to construct scientific knowledge. Visuohaptic simulations, an active learning tool, incorporates the affordances of physical and virtual manipulatives for learning. However, the benefits of visual and haptic feedback for learning science is not clear.

Studies comparing the pretest and posttest scores, using mostly quantitative data analysis methods, suggested that haptic feedback did not provide an advantage for learning (VHS = VM). When the interaction with the learning tool is considered in the analysis, learners using a VHS showed positive behaviors towards learning than students in the VM condition (e.g., fixation time in critical elements of the content). The studies presented in chapter 5 and chapter 6 attempted to fill the gap in research of the value of the haptic and visual feedback for learning friction. Studies explored the difference in students' conceptual knowledge at different stages of the study (e.g., pretest, interactions) and used qualitative methods of analysis to deepen the advantages of visual and haptic feedback.

CHAPTER 3. THEORETICAL FRAMEWORK

This chapter has four main sections. The first section defines embodied cognition and the notions of embodied cognition. The second section presents two models of embodied cognition, mental imagery and embodied language, used for investigating the development of the cognitive process, including learning. The third section focuses on the guidelines and a taxonomy for the design of embodied learning environments. Finally, the fourth section focuses on summarizing the implications of embodied learning in this research.

3.1 Embodied cognition

Embodied cognition states that body, brain, and environment regulate cognition (Barsalou, 1999; Dourish, 2001; Lindgren & Johnson-Glenberg, 2013; Turner, 2016a; Varela, Thompson, & Rosch, 1991). The human brain is not the sole cognitive source for learning and problem-solving. The body and environment are additional resources available to humans for solving problems (A. Wilson & Golonka, 2013).

Human's sensorimotor capabilities, embedded within the psychological, biological, and cultural contexts, are a foundation of human intelligence, self-awareness, skilled behavior, affective regulation, and cognitive regulation (Ionescu & Vasc, 2014; Varela et al., 1991). Furthermore, Clark (1997) expanded the role of the body in cognition by shaping the term of *mini-brains*, which indicates that the body is also able to perform a cognitive task. For instance, during a motoric activity such as hitting a ball, the muscles work as mini-brains of the action.

The environment's affordances activate the brain's areas for motor action and sensor action (e.g., perception) during a task's performance. For instance, a successful return serves performed by a tennis player is influenced by the server's critical regulatory information. Expert tennis players spend more time looking at the opponent position, racquet, and ball during the service, while the novices often mainly focused on the ball (Goulet, Bard, & Fleury, 1989).

3.1.1 Notions of embodied cognition

After a literature review in embodied cognition, M. Wilson (2002) identified six claims that characterize embodied cognition (1) cognition is situated; (2) cognition is time-pressured; (3) we off-load cognitive work onto the environment; (4) the environment is part of the cognitive system; (5) cognition is for action; and (6) offline cognition is body-based.

'Cognition is situated' refers to the idea that cognition takes place in a context; activities are distributed between the subject(s) and environment (Suchman, 1987). Human's information processes are unpredictable and messy; plans can change throughout the activity's development due to the environment's affordances and society's rules (Dourish, 2001; Suchman, 1987). The use of language is an example of a situated cognition process (Barsalou, 2008). Words and expressions can change depending on the subjects and context of the conversation. However, the situated view of cognition does not characterize the cognitive process that occurs without interaction subject-environment. For instance, situated cognition does not characterize the human's ability to think about the past and the future, modifying the circumstances to think about different outcomes (e.g., what would have happened if I had not decided to do a Ph.D.?) and can create representations of a situation explained by another person.

Conceptual learning is rooted in body experiences and the context (Abrahamson & Lindgren, 2014; Barsalou, 2008). If a student is learning a concept and cannot recall a perceptual experience related to the concept, the student may perceive it as difficult to learn (Barsalou, 2008). When the context and knowledge are embedded, the learning process is naturally favored—contrary, the decontextualization of knowledge (e.g., lectures) promotes incomplete and naïve knowledge (J. Brown, Collins, & Duguid, 1989; Spiro, Feltovich, Jacobson, & Coulson, 2013). Differences in performance between classroom settings and solving everyday problems may result from incomplete and naïve knowledge (e.g., know that metal is a conductor of electricity and use a metal tool to fix a short circuit) (Spiro et al., 2013). Hence, one challenge in science education is the integration of knowledge within a context to face the actual challenges of the real world (Härtig, Nordine, & Neumann, 2020).

The second view *'cognition is time-pressured'* refers to the idea that cognitive processes are responses to inputs (e.g., environment inputs). The environment and the precise moment of the input influence the output (e.g., pressing the emergency button after listening to an alarm). However, because human's cognitive capabilities are limited, receiving multiple inputs may result in slower or inaccurate responses due to the representational bottleneck (Clark, 1997).

The third view *'humans offload cognitive work onto the environment'* refers to the idea that humans simplify cognitive processes by manipulating their environment and using external resources. Using external resources to acquire knowledge or solve a problem saves time and contributes to its success. One example of offloading cognitive work to the environment is provided by Kirsh and Maglio (1994). Kirsh and Maglio (1994) investigated the cognitive process involved in playing Tetris. Kirsh and Maglio (1994) found that the physical manipulation of figures (e.g., rotation of figures) helped participants with the spatial reasoning required to solve a game. Based on their findings, Kirsh and Maglio coined the term *epistemic actions*, which refers to external actions used to generate computational offloading.

The fourth view *'the environment is part of the cognitive system'* refers to the idea that humans achieve solutions by distributing the cognitive load of a process between subjects, artifacts, and the situation (Hollan, Hutchins, & Kirsh, 2000). Therefore, the analysis of cognition, considered a system, contemplates all the factors involved (i.e., spatially or temporally characteristics) and the influences of one factor over others (e.g., how the distance between subjects affect the time for achieving a goal).

Johnson-Glenberg et al. (2014) investigated the impact on learning chemistry in a mixed reality environment vs. a traditional learning environment. The only difference between conditions was the learners' interaction with the learning material; the virtual reality environment required the learners to use their body for learning (e.g., gestures) and have social collaboration. The lecture required the learners to manipulate the laboratory equipment. Researchers found better outcomes in students' knowledge in the virtual environment than in the traditional learning environment (mean increment before and after the intervention of 27.79 vs. 4.66, effect sizes of 1.09 vs. 0.3). Johnson-Glenberg et al.

(2014) attributed the outperformance of the virtual environment to factors such as the embodiment (e.g., grounding the knowledge instead of inducing mental simulations) and the collaboration among students. Furthermore, Johnson-Glenberg and colleagues suggested four perspectives of why the collaboration in the virtual environment produced effective learning: (a) motivation, (b) social cohesion, (c) cognitive developmentalist, and (d) cognitive elaboration. Motivation and social cohesion referred to the students' interest in growing and achieving group goals. The cognitive developmentalist is related to high-performance students' influence over the low-performance students in discovery learning and creative thinking. The cognitive elaboration occurred when each student individually explained aspects of the material .

The fifth view *'cognition is for action'* refers to the idea that the cognitive process occurs in the function of activity. Memory and perception improve cognitive control of the environment and work in function of the action (M. Wilson, 2002). For instance, information from the environment is gathered through the eyes and processed by higher cognitive areas of the brain to create internal mental representation. The short-term memory completes the mental representation if the information gathered is regularly used. The long-term memory completes internal mental representations if the information is not used regularly. Once created the internal mental representation, the subject provides an output that will help control and adapt to the environment. For instance, Zwaan and Taylor (2006) experimented with thirty participants in rotated a knob while visualizing a knob rotating on a computer screen. Participants responded faster when the visual and the manual rotation were in the same direction. Results suggested that visual rotation affected the performance in the manual rotation.

The last view is *'offline cognition is body-based'* refers to the idea that humans do more than offload information to the environment. Humans also offload information onto perceptual and motor control systems. Gesturing while speaking is one way to cognitive offload. Hence, gestures cannot be considered pure kinesthetic symbols of the speaker. Gestures are symbols that contain a full range of information of what the speaker is talking about (McNeill, 1994).

3.2 Models of embodied cognition

Two cognitive science models used for investigating the benefits of the embodiment in the development of the cognitive process, including learning, are mental imagery and the embodied language. The following sections describe the models.

3.2.1 Mental imagery

Mental imagery is the ability to generate and manipulate mental images in mind to generate predictions based on prior experiences (Kosslyn, 1994; Moulton & Kosslyn, 2009). Mental imagery depends on the perceptual representations and activation of the brain's perceptual systems (Jeannerod, 1995; Moulton & Kosslyn, 2009). Thus, mental imagery is often described as "seeing, hearing, feeling, with the mind eye" (Botzer & Reiner, 2005; Cattaneo & Silvanto, 2015; Kosslyn, 1994).

Two theoretical viewpoints deal with mental imagery; the pictorial theory and the propositional theory (Tye, 1984). The difference between the theoretical views is the mental process used. The pictorial account posits that during mental processes, humans create and manipulate images in their minds. The propositional theory posits that there is no picture-like requirement for mental imagery (Pylyshyn, 2003). Like reasoning, the propositional representation consisted of an abstract system of symbols that can be used to express the mind's content. According to Pylyshyn, the generation of pictures in the mental process results from the instruction, e.g., if people are asked to imaging an object, they will simulate the object in their heads based on their tacit knowledge. This simulation occurred because human cognition is sensitive to the context and how the problem is framed (Pylyshyn, 2003).

The pictorial theory posits that the environment's perceptual inputs influence mental images' creation during the mental processes (Kosslyn, 1994; Kosslyn, Thompson, & Ganis, 2006). When a perceptual input is present, the mental imagery influences the environment. For instance, when a person is asked to imagine a landscape, and the person is in the presence of images in warm colors, the person can imagine the landscape during sunset. (e.g. Segal & Gordon, 1969). However, mental imagery can occur in the absence of perceptual input, e.g., asking a person to imagine a landscape (Rinck & Denis, 2004).

In the study performed by Shepard and Metzler (1971), participants judged if a pair of 3D figures had the same shape. Eight participants judged 1600 pairs of figures, which half of the pairs were the same figure but in different angular positions, and the other half were different figures (mirror shapes). Shepard and Metzler (1971) found that reaction time was a function of the rotation of the figures; the higher the rotation between figures, the higher the reaction time. Participants indicated that they pictured the figure in their mind for solving the exercises and performed the rotation Chu and Kita (2011). Risko, Medimorec, Chisholm, and Kingstone (2014) had similar results in their experiments investigating the analysis of shape in the function of the angular position (e.g., higher reaction time with the increment of the angular difference between the objects).

The creation of mental images is associated and disassociated with memory. Cases of mental imagery disassociated from memory occur when a person creates mental images of situations not experienced before. For instance, following the previous example of imaging a landscape, by describing a specific landscape during sunset when the person has not seen the place during the sunset (Segal & Gordon, 1969).

The creation of mental images associated with the memory occurs when the working memory (WM) connects the perception with either short-term memory (STM) or long-term memory (LTM). Baddeley (2007) defined WM as "temporary storage system that underpins our capacity for coherent thought" (Baddeley, 2007, p.1). For example, when a picture of a landscape is presented to a person and then asked to describe the picture, the information retrieval is from the STM. If there is no picture presentation, the retrieval of the information for the landscape description was from the LTM. The mental imagery generated from the STM is more vivid and detailed than the mental imagery generated from the LTM (Cattaneo & Silvanto, 2015).

The Dual Coding Theory (DCT) explains how the stimulation of images occurs (Paivio, 1991). DCT proposed that there are two mental codes, the verbal and non-verbal, which influence the creation of mental imagery. The verbal system, based on language, contains all sensory forms, such as visual, auditory, articulatory (Sadoski & Paivio, 2013). The verbal system maintains the hierarchy and rules of the language. When a word is heard (e.g., apple), the picture is retrieved (e.g., from the LTM or STM), and it activates the visual memory trace. The activation of the visual memory trace explains why the recall of concrete words is easier than recalling abstract words (Cattaneo & Silvanto, 2015). The non-verbal is also called perceptual experience. It includes the modality-specific sensory forms that are based on the non-verbal perceptual system such as sounds, images, and tactile sensations (Sadoski & Paivio, 2013).

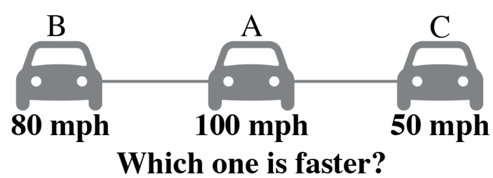
According to DCT, mental imagery plays a role in memorization, learning, reasoning, and scientific thinking (Cattaneo & Silvanto, 2015). Rieber, Tzeng, and Tribble (2004) experimented with the processes of learning and interaction with computer simulations. A total of 52 college students learned about Newton's motion laws by moving a ball to a target location. Participants had 30 trials; in the first 20 trials, participants succeed if the ball reached the target location; in the last ten trials, participants succeed if the ball reached the target location and stopped its motion. Participants were assigned to one of the following conditions: (a) simulation + graphical feedback (C1), (b) simulation + graphical feedback + content explanation (C2), (c) simulation + textual feedback (C3), (d) simulation + textual feedback + content explanation (C4). Textual feedback consisted of formulas and numerical readouts of the ball position, while graphical feedback in the ball's graphics and animated position. The content explanations aligned the experience with the physics laws using text and animated graphics. The content explanations were given during the interaction with the simulation (e.g., every two tries, one content explanation popped out). The researcher assessed explicit and implicit knowledge of motion. Explicit knowledge was assessed in the multiple-choice pretest and a posttest. Implicit knowledge was assessed in simulation performance (e.g., if students reached the goal).

The pretest-posttest comparison showed that (a) all participants had significantly higher scores in the posttest $\Delta C1 = 22, \Delta C2 = 38.5, \Delta C3 = 9.6, \Delta C4 = 26.5$, (b) exposure to embedded explanations resulted in higher learning gains, and (c) posttest scores were significantly different between the conditions, being graphical feedback + content explanations the best combination for the students. Results of the simulation performance showed that (a) students that received graphical feedback performed better in the simulation than students that received textual feedback, and (b) content explanations did not influence the participants' performance in the simulations. Findings suggested that providing information to participants in verbal and non-verbal modalities resulted in an increment of the explicit knowledge (e.g., higher posttest scores). The alignment in the non-verbal modality between the implicit knowledge (e.g., know how to do it) and the graphical feedback may facilitate the learning of Newton's laws of motion. Content explanations did not influence the implicit knowledge during the interaction with the simulation. Rieber and colleagues concluded that (a) simulations helped students to understand Newton's laws of motion, (b) to provide feedback during the interaction with the simulation is required to promote explicit and implicit knowledge, (c) the modality alignment between the simulation and the graphic feedback helped students to perform better in the posttest, (d) content explanations were not required during the use of the simulation. Belland, Walker, Kim, and Lefler (2017) performed a literature revview of the use of computer simulations for learning STEM and concluded that different methods of scaffolding (e.g., implicit, explicit, verbal and non-verbal) positively influenced learning.

In deductive reasoning, mental imagery helps to the creation of information from the statements (Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002). Reasoning and mental models are strongly interconnected (DeSoto et al., 1965). Mental models are visuospatial representations of the argument that is constructed and evaluated

(Johnson-Laird, 1983). Mental models are used as a form of analogical-pictorial format, created based on the inferences of the statements provided to motivate the reasoning. The result of the deductive reasoning occurs when a person reads the mental image; where the truth of the premises ensures the truth of the conclusion (Knauff & May, 2006).

According to DeSoto et al. (1965), the construction of the unitary mental representation is based on two principles. First, the construction of the relationship between premises in the occidental culture follows a top to bottom and left to the right array. Second, it is easier to represent a premise if its first term is an end-anchor instead of a middle-anchor. The construction of the mental representations also occurs in the absence of visual stimuli (Knauff et al., 2002). Figure 3.1 shows an example of DeSoto and colleagues' principles.



Representation 1	**Representation 2**	**Representation 3**
A is faster than B	B is slower than A	A is faster than B
B is faster than C	B is faster than C	B is faster than C

Figure 3.1. Mental models for reasoning. (DeSoto et al., 1965)

Figure 3.1 shows the speed of three cars and three possible representations of the reasoning. Representation 1 and representation 2 followed the first principle of construction. The statements are written from top to bottom and left to right. Representation 1 also followed the second principle (e.g., the first premise used is A, that is, and end-anchor), while Representation 2 used as anchor Car B, a middle-anchor. According to DeSoto et al. (1965) Representation 1 is easier to read than Representation 2. Representation 3 did not follow the principles; hence it is harder to read than the first and second representations.

Kosslyn (1994) proposed a model for mental imagery composed of visual imagery and spatial imagery. Visual imagery represents the object characteristics (e.g., color, shape, and other details), while spatial imagery represents the spatial relationship between the object, the location, and the movement performed by the object. Spatial imagery is critical to deduce an outcome correctly. For instance, research in mathematics suggests that spatial thinking is required for problem-solving (Hegarty & Kozhevnikov, 1999; Owens & Clements, 1998; Van Garderen, 2006).

Hegarty and Kozhevnikov (1999) investigated the role of the visuo-spatial representation in solving problems in mathematics. Thirty-tree middle school students solved fifteen problems (e.g., how many trees can you plant in fifteen meters if each tree should be separate five meters). Researchers found that students that used visual-spatial strategies to solve the problems performed better ($M = 7.76$, $SD = 3.43$) than students that used pictorial representations ($M = 5.76$, $SD = 3.6$). Furthermore, the use of pictorial representations had a marginally significant negative correlation with mathematical problem solving ($p = 0.056$).

Similar results were obtained by Van Garderen (2006) in the mathematics domain. Van Garderen investigated the methods used for mathematics problem-solving in sixth-grade students ($n = 66$). The problem indicated that if the diameter of a can of peaches is 10 units, how many peaches will fit in a unit of 40x30 units? Participants in their study were categorized into three types: with learning disabilities, average achievers, and gifted students. Results showed that gifted students used more schematic imagery than pictorial imagery ($Mg = 6.77$, $SDg = 3.29$ vs. $Mp = 2.86$, $SDp = 2.32$), see Figure 3.2. Average achievers and students with learning disabilities used more pictorial imagery than schematic imagery (average achievers: $Mp = 3.22$, SDp = 2.98 vs. $Ms = 4.45$, $SDs = 2.89$; learning disabilities: $Mp = 5.36$, $SDp = 2.59$ vs. $Ms = 1.64$, $SDs = 1.5$). Significant differences were found in the use of schematic and pictorial images in gifted students and students with learning disabilities (e.g., significant more use of schematic images by the gifted students). No significant differences were found in the use of images between the gifted and the average students. Van Garderen also found that using pictorial imagery for problem solving in mathematics is negatively correlated with the use of schematic imagery, $r(64) = -0.37, p < 0.01$. The use of pictorial images is negatively correlated with performance, and schematic use of images is positively correlated with performance.

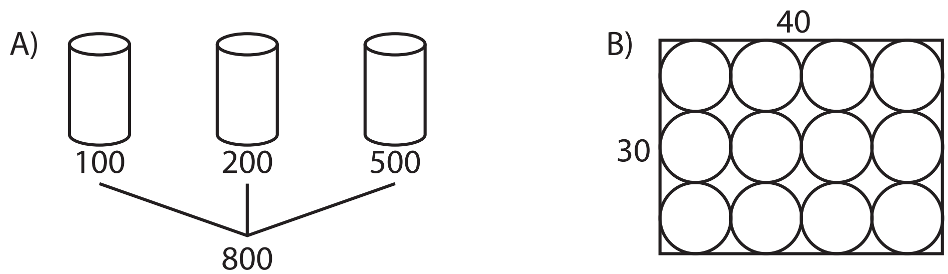


Figure 3.2. Pictorial (A) and schematic (B) images from (Van Garderen, 2006)

3.2.2 Embodied language

Embodied cognition recognizes the mind as inherently embodied, thought is mostly unconscious, and abstract concepts are highly metaphorical (Lakoff & Johnson, 1980). The brain makes sense of the environment using spatial positions; for example, the glass is in front of the phone. The phone has no front or back, but humans can understand the idea. The use of metaphors helps humans to understand different concepts, including the abstract concepts in science. For instance, by explaining why a heavy object is not moving when a force is applied, a person can indicate that the object does not want to move because it is heavy.

Embodied cognition states that language comprehension has a direct correspondence with the physical interactions, motor simulations, and perceptual experiences a learner experiences within their environment (Beilock et al., 2008; Louwerse & Jeuniaux, 2008). Furthermore, the representation of an entity or event is achieved by recruiting the sensorimotor experience obtained during the event or entity occurred.

Studies relating the language processing and visual perception found that visual perception is facilitated by embodied simulation of the comprehended sentence. For instance, Meteyard et al. (2007) 's study found that when participants (*n* = 20) heard a motion-related verb that matched with a motion of dots in a screen (e.g., upward verb and the dots moved upward), the perceptual sensitive was higher, the internal decision threshold was lower, and the reaction time was lower than when the verb and the motion mismatched. Likewise, Meteyard, Zokaei, Bahrami, and Vigliocco (2008) found the reverse effect; the visual motion interfered with the processing of motion-related verbs.

Beilock et al. (2008) measured language comprehension of actions among ice-hockey experts (*n* = 12), ice-hockey novices (*n* = 9), and ice-hockey fans (*n* = 8), who never played hockey before. Participants passively listened to ice-hockey-related sentences and daily-life sentences during functional magnetic resonance imaging (fMRI) and then completed a posttest. During the posttest, participants listened again the daily life and hockey sentences and observed images. Participants determined if the image described the sentence heard by saying “yes” or “no”. Results showed different outcomes in the action-match analysis (response time when the image and the sentence matched vs. when the image and the sentence mismatched). All the participants, regardless of the hockey expertise, had a statistically significant lower response time in sentence-image matches for everyday sentences. For hockey sentences, experts and fans showed a statistically significant lower response time in sentence-image matches. Response time was not different in matches and mismatches of sentences and images in novices' participants. Hockey experts and fans activated different brain areas while listening to hockey sentences than the novices' players. Experts and fans activated the left dorsal premotor cortex brain region, and novices activated the right dorsal sensory-motor cortex. The activation of the right dorsal sensory-motor cortex was negatively correlated with the hockey experience $(r = -0.45, p < 0.02)$. The left dorsal lateral premotor cortex is a brain region normally devoted to higher-level action selection and implementation. Results suggested two main findings: (a) there are differences in language comprehension and activated areas of the brain for comprehending the sentences between participants with hockey experience and no hockey experience, and (b) hockey sentences comprehension was not facilitated by motor experience since experts and fans obtained similar results.

3.2.3 Embodied language in physics

The language used to explain physics concepts is often highly metaphorical and, therefore, abstract. Physics educators often use conceptual metaphors to convey a physical concept or analogical model, such as metaphors, to construct new ideas (Brookes & Etkina, 2007). Language usage in students' explanations of physical systems also shows frequent misconceptions due to reasoning from everyday experiences. For example, Meltzer (2004) observed that students learning thermodynamic systems often focused only on the beginning and endpoints of the process and ignored the path taken. This observation was attributed to the student's conceptualizing heat as a substance and the thermodynamic systems as a container. Therefore, it is essential to note that our everyday physical experiences with the world around us greatly influence our reasoning in learning about the physical world in STEM education.

On the other hand, our common usage of everyday language can, in turn, influence our interpretation and understanding of physical experience (S. Brown & Salter, 2010). Hence, a bi-directional approach between teaching the students to learn through embodied cognition and tuning their language while reasoning scientific concepts must be considered.

3.3 Designing embodied learning environments

The design of embodied learning environments may promote the orchestration between the modes of information (e.g., visual, auditory, tactile) and the link between modes and content knowledge. For that, Abrahamson and Lindgren (2014) proposed guidelines for the design of embodied learning environments, and Johnson-Glenberg (2018) proposed a taxonomy of embodied learning. The following sections expanded the guidelines and taxonomy in embodied learning.

3.3.1 Embodied learning guidelines

Abrahamson and Lindgren (2014) provided guidelines for the design of embodied learning materials. The guidelines provide information to face the challenges of three main elements: activities, materials, and facilitation. Embodied activities should promote the body's use for learning (e.g., learners moving in a 3D space). Learners should use their perceptual and motor systems to interact with the environment. The organization of the learning content is incremental, where learners can build knowledge progressively.

Materials used in an embodied learning activity must orchestrate the modalities presented. For instance, simultaneous tactile and visual stimuli should be oriented to reach the same goal. Learner's actions during the learning activity are goal-directed and incremental (from a simple action to a more complex action). Actions performed by learners are similar to the actions performed in real-life. Feedback provided to learners should be in real-time.

Embodied learning activities should facilitate conceptual development by unfolding conceptual information of the phenomena. For instance, virtual environments can provide information that, under other circumstances, would not be possible (Zacharia & Michael, 2016). The learning activity must guide the learner to understand the phenomena from different perspectives. To facilitate the material's comprehension, a method suggested by (Abrahamson & Lindgren, 2014) is to ask learners about the feedback received and promote the connection feedback-learning content.

3.3.2 Embodied learning taxonomy

Johnson-Glenberg (2018) proposed a taxonomy of embodiment for education in virtual environments (VR). The taxonomy contemplates three constructs: sensorimotor engagement, congruence of gestures, and immersion and presence.

Sensorimotor engagement via gestures refers to the gesture's magnitude to manipulate the 3rd dimension environment (e.g., the whole body, only arms). The more parts of the body required to interact with the environment, the higher the sensorimotor engagement.

Congruence of gesture refers to the importance of the body movement to achieve the goal of learning. For instance, if movements are random and do not provide information on the content knowledge, this construct is low. Opposite, if the movement is goal-direct and well mapped with the content knowledge, this construct is high. Moreover, a high magnitude of gesture combined with a low congruence may not provide a learning advantage.

Immersion/presence contemplates the technology and the learner's perception (e.g., how much the technology used provided a sense of immersion, and how much of that immersion is perceived by the learner). It is subjective from the learner's perspective (e.g., how much did a learner feel with the learning content).

3.4 Implications of the embodied learning for this study

Research in cognitive sciences is continuously evolving and opening debates for answering the question of how do humans abstract and acquire concepts (e.g. Chatterjee, 2010; Mahon, 2015; Pylyshyn, 2003). Far from ignoring the debate, this research does not focus on theoretical issues of embodied cognition. This research focuses on the use of hands-on tools for learning friction concepts. Prior research aimed to investigate the use of hands-on tools for learning used embodied learning as a theoretical framework. For instance, Han and Black (2011) and Höst et al. (2013) used embodied learning as the theoretical framework for investigating the role of haptic feedback in learning physics.

The selection of embodied learning as a theoretical framework is justified by the body's direct correspondence for interacting with the hands-on tools. In this research, the concept of friction and the hands-on tools, a physical manipulative tool and a visuohaptic simulation, had a link with body experiences. The motor and visual perceptual systems are activated during the interaction with the hands-on tools. Humans experience and develop explanations of forces in daily life (e.g., while walking, pushing objects, or holding objects) (Gopnik, 2010). Embodied learning has therefore implications for the design of the learning experience used in this research. Specifically, for the learning materials, embodied learning proposed that verbal and non-verbal modalities promote the acquisition of science concepts (Barsalou, 2008; Rieber et al., 2004).

Abrahamson and Lindgren (2014) proposed guidelines for the design of the activities, materials, and facilitation. The guidelines focused on linking content knowledge and body actions for learning and scaffolding the learning process. Thus, Abrahamson and Lindgren (2014) guidelines impacted the design of the learning tools and worksheets. Similarly, the taxonomy proposed by Johnson-Glenberg (2018) oriented this investigation in the design of the hands-on tools and the worksheet considering the three constructs of embodied learning, sensorimotor engagement, congruence of gestures, and immersion and presence. The virtual environments enhanced experiences to unfold information that is not available in a real-life environment (e.g., showing invisible information). The actions (e.g., gestures) allows learners to understand the concepts in virtual environments.

For the research design, mental imagery and embodied language informed this research in designing the research questions and how to prompt learners' conceptual knowledge. For instance, the use of open-ended questions has been found to promote everyday language for answering physics problems (S. Brown & Salter, 2010), and has allowed researchers to understand the impact of the learning activity in the construction of explanations. The research question focused on how the learning, through the visual and haptic feedback, promote conceptual knowledge of friction. Chapter 4 provides details about the learning tools' design and how the embodied learning considerations were implemented. Chapter 5 and Chapter 6 provide details of the research design used.

3.5 Chapter summary

This chapter presented Embodied learning as the theoretical framework used in this investigation for guiding the design of learning materials and the research design. Moreover, this chapter presented the underpinnings of embodied learning as a theory for linking body actions with conceptual learning and designing and conducting research under the embodied learning framework. For instance, embodied learning suggests bringing past learning experiences and promoting the body's use to acquire knowledge facilitates the comprehension of abstract concepts (Barsalou, 2008). Also, for the research design, embodied learning suggested investigating how the body's actions impact learning and what challenges students face during the learning activity.

The next chapter focuses on the design of the embodied learning experience and how the learning experience considered the affordances of physical manipulatives and virtual manipulatives for learning (Zacharia & Olympiou, 2011), the guidelines for embodied learning (Abrahamson & Lindgren, 2014), and the taxonomy for embodied learning design (Johnson-Glenberg, 2018).

CHAPTER 4. LEARNING DESIGN

Chapter 4 presents the learning design for teaching and learning statics concepts in undergraduate engineering courses. This Chapter focuses on general aspects of the learning design across the studies presented in Chapter 5 and Chapter 6. Specific details of the learning design per study are presented in each Chapter.

The elements considered in the learning design are the learning objectives, learning context, pedagogy, and scaffolding. The pedagogy and scaffolding section describes the learning tools and the worksheets designed for learning the concepts of friction. The learning tools designed were a physical manipulative tool (PMT), a visuohaptic simulation (VHS), and the worksheets that guided the interaction with the PMT and the VHS.

A multidisciplinary team carried out the development of the materials. Experts in physics, mechanical engineering, computer simulations, education, and design, ensuring that the content was aligned with the physics laws and the technology capabilities (e.g., the haptic device used had three degrees of freedom). The materials were revised on multiple occasions by the design team and external personnel with physics and mechanical engineering knowledge.

4.1 Learning objectives

The goal of the learning materials is to provide a guided, embodied experience for learning friction concepts. Specifically, the learning experience focused on two main concepts, the role of the objects' weight in friction, and the role of the object's size in friction. The selection of the concepts taught by the learning experience was based on the results of the Force Concept Inventory (Hestenes et al., 1992), Static Concept Inventory (Steif & Dantzler, 2005), and the findings in the prior studies of Walsh et al. (2017) and Yuksel et al. (2019).

Hestenes et al. (1992) and Steif and Dantzler (2005) found that students had multiple misconceptions about the forces acting on resting and moving objects. For instance, students have problems identifying that gravitational force and normal force act on an object resting on a surface. Also, students failed to recognize the role of the friction force in objects in movement. Students considered that the object's force needed to be higher than the weight for moving an object.

Walsh et al. (2017) and Yuksel et al. (2019) explored the role of the friction force when objects are being pushed on a surface. The conceptual knowledge investigated in Walsh et al. (2017) and Yuksel et al. (2019) is the role of the object's weight in friction and the role of the object size in friction.

For learning the role of the object's weight in friction (conceptual question 1, CQ1), learners compared the difference between pushing two cubes with the same size but the different weights on a surface. The numerical value of the weight and the cube's size were not provided to learners on any conceptual question. For instance, CQ1 specified to compare the differences between pushing Cube 1 vs. Cube 2. Cube 1 was large and light, and Cube 2 was large and heavy. An example of a statement used for evaluating CQ1 was *What happens when you push two cubes made from the same material and with the same size, but with different weights (one half the weight of the other) on a surface?*

For learning the role of the object's size in friction (conceptual question 2, CQ3), learners compared the difference between pushing two cubes with the same weight but the different sizes on a surface (Cube 2, large and heavy, vs. Cube 3, small and heavy). An example of a statement used for evaluating CQ2 was *What happens when you push two cubes made from the same material and with the same weight, but with different size (one half the size of the other) on a surface?*. The studies presented in Chapter 5 and Chapter 6 focused on the same conceptual knowledge of friction.

4.2 Learning context

The context for learning with the tools designed in this study is a laboratory setting of an introductory physics course at the college level. The learning materials do not replace a lecture on friction concepts. Materials provide an embodied learning experience of friction concepts after formal instruction in a lecture. Prior knowledge and prior experience of friction concepts are required for acquiring knowledge with the learning tools.

Learner's interactions with the learning tools are individual; each learner used a visuohaptic simulation or a physical manipulative tool to complete the worksheets. Before the interaction, the course professor and the teacher assistant will explain how to use the learning tools. Instructors also will help students to solve questions during the learning experience.

4.3 Pedagogy and scaffolding

The learning theory that influenced the learning design of the materials was **embodied learning**. Embodied learning posits that the use of the body may facilitate the process of learning abstract concepts (Abrahamson & Lindgren, 2014). The body's use provides advantages to the learning process from different perspectives, including contextualizing the learning experience and reducing the cognitive load.

The body's use for learning contextualizes the learning process in a setting similar to how humans experience the phenomenon (J. Brown et al., 1989; Höst et al., 2013). If a learner cannot recall a prior embodied experience, the learner may perceive the concepts as difficult (Barsalou, 2008). For instance, learners may experience the frictional force by pushing an object on a surface. Moreover, the body experiences influence the recalling of concepts by influencing the mental imagery (Kosslyn, 1994; Moulton & Kosslyn, 2009).

The use of the body for learning may reduce the cognitive load during the process of learning (Paas & Sweller, 2014). Interactions with the environment activate the nervous system and create a communication between the body and the tangible objects (Barrett, 2011; Pfeifer & Bongard, 2007; M. Wilson, 2002), and provide to learners the possibility of offloading information to the environment (Kirsh & Maglio, 1994). Furthermore, sensorimotor actions for performing conscious and unconscious actions (e.g., learn how to kick a ball and to kick a ball in a game) do not always require the mind to work (Abrahamson & Lindgren, 2014; Barsalou, 1999; Gallagher, 2005; M. Wilson, 2002).

The use of the learning tools (i.e., the visuohaptic simulation and the physical manipulative tool) require learners to synchronize the visual and the touch modalities in a controlled and conscious manner that promoted the reduction of the cognitive load and the intentional interactions for enhancing knowledge of CQ1 and CQ2. Later, learners may be able to explain the friction concepts and apply the knowledge in another context.

For achieving the learning tool's goal, we followed the guidelines for designing embodied learning experiences by Abrahamson and Lindgren (2014). The guidelines are divided into three main elements, activities, materials, and facilitation. For the **activity** design, the embodied learning experiences may focus on promoting the recall of prior knowledge and increasing the learning concepts' complexity.

For the **materials** design, the embodied considerations are the orchestration of the modalities, the interaction with the tools, the feedback provided to learners, and manipulating the virtual environment. The learning materials may facilitate the interaction and the acquisition of conceptual knowledge through different modalities (e.g., visual and tactile). For the **facilitation** of the embodied experience, the learning tools considered the way learners experienced the friction forces in natural environments and the affordances of the virtual environments of unfolding the phenomena (e.g., showing microscopic information).

4.3.1 The learning tools

Students interacted with the physical manipulative tool (PMT) and the visuohaptic simulation (VHS) for learning about friction. The learning tools contained two elements, cubes, and board. The cubes and the board were physical objects in the PMT and virtual objects in the VHS.

The board used for sliding the cubes had three surfaces, with different friction coefficients, cardboard paper as the smooth surface, fabric as the medium smooth surface, and sandpaper as the rough surface. The material selection was based on the findings of Walsh et al. (2017), that reported that learners related smooth materials with no texture (e.g., cardboard, ice) and rough surfaces with textured materials (e.g., wood, sandpaper).

The objects used for grabbing and sliding were three cubes. Cubes shared similarities and differences among them. Cube 1 and Cube 2 have the same size (7.5cm of edge) but different weights (Cube 1 = 210g, and Cube 2 = 291g). Cube 2 and Cube 3 have the same weight but different sizes (Cube 3 edge = 5cm). By comparing Cube 2 and Cube 3, students learned about the role of the objects' size in friction. Figure 4.1 shows the PMT and its main characteristics.

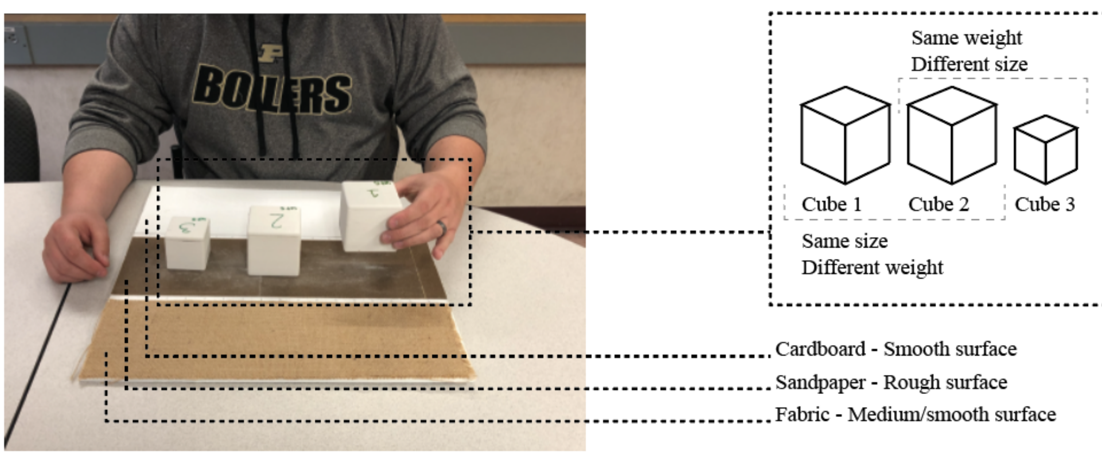


Figure 4.1. Physical Manipulative Tool (PMT).

The VHS was implemented in C++ using the Chai3D, OpenGL, and GLSL. The learners interacted with the Falcon Novint® to manipulate the virtual environment and receive haptic feedback. Figure 4.2 shows a learner interacting with the VHS. The location of the haptic device depended on the dominant hand of the learner. For instance, left-handed students located the haptic device on the left side of the laptop.

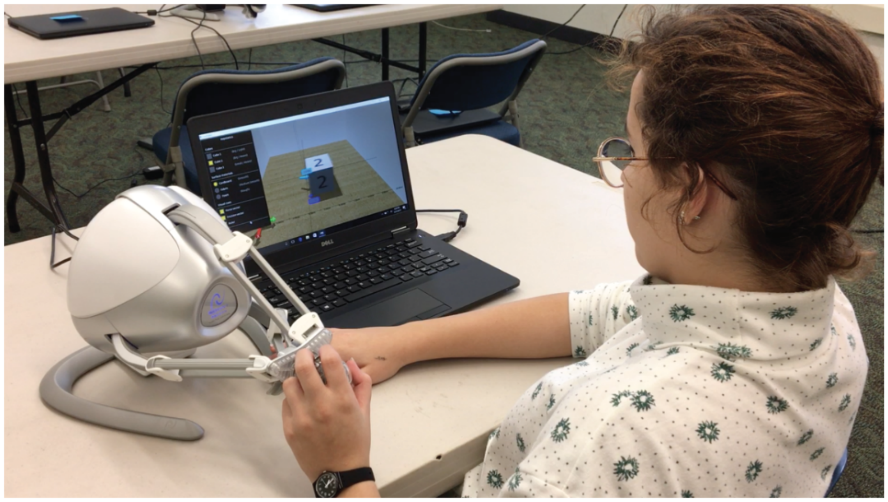


Figure 4.2. Visuohaptic simulation (VHS).

Walsh et al. (2017), found that learners interacting with the PMT recognized differences in size between the cubes (e.g., Cube 3 was the smaller), variations in weight on objects of the same size (Cube 1 vs. Cube 2), and the rough from the smooth materials. However, learners had problems identifying the similarities in weight when they had different sizes (Cube 2 vs. Cube 3). Identifying that two objects have the same weight when their densities are different is called the size-weight illusion. Researchers explain the size-weight illusion from two perspectives. The first perspective is that humans expect larger objects to be heavier than smaller objects, mostly when both are made with the same material. The second perspective is that humans' perception of weight depends on the pressure and muscles involved in lifting the object (Wolf, Bergmann Tiest, & Drewing, 2018). When the densities' difference decreased, humans perceive the objects as similar in weight, suggesting that weight was judged by density and not size. Furthermore, the way humans interact with the objects influences the perception of weight. For instance, there is finer discrimination of weight when objects are picked with the fingers than from the hand's palm. Muscular sensations, in addition to pressure sensations, facilitates the recognition of the weight (Murray, Ellis, Bandomir, & Ross, 1999).

Another problem found in Walsh et al. (2017) was that cubes rotated when learners applied a force to push them. When the cubes rotated, learners had problems determining if the force applied to two different cubes were the same (e.g., learners reported not knowing if they applied the same force for pushing Cube 2 and then Cube 3).

The VHS took advantage of the virtual environment to maintain the affordances and overcome the PMT's hindrances. For instance, the VHS constrained the cubes' rotation and provided enhanced visual feedback for showing information not available in the natural environment (e.g., force magnitude). Also, the virtual environment exaggerated the maximum force feedback to make the haptic experience easier to be perceived and distinguished.

The laptop screen displayed the virtual environment's 3D visual information in two different ways, minimal and enhanced. Minimal visual information showed learners the same information as the natural environment of the PMT. For instance, learners saw the displacement distance of the objects pushed on the surfaces. The minimal visual feedback did not show numerical values or force direction.

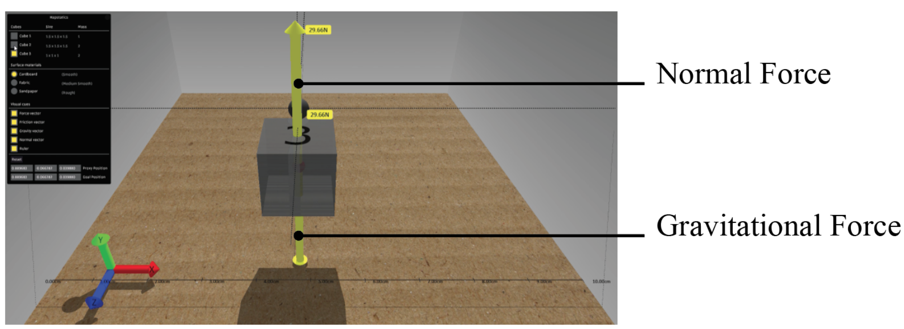


Figure 4.3. Enhanced visual feedback when lifting Cube 3.

The enhanced visual feedback took advantage of the virtual environment and showed the learners non-visible information on the friction phenomenon. The non-visible information showed the forces acting on the cube pushed (i.e., normal force, gravitational force, frictional force, and applied force), or lifted (i.e., normal force, gravitational force). The arrow's color code and size in the enhanced visual feedback showed differences in the forces' magnitude. Warm colors arrows displayed accompanied by large forces, and cold colors arrows displayed accompanied by small forces. Enhanced visual feedback always showed the numerical value of the forces. Figure 4.3 shows the enhanced visual feedback when learners lifted Cube 3.

As shown in Figure 4.3 the forces acting on Cube 3 are the Normal force (Ff) and Gravitational force (Fg). The magnitude of the forces were 29.66 Newtons each ($Fn = Fg$). The arrowhead showed that the Normal force direction was in the y-positive direction. The direction of the Gravitational force was in the y-negative direction. Figure 4.4 shows the enhanced visual feedback when learners pushed Cube 3.

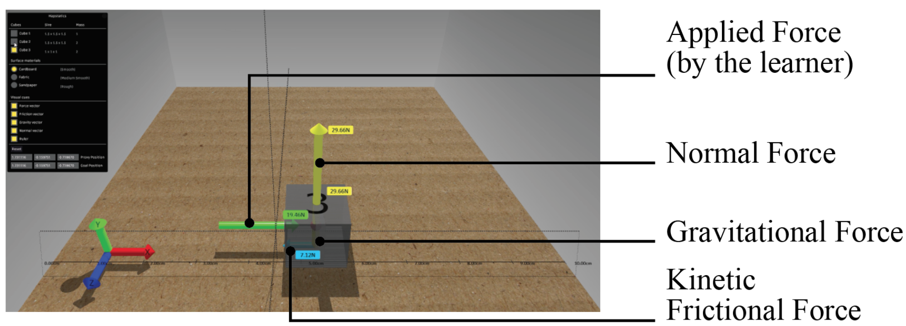


Figure 4.4. Kinetic frictional force of Cube 3.

As shown in Figure 4.4, the forces acting on Cube 3 while being pushed are the Normal force (F_n) and Gravitational force (F_g), the Applied force (F_a), and the kinetic Frictional force (F_f). The Gravitational force and Normal force's magnitude were 29.66 Newtons each ($F_n = F_g$). The value of the Applied force was 19.46 Newtons, and the kinetic Frictional force was 7.2 Newtons ($F_f < F_a$). The arrowhead showed that the Applied force direction was in the x-positive direction. The direction of the Frictional force was in the x-negative direction. Figure 4.5 shows the static Frictional force acting on Cube 3.

As shown in Figure 4.5. the value of the kinetic Frictional force ($F_f = 7.2$ N) was lower than the static Frictional force ($F_f = 11.84$ N). Cube 3 in Figure 4.4 was moving and static in Figure 4.5.

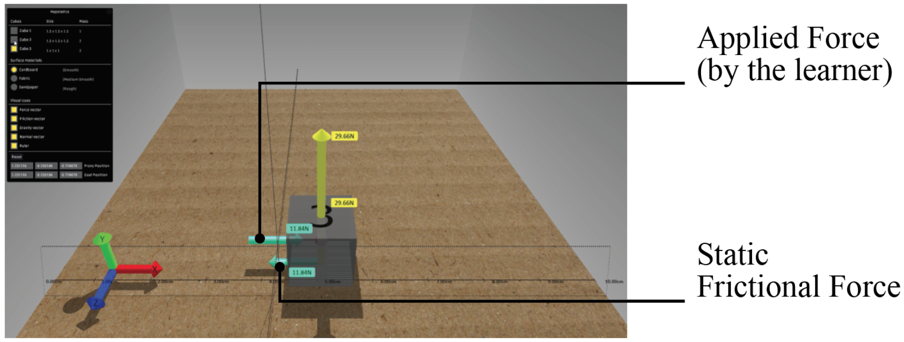


Figure 4.5. Static frictional force of Cube 3.

When the enhanced visual feedback was active, the control panel showed information about the cubes, surfaces, and forces acting on the cubes. Figure 4.6 shows the control panel. The left side image shows the control panel when the VHS showed minimal visual cues, and on the right with enhanced visual cues.

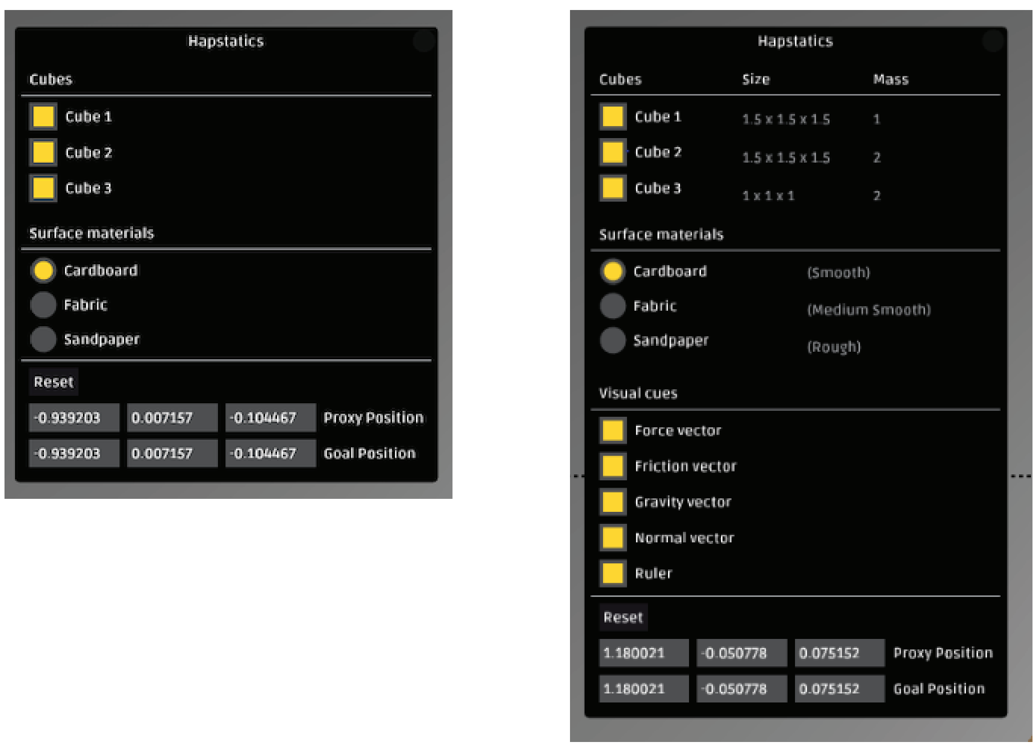


Figure 4.6. Control panel of the VHS.

Learners used the mouse of the computer for activating the elements of the VHS. For putting the cubes in the scene, learners selected the cubes from the control panel. At least one cube is in the scene, and up to three cubes. For changing the surface, learners selected the surface from the control panel. Only one surface was active on the scene. The enhanced visual cues showed the forces acting on the cubes. Learners had the possibility of turning on/off the forces. The enhanced visual cues also showed the cube's dimensions, mass, and surface characteristics (e.g., smooth, rough, or medium smooth). In the control panel, learners enable/disable the ruler. The ruler is on the bottom side of the screen. Learners were able to measure the traveled distance by the cubes when sliding on the surface. Figure 4.7 shows Cube 1, Cube 2, and Cube 3 on the sandpaper (rough surface).

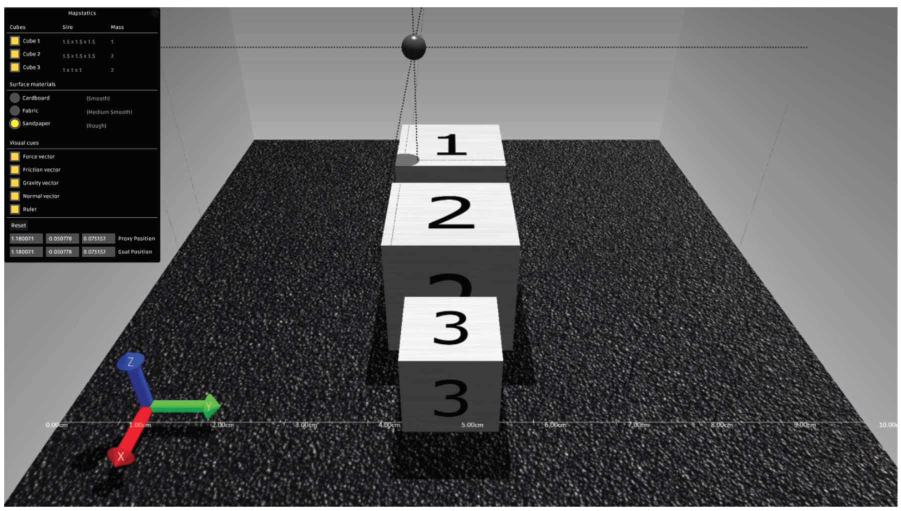


Figure 4.7. Cubes of the VHS on sandpaper.

The Falcon Novint® provided the kinesthetic feedback and force feedback (see the device in Figure 4.2). The arm movement for interacting with the virtual environment using the Falcon device provided the kinesthetic feedback. The magnitude of the force required to move the cubes in the virtual environment was proportional to the arm movement (e.g., the larger the arm movement, the higher the force). Force feedback was the sensation of force required by the learner to push or lift the cubes in the virtual environment. Students applied a higher force to push a cube on a rough surface than on a smooth surface. Learners experienced haptic feedback when they received force and kinesthetic feedback at the same time.

The VHS allows the activation of the force feedback and the enhanced visual cues. The affordance of the VHS allows the investigation of the value of the haptic and the visual feedback for learning friction concepts. Chapter 5 evaluated different visual and haptic feedback configurations for learning friction (e.g., simultaneous H+V, sequenced $H \rightarrow H+V$.

4.3.2 Affordances of the learning tools

Zacharia and Michael (2016) and Fritz and Barner (1999) summarized the affordances of the physical manipulatives and the virtual manipulatives for learning sciences and its relationship with the PMT and VHS.

- Affordance 1. Exposed students to experimentation skills (e.g., testing hypothesis: Learners used the PMT and the VHS for testing the predictions of the role of the objects' weight in friction (CQ1) and the role of the objects' weight in friction (CQ2). There was no limitation imposed by the learning tools for the number of trials for testing a hypothesis. PMT and VHS provided feedback after every trial.
- Affordance 2. Allowed learners the manipulation of the learning materials:In the PMT, there was no limitation for manipulating the learning materials (e.g., learners grab and move the cubes freely). In the VHS, movements were limited to grab and push. For grabbing, learners moved the cube up and down. For pushing, learners moved the cubes from side to side (e.g., left to right).
- Affordance 3. Allowed learners the direct observation of the phenomena: Learners inferred about the friction phenomenon using the PMT and the VHS with minimal visual feedback. The enhanced visual feedback showed the forces acting on the cubes while learners pushed or lifted the cubes.

- Affordance 4. Promoted the participation in science instruction: PMT and VHS are considered active learning tools.
- Affordance 5. Allowed learners to have multiple sensory feedback: Learners had multiple sensory feedback. The learning tools provided mainly visual and tactile information. In the VHS, the computer screen provided the visual feedback and the tactile feedback by the haptic device. The feedback provided by the PMT resulted from the real-life interaction with objects.
- Affordance 6. Promoted the development of psychomotor skills: not applicable.
- Affordance 7. Allowed learners to use the body for learning: The PMT promoted the upper body's use for the interaction with the learning material, but there was no limitation of movements. The VHS restricted the interaction to the upper-body.
- Affordance 8. Allowed the modification of variables that are hard to modify in real life: Variables in the PMT and VHS were fixed. No manipulation of the variables occurred.
- Affordance 9. Allowed the use of multiple linked representations: Learners had multiple sensory feedback. The learning tools provided mainly visual and tactile information. In the VHS, the computer screen provided the visual feedback and the tactile feedback by the haptic device. The feedback provided by the PMT resulted from the real-life interaction with objects.
- Affordance 10. Errors were minimized in the environment to improve the comprehension of the concept: In the PMT, the scientific phenomenon was presented as it is (e.g., the PMT did not limit the presence of error). The VHS constrained the rotation of the cubes and did not provide information about the cubes' material.
- Affordance 11. Provided real-time feedback: All feedback provided by the PMT and VHS was in real-time.

- Affordance 12. Provided observable outcomes, no matter the complexity of the concepts: Learners observed the cubes' motion based on a force applied to lift or push the objects. The enhanced visual cues provided non-visible information of the forces (e.g., the forces' direction and magnitude).
- Affordance 13. Experiments were performed in a safe environment for the students: The PMT and the VHS did not represent a risk for the learners.

4.3.3 The worksheets

The pedagogical approach of prediction-observation-explanation phases to probing understanding by White and Gunstone (1992) guided the learning experience.

According to White and Gunstone (1992), learners must engage with the activity by thinking critically, analyzing the friction variables, experiencing the forces, and revising their prior knowledge. White and Gunstone considered that a single instrument is not enough for evaluating the understanding of science concepts; hence, the authors suggested a technique composed of three-phases, prediction, observation, and explanation.

Learners provided answers based on their prior knowledge and their prior experiences for answering the prediction phase. Once completed the prediction phase, learners interacted with the learning tools for observing the friction phenomenon. Learners answered the friction conceptual questions based on the experience with the learning tool. The final stage required learners to contrast their predictions and observations to elaborate on the friction phenomenon's final explanation. Answers on the confirmation stage are influenced by the prior knowledge and the experience with the learning tool. Figure 4.8 shows a general pipeline of the learning activity and its relationship with the learning tools.

The questions asked in the worksheet of prediction and confirmation are the same. The difference between worksheets is only the moment that learners answer the questions. Before using the learning tool, learners answer the prediction. After using the learning tool, learners answer the confirmation worksheet. For the experiments presented in Chapter 4 and Chapter 5 we used the prediction worksheet as a pretest and posttest.

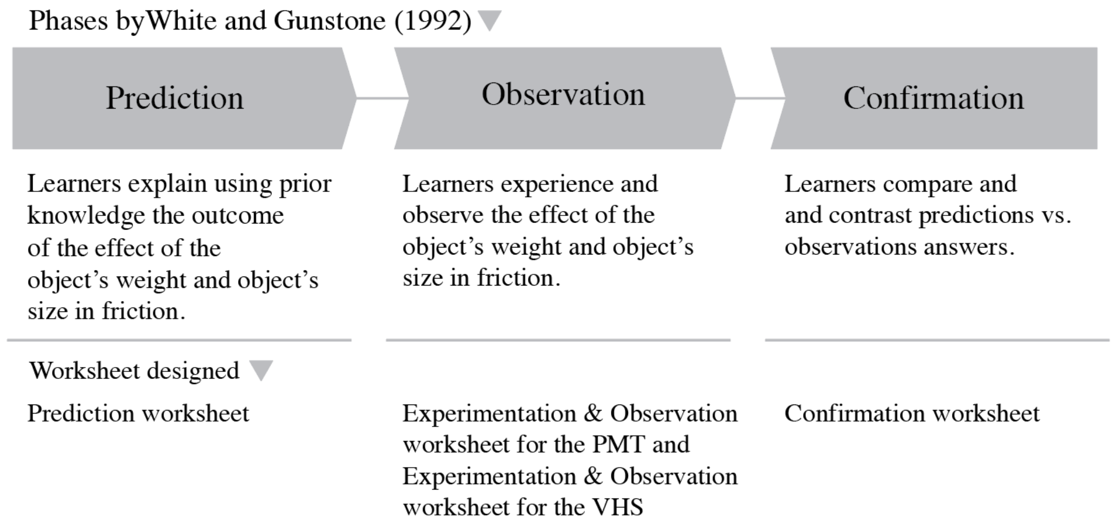


Figure 4.8. Scaffolding.

The prediction worksheet guides learners from focusing on the forces acting on a single cube to compare the forces acting on two cubes. Figure 4.9 shows the question's scaffolding.

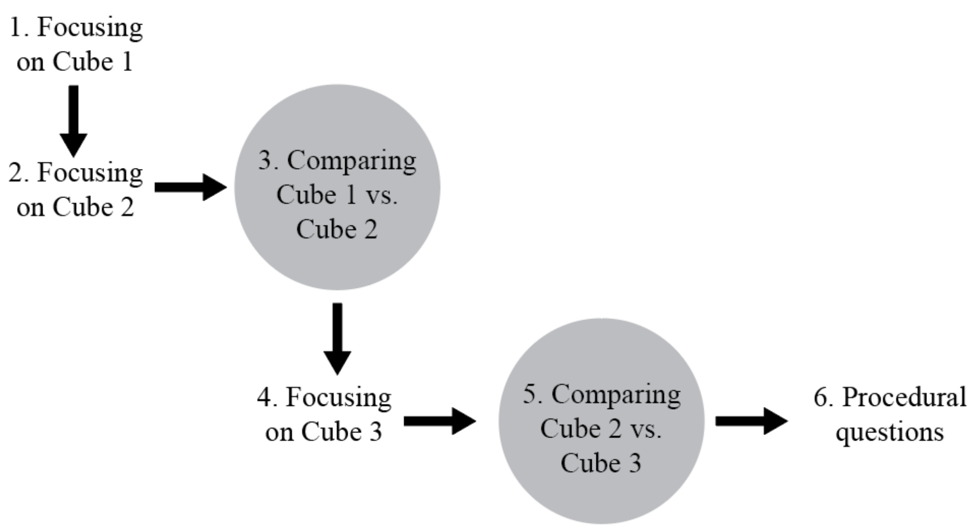


Figure 4.9. Scaffolding of the Prediction and Confirmation worksheets.

Each worksheet consisted of five steps. For the steps focusing on a specific cube, learners indicate the forces acting on a cube in different scenarios. For instance, in the first step, learners focuses on Cube 1 when (a) Cube 1 is stationary , (b) Cube 1 is stationary and a force is being applied in the x-positive direction and Cube 1 does not move, and (c) Cube is stationary and a force is being applied in the x-positive direction and the cube moves. The surface where Cube 1 is sliding has a low coefficient of friction (e.g., smooth surface). Once completed the questions, learners answer question *a* to *c* but with Cube 1 sliding on a surface with a high coefficient of friction (e.g., rough surface). For the second step, learners answer the same questions on Step 1 but using Cube 2. The third step consists of comparing the differences between pushing Cube 1 and Cube 2 on a smooth surface, and then on a rough surface. The fourth step focused on Cube 3, and the fifth step compares the differences between pushing Cube 2 and Cube 3 on a smooth and then on a rough surface. The sixth step consists of procedural questions.

The observation worksheet followed a similar process as the Prediction worksheet. The difference is that the Observation worksheet adds a step of recognition of the cube's characteristics before focusing on Cube 1 and that the Observation worksheet does not include procedural questions.

The step of recognition requires that learners identify the characteristics of Cube 1, cube 2, and Cube 3, and the sliding surfaces. The questions are

1. Which cube is the smallest? (correct answer: Cube 3).
2. Which cube is the densest? (correct answer: Cube 3).
3. What is the difference between Cube 1 and Cube 2? (correct answer: Cube 2 is heavier than Cube 1).
4. What is the difference between Cube 2 and Cube 3? (correct answer: Cube 2 is bigger than Cube 3).
5. In which surface the cubes experienced the highest friction? (correct answer: sandpaper)
6. In which surface the cubes experienced the least friction? (correct answer: cardboard)

Participants in the VHS conditions lifted (for identifying the weight) and slid (for identifying the friction force) the cubes on the three different surfaces (cardboard, fabric, and sandpaper) for answering the Recognition question. Participants in the PMT condition answered the recognition questions twice, using the palm-method (see Figure 4.10 a) and secondly using the bag-method (see Figure 4.10 b). Figure 4.10 illustrates the PMT methods.

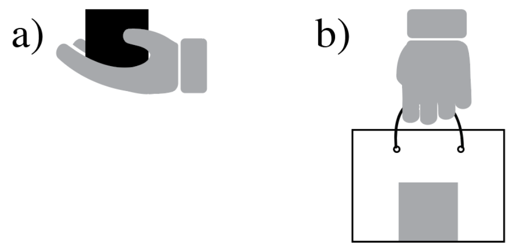


Figure 4.10. PMT methods to compare cubes: a) palm-method and b) bag-method.

The palm-method guided students to hold the cubes in the palm of their hands and answer the recognition questions. The bag-method guided students in putting the cubes on a bag and holding the bag to answer the recognition questions. As of the second stage of the worksheet, there were no differences between the VHS and PMT conditions. Once completed the recognition phase, participants continue with the step of Focusing on Cube 1 explained before.

4.4 Embodied characteristics of the learning tools

The design of the learning materials followed the embodied learning design guidelines provided by Abrahamson and Lindgren (2014). The implementation of the guidelines for the activity was:

- Promote recalling of prior knowledge: the design of the worksheet considered the recalling of prior knowledge and prior experiences before interacting with the PMT and VHS. Students predicted the outcome of pushing the cubes on a surface (e.g., CQ1 and CQ2) based on their prior knowledge and prior experiences.

- Incremental complexity: the worksheet guided the learners to focus on sliding a specific Cube (e.g., worksheet section of focusing on Cube 1) and then comparing the sliding properties of two cubes (e.g., worksheet section of comparing Cube 1 and Cube 2).

The implementation of the guidelines for the materials was:

- Orchestration of modalities: the PMT provides simultaneous haptic and visual feedback to learners. Feedback in the VHS is provided simultaneously (i.e., H+V) or sequenced (e.g., $H \rightarrow H+V$)). The studies investigated the best modality for interacting with the VHS.

- Intuitive interaction: learners interacted with the PMT in the same way they interacted with objects in real-life. The interaction with the VHS is based on the real-life interaction (e.g., up and down movement for lifting the cubes). Explanation about how to use of the haptic feedback was provided before answering the conceptual questions.

- Feedback: feedback in PMT and VHS was provided in real-time.

- Experience in the virtual world: the control of the virtual environment of the VHS was by manipulating the haptic device. Students felt the forces acting on the cubes when they pushed or lifted the objects in the virtual environment.

The implementation of the guidelines for the facilitation was:

- Enacting functional metaphors: the movements performed by the learners to move the cubes in the virtual environment are based on the movements of lifting and pushing objects in real-life. With the haptic feedback, learners felt the forces acting on the cubes. With the enhanced visual feedback, learners observe the forces acting on the cubes.

- Enhancing the environment to unfold information: enhanced visual feedback show the forces acting on the cubes. Color-code, the arrow's size, and the numerical value of the force provide information of the force magnitude.

- Describe the feedback: the experimentation and observation questions for CQ1 and CQ2 focused on asking learners about the feedback received (e.g., what do you feel?)

Figure 4.11 shows the PMT's level of the embodiment according to the taxonomy provided by Johnson-Glenberg (2018).

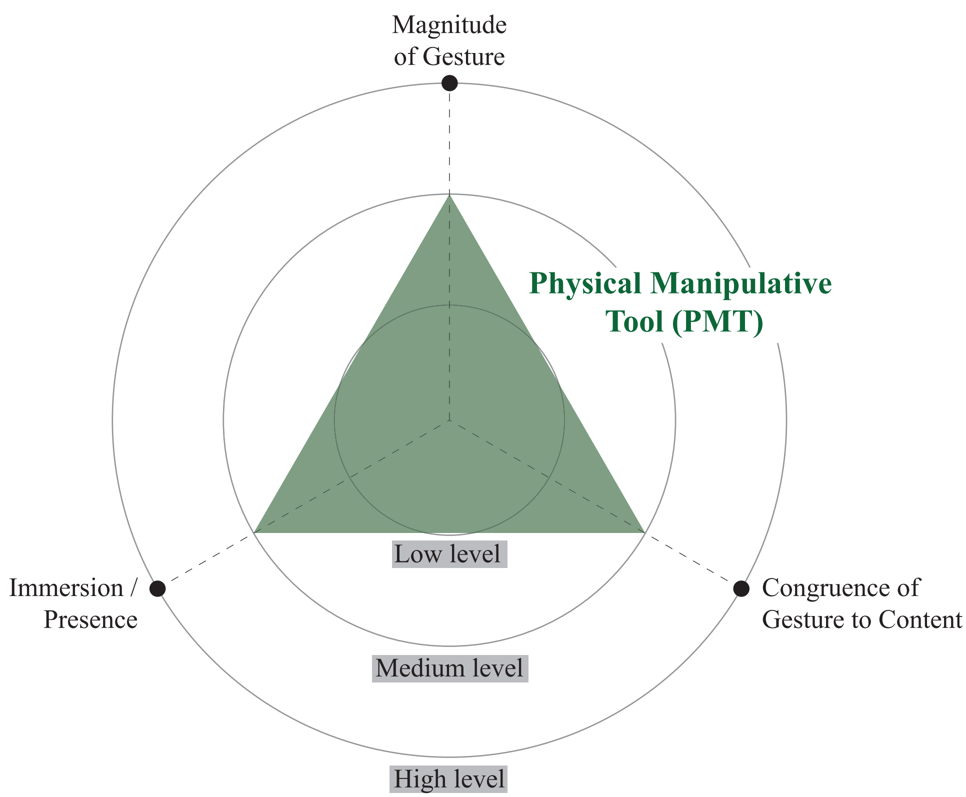


Figure 4.11. PMT according Johnson-Glenberg (2018)'s taxonomy.

The magnitude of the gestures, congruence of gesture to content, and immersion and presence are considered medium-level. The magnitude of the gesture is medium-level because the PMT limited the motion to the upper body. The congruence of gesture content is also considered medium-level because there is no restriction in the gestures perform. For instance, learners can focus on the cubes' density to describe the outcomes for CQ1 and

CQ2. The third component of the taxonomy, the immersion and presence, is considered medium-level because the tactile feedback worked in two ways, from the tool to the learner, and from the learner to the tool (e.g., manipulate the objects to feel its weight, and apply a force to move the objects). Figure 4.12 shows the VHS's level of the embodiment.

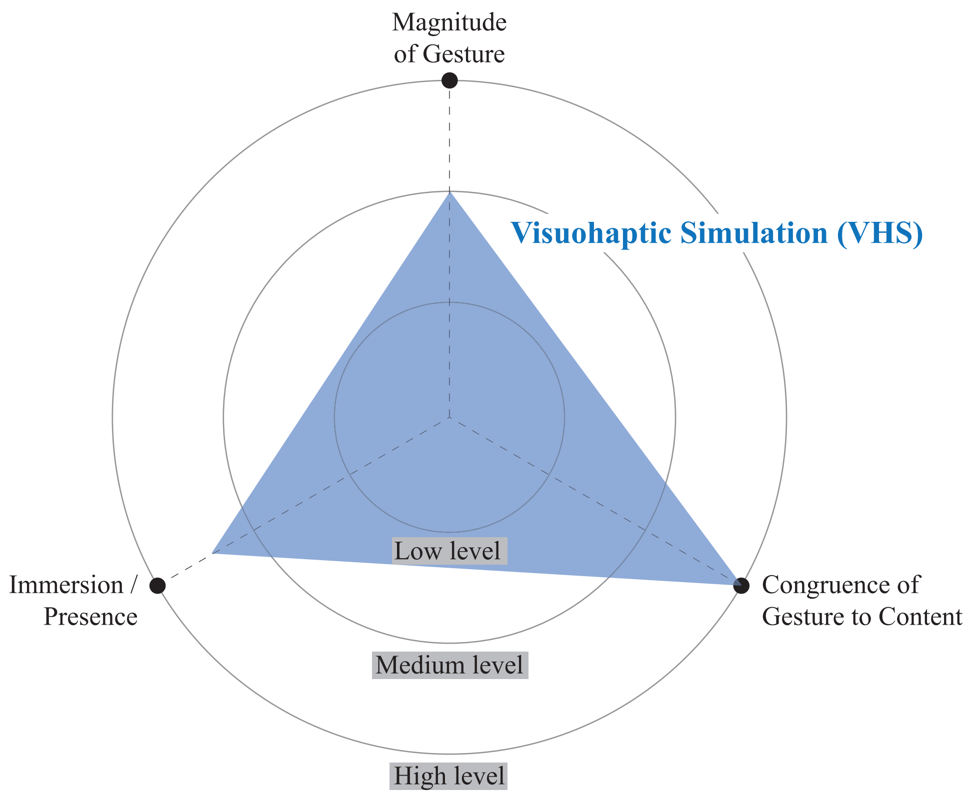


Figure 4.12. VHS according Johnson-Glenberg (2018)'s taxonomy.

The VHS's components of congruence of gesture to content are high-level. Actions allowed for the learner using the VHS promote the learning of friction concepts. The component of immersion and presence is considered somewhere in the middle between high-level and medium-level. The combination of enhanced visual cues and haptic feedback (H+V) provides learners a learning experience beyond real-life experience. The gestures in the VHS provide information about the forces acting on the cubes. The magnitude of the gesture is medium-level because the interaction is restricted to the upper body.

4.5 Chapter summary

Chapter 4 showed the learning design process for the friction embodied experience. The experience consisted of a guided activity using a physical manipulative tool (PMT) or a visuohaptic simulation (VHS) to learn friction concepts. The learning experience focused on teaching the concepts of the role of the object's weight in friction (CQ1) and the role of the object's size in friction (CQ2). For answering CQ1, learners compared the differences between pushing two cubes with the same size but the different weights on a surface (one cube had double the weight than the other). For CQ2, learners compared the differences between pushing two cubes with the same weight and the different sizes on a surface (one cube was double size than the other).

The guidance of the activity followed the three-phases approach by White and Gunstone (1992). For answering the conceptual questions in the prediction and confirmation phases, learners recalled prior learning and prior experiences. Learners used no learning tool during the prediction and confirmation phases. During the experimentation and observation phase, learners interacted with the PMT or the VHS for answering CQ1 and CQ2. The experimentation and observation worksheet guided the interaction with the PMT and VHS. During the interaction, learners received haptic and visual feedback when lifted the cubes and pushed the cubes across the surface.

The design of the learning tools considered the embodied guidelines provided by Abrahamson and Lindgren (2014), and the affordances of the physical and virtual manipulatives for learning listed by Zacharia and Michael (2016) and Fritz and Barner (1999). Table 4.3.2 and Section 4.4 showed considerations for the design of the learning experience. Figure 4.10 and Figure 4.11 classified the level of embodiment of the PMT and the VHS according to the embodied taxonomy proposed by Johnson-Glenberg et al. (2014).

Chapter 5 and chapter 6 provide the results of implementing the learning experience in a laboratory session of an introductory physics course at the undergraduate level.

CHAPTER 5. PHYSICAL MANIPULATIVES VS. VISUOHAPTIC SIMULATIONS

The first study investigated the effect of two hands-on tools, the Physical Manipulative Tool (PMT) and the Visuohaptic Simulation (VHS), in students' conceptual knowledge of friction concepts. Participants (n = 206) interacted with the PMT or the VHS in a laboratory session of an introductory statics course. Participants using the VHS followed one of four configurations: visual V, haptic H, visual and haptic simultaneously $H+V$, and sequenced with haptic first and then, haptic and visual combined ($HH+V$).

5.1 Research questions

The first study focused on comparing two tactile tools for learning Physical Manipulative Tool (PMT) vs. Visuohaptic simulation (VHS). The research questions are:

1. What are the differences in student's explanations of friction concepts (i.e., role of the object's weight in friction, and role of the object's size in friction) between interacting with a physical manipulative tool (PMT) and a visuohaptic simulation (VHS)?
   H_{o1}: PMT and the different VHS configurations provide the same learning advantages to students (PMT = VHS).
   H_{a1}: PMT and the different VHS configurations provide different learning advantages to students (PMT $\neq$ VHS).

2. What is the influence of VHS's visual and haptic feedback on students' conceptual knowledge of the role of the objects' size in friction?
   H_{o2}: haptic and visual feedback influence the conceptual learning of friction similarly (H = V).
   H_{a2}: haptic and visual feedback influence the conceptual learning friction differently (H $\neq$ V).

The first research question focused on two friction concepts, the role of the object's weight in friction (CQ1) and the role of the object's size in friction (CQ2). To answer the research question, we performed three types of analysis per conceptual question. First, we used inferential analysis for comparing pretest scores and posttest scores. We used Tukey HSD post-hoc for the analysis of posttest scores. The second analysis focused on the descriptive statistics of the answers per physic variable (i.e., friction force, speed, acceleration, and traveled distance). The alternative hypothesis of the first research question (PMT $\neq$ VHS) is supported by the claim that visuohaptic simulations combine physical and virtual manipulatives' affordances into a single learning experience (Höst et al., 2013).

For the second research question, we focused on the conceptual question of the role of the object's size in friction (CQ2). The selection of CQ2 was made based on the results suggesting that students had problems answering CQ2 in the pretest and posttest. CQ1 (compared to push two cubes of the same size but the different weight) is an intuitive concept for students (Walsh et al., 2020). The alternative hypothesis of the second research question ($H \neq V$) is supported by the claims that haptic and visual feedback are different learning modalities and that visual and haptic feedback have different affordances for the interaction with the learning tools (Fritz & Barner, 1999; Gopnik, 2010).

5.2 Participants

Participants (n = 206) were students enrolled in an applied statics course taught during the semester of Fall 2018 and Spring 2019. Table 5.1 shows the participant's characteristics per condition.

Table 5.1 shows that 87.38% of the participants were male, 81.55% had experience in physics courses at a high school or college level, and most students were freshmen (42.33%) or sophomore (36.41%). Additionally, more than 94% of the participants reported being enrolled in a program related to engineering (e.g., mechanical engineering technology, robotics, mechatronics).

Table 5.1. Participant's characteristics

Conditions	N	Participant's characteristics						
		Gender*		Prior experience		Level		
		M	F	HS or college	No courses	Freshmen	Sopho more	Other
PMT	35	91.43	5.71	80.00	20.00	25.71	54.29	20.00
Haptic *H*	48	91.67	8.33	83.33	16.67	33.33	43.75	22.92
Visual *V*	47	85.11	12.77	82.98	17.02	44.68	29.79	25.53
Simultaneous: $H + V$	22	86.36	13.64	86.36	13.64	68.18	18.18	13.64
Sequenced: $H \rightarrow H + V$	54	83.33	16.67	77.78	24.07	48.15	31.48	20.37

*remaining percentage to complete the 100% correspond to participants not answering the question.

The applied statics course had a structure of two lectures of one hour each and a laboratory section of two hours per week. Students completed the study during the 13th week of the semester during the laboratory section. The course did not change from one semester to another; the same instructor taught the course, and the instructor used the same syllabus and the same learning materials. We only considered data collected during the fall semester for the nine participants who retook the spring semester course. The researchers did not have control over the course registration process.

5.3 Context

The study took place in the laboratory session of an introductory statics course. For this study, we had two settings: one for interacting with the VHS and the other for interacting with the PMT. The VHS setting had twenty-eight stations, and the PMT setting had eleven stations. For the settings, we only considered the number of haptic devices and laptop computers available and space (e.g., door, power outlets, number of tables). No other variable was considered for the classroom configuration (e.g., number of participants per group). The author of this dissertation was presented in all the laboratory sections, collected and organized the documents and provided verbal explanations to learners when needed. The teacher assistant of the course and other researchers were trained to assisted the author of this dissertation in the laboratory sections.

Upon arrival at the laboratory session, participants sat in one of the available VHS stations. If the number of students enrolled in the laboratory session was higher than twenty-eight, the remaining participants sat in the PMT classroom. Figure 5.1 shows the laboratory setting of the VHS stations.

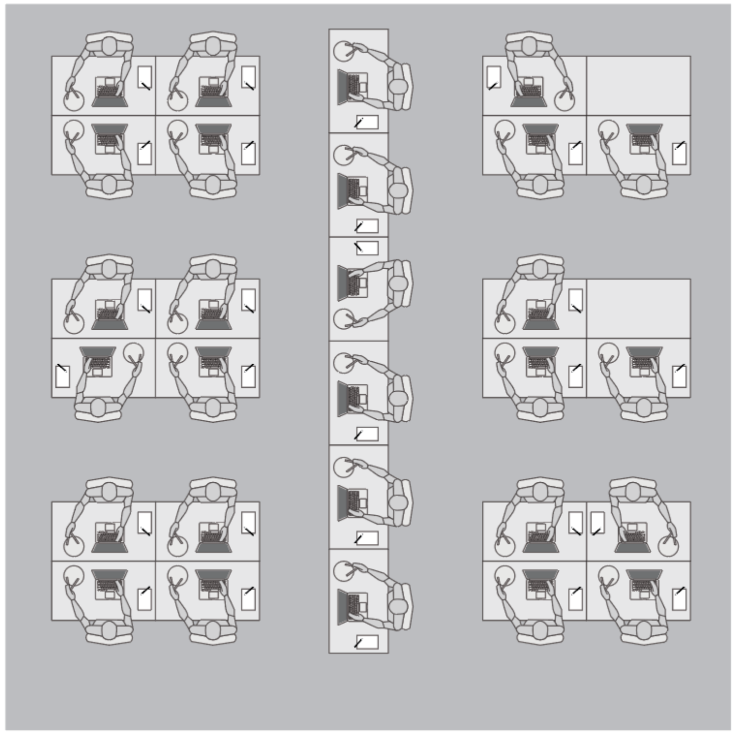


Figure 5.1. Laboratory setting of the VHS stations.

As shown in Figure 5.1, students worked individually in the learning activity. At the beginning of the activity, researchers told students to place the haptic devices to their right or left, depending on which hand they considered their dominant hand (e.g., left-handed or right-handed). Figure 5.2 shows the laboratory setting of the PMT stations.

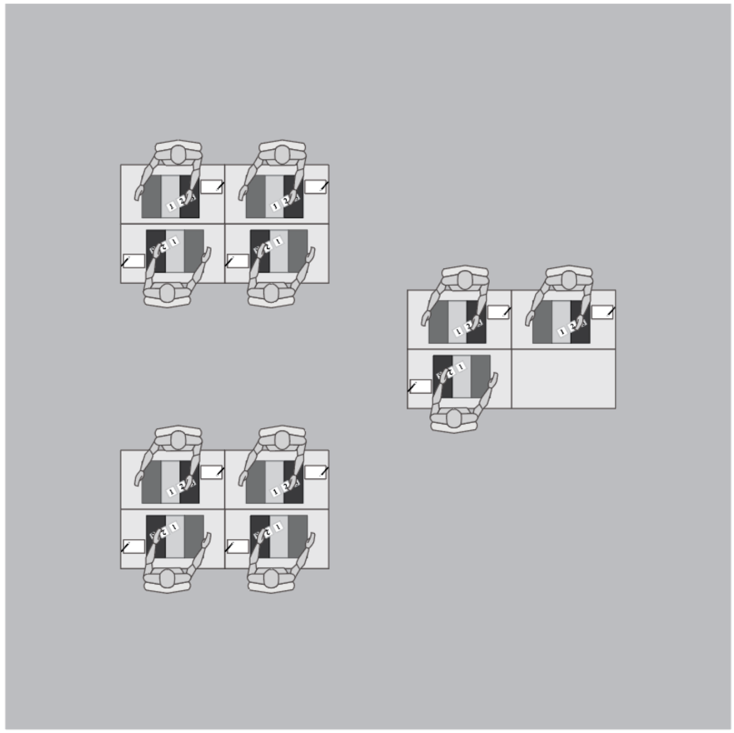


Figure 5.2. Laboratory setting of the PMT stations.

As shown in Figure 5.2, students worked individually in the learning activity using the PMT. On occasions, two participants shared the same PMT during the learning activity, but each student answered the questions individually. In both classrooms, VHS and PMT, the discussion between the students was not encouraged nor prohibited. Students decided where to sit in the classroom upon arrival (e.g., researchers did not arrange spaces for the students), and one or two researchers or the teacher assistant were available for clarifying instructions.

5.4 Procedures

Participants completed the study in two days. During the first day, participants attended the friction lecture and completed the pretest. During the second day, participants interacted with the corresponding hands-on tool (e.g., VHS or PMT) to learn friction concepts and complete the posttest. Figure 5.3 shows the procedures pipeline.

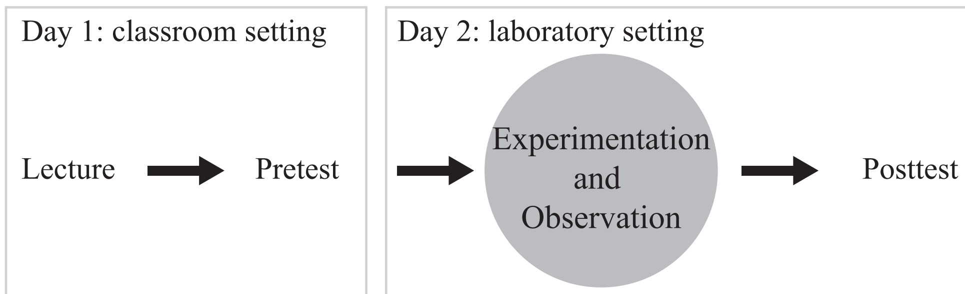


Figure 5.3. Procedures pipeline.

Students individually interacted with a visuohaptic simulation (VHS) or a physical manipulative tool (PMT) during the course's laboratory section. For students in the VHS condition, we randomly assigned each laboratory section to a different configuration of the VHS condition. The different configurations of the VHS condition were: Visual (V), Haptic (H), Simultaneous H+V, and Sequenced HH+V. The difference between the conditions was the type of feedback received. Table 5.2 shows the types of feedback provided for each of the conditions.

Learners received at least one type of haptic information and one type of visual information. Participants in the PMT condition received kinesthetic feedback, force feedback, and the physical environment's visual cues. Participants in the VHS conditions received the force feedback through the haptic device (e.g., Falcon Novint) and the visual feedback through the computer laptop screen. Participants in the *PMT, V, H*, and simultaneous *H+V* conditions, received the haptic information and the visual information during the same interaction with the visuohaptic simulation. The sequenced $H \rightarrow H+V$

Table 5.2. Condition's feedback characteristics.

<table>
<tr><th rowspan="2">Condition</th><th rowspan="2">N</th><th colspan="2">Haptic feedback</th><th colspan="2">Visual feedback</th></tr>
<tr><th>Kinesthetic feedback</th><th>Force Feedback</th><th>Minimal visual feedback</th><th>Enhanced visual feedback</th></tr>
<tr><td>PMT</td><td>35</td><td>Yes</td><td>Yes</td><td>Yes</td><td>No</td></tr>
<tr><td>Haptic, H</td><td>48</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td>Visual, V</td><td>48</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Simultaneous: $H + V$</td><td>22</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>First interaction Sequenced: $H \rightarrow H + V$</td><td rowspan="2">54</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td>No</td></tr>
<tr><td>Second interaction Sequenced: $H \rightarrow H + V$</td><td>Yes</td></tr>
</table>

approach required two interactions with the visuohaptic simulation. During the first interaction, participants in the sequenced approach were treated as the haptic condition. During the second interaction, participants were treated as the simultaneous haptic + visual condition $H+V$. Figure 5.4 shows the relationship between the learning tools and conditions.

5.5 Assessment questions

The study used three instruments, one for the pretest and posttest, two for the experimentation and observation phase (one for guiding the interaction with the VHS, and the other for guiding the interaction with the PMT). The three instruments focused on two main friction concepts: the object's weight in friction (CQ1) and the role of the object's size in friction (CQ2). Pretest and posttest instrument followed the prediction. For ensuring that all participants received the same instructions and materials, the author of this document designed and printed the documents distributed to the participants. Also the author provided before the pretest and at the beginning of the laboratory section verbal instructions that clarifies the expected role of the participants (e.g., provide the answers to the questions in the most clear way).

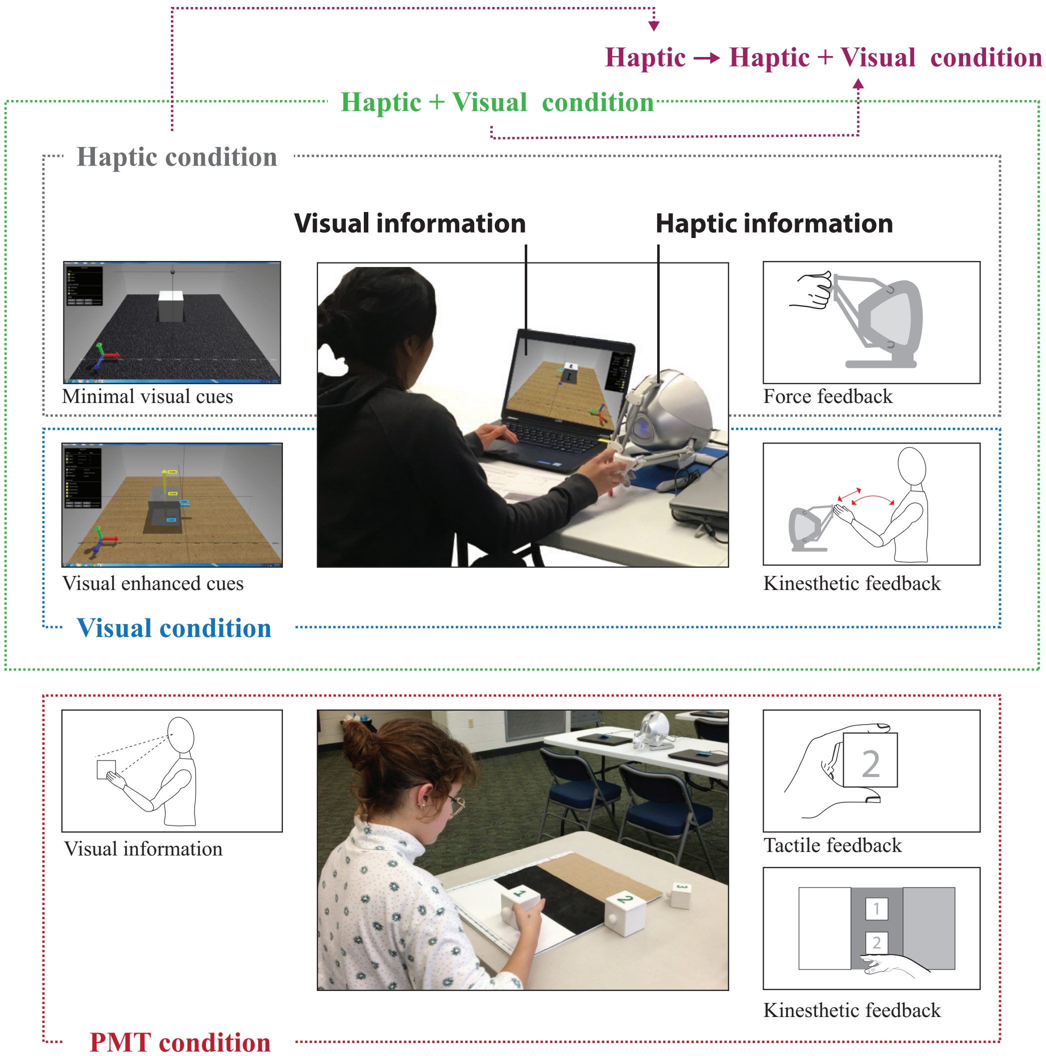


Figure 5.4. Relationship between the conditions and the learning tools.

5.5.1 Pretest and posttest questions

The instrument used in the pretest and posttest had four multiple-choice questions per conceptual question. In CQ1, students compared the differences between pushing two cubes of the same size but the different weight (Cube 1 lighter than Cube 2) on a smooth surface. The questions of CQ1 were:

1. The frictional force of Cube 1 is higher, lower, or equal (<, >,=) to the frictional force of Cube 2.

2. The speed of Cube 1 is higher, lower, or equal ($<$, $>$,=) to the speed of Cube 2.

3. The acceleration of Cube 1 is higher, lower, or equal ($<$, $>$,=) to the acceleration of Cube 2.

4. Assuming that you applied the same force to Cube 1 and Cube 2: the traveled distance of Cube 1 is higher, lower, or equal ($<$, $>$,=) to the traveled distance of Cube 2.

In CQ2, students compared the differences between pushing two cubes with the same weight but different size (Cube 3 smaller than Cube 2) on a smooth surface. The questions of CQ2 addressed the same issues of CQ1 but comparing Cube 2 with Cube 3, which had the same weight, but different size. For instance, we asked if the frictional force of Cube 2 is higher, lower, or equal ($<$, $>$,=) to the frictional force of Cube 3.

5.5.2 Experimentation and observation questions

The experimentation and observation worksheet guided the interaction with the PMT and the VHS. The experimentation and observation phase followed the steps described in Section 4.3.3. Participants started by identifying the cube's characteristics (Recognition Step), followed by the sliding Cube 1 on three different surfaces (cardboard, fabric, and sandpaper). For the first three questions, the learners compared the differences in certain applied force, speed, and traveled distance of Cube 1 sliding on cardboard vs. Cube 1 sliding on fabric. The questions asked were:

1. On fabric, the applied force required to move Cube 1 is ($<$, $>$,=) than the force required to move Cube 1 on cardboard because
   (a) The fabric surface has a greater coefficient of friction.
   (b) The cardboard surface has a greater coefficient of friction.
   (c) Because cardboard and fabric have the same sliding properties.
   (d) I do not know.
   (e) Other (please write it down).

2. On fabric, the speed of Cube 1 is ($<$, $>$,=) than the speed of Cube 1 on cardboard.

3. If you applied the same force to move Cube 1 on cardboard than on fabric. The traveled distance of Cube 1 on fabric (<, >,=) than the traveled distance of Cube 1 on cardboard.

For the fourth, fifth, and sixth questions of the first step of the Experimentation and Observation worksheet, participants compared the applied force, speed, and traveled distance of Cube 1 sliding on fabric vs. Cube 1 sliding on sandpaper. The second step of the experimentation worksheet followed the questions and comparison of the first step, but instead of using Cube 1, it focused on Cube 2 (e.g., comparing the differences in applied force between sliding Cube 2 on cardboard vs. Cube 2 on fabric). The third step of the Experimentation and Observation worksheet focused on the effect of the object's weight in friction (CQ1). Learners compared the differences of sliding Cube 1 and then Cube 2 on a smooth surface. The questions asked were:

1. The applied force required to move Cube 1 on a smooth surface is (<, >,=) than the force required to move Cube 2 because
   (*a*) Cube 1 is lighter than Cube 2.
   (*b*) Cube 1 is denser than Cube 2.
   (*c*) Cube 2 is denser than Cube 1.
   (*d*) Light objects slide easy on any surface.
   (*e*) Differences between cubes are not important because the surface is smooth.
   (*f*) There are no differences between Cube 1 and Cube 2.
   (*g*) I do not know.
   (*h*) Other (please write it down).

2. The frictional force required to move Cube 1 on a smooth surface is (<, >,=) than the frictional force of Cube 2 because
   (*a*) Cube 1 is lighter than Cube 2.
   (*b*) Cube 1 is denser than Cube 2.
   (*c*) Cube 2 is denser than Cube 1.
   (*d*) Light objects slide easy on any surface.
   (*e*) Differences between cubes are not important because the surface is smooth.

(f) There are no differences between Cube 1 and Cube 2.

(g) I do not know.

(h) Other (please write it down).

3. The speed of Cube 1 on a smooth surface is ($<$, $>$,=) than the speed of Cube 2 on smooth.

4. The acceleration of Cube 1 on a smooth surface is ($<$, $>$,=) than the acceleration of Cube 2 on smooth.

5. The traveled distance of Cube 1 on a smooth surface is ($<$, $>$,=) than the traveled distance of Cube 2 on smooth.

The fourth step of the Experimentation and Observation worksheet focused on sliding Cube 3 on the three different surfaces (i.e., cardboard, fabric, and sandpaper). Learners answered the same questions as the first step and the second step of the worksheet (e.g., comparing the speed of Cube 3 sliding on cardboard vs. sliding on fabric). The fifth step of the experimentation worksheet focused on the effect of the object's size in friction (CQ2). Learners compared the differences of sliding Cube 2 and then Cube 3 on a smooth surface. The fifth step followed the same questions as the fourth part, but instead of compared Cube 1 vs. Cube 2, participants compared Cube 2 vs. Cube 3.

5.5.3 Relationship between questions and learning tools.

During the interaction with the PMT and the VHS, students experienced the concepts of friction force, speed, acceleration, and traveled distance through the visual and haptic feedback. The haptic feedback allowed learners to feel the friction when sliding the cubes. Students in the Simultaneous H+V condition felt and saw the friction force. Similarly, in the second interaction with the VHS, students in the Sequenced $H \rightarrow H+V$ Condition felt and saw the friction force. Students in the Visual V condition saw the magnitude of the friction force. Students in the Haptic H and PMT conditions felt the friction force.

Regardless of the condition, participants determined the difference in speed, acceleration, and traveled distance between cubes only by visual information. The enhanced visual cues did not provide information on the values of the magnitudes of speed, acceleration, and traveled distance. Students determined that Cube 1 was faster than Cube 2 by visualizing the cubes sliding across the surface. Acceleration and traveled distance were determined using the same procedure used for speed.

5.6 Data Analysis

For this study, we analyzed the answers regarding the frictional force, speed, acceleration, and traveled distance between pushing two objects of the same weight by different sizes in friction. All questions used a multiple-choice format, with one correct answer and two distractors. Correct answers received one point, and no answer or incorrect answers received zero points.

For answering the first research question, comparing the PMT vs. VHS, and investigating the visual and haptic feedback's influence, we used descriptive and inferential statistics. For comparing the pretest vs. posttest scores (e.g., learning gains per condition), we used a paired t-test. We also calculated Cohen's *d* effect size for each condition. According to Rubin (2012), a strong effect size is $|\ d\ | > 0.8$; moderate to strong effect size when $0.65 < |\ d\ | < 0.8$, moderate when $0.4 < |\ d\ | < 0.65$; weak to moderate $0.2 < |\ d\ | < 0.4$, and weak when $|\ d\ | < 0.2$. One-way ANOVA and Tukey HSD post-hoc analysis were used to compare the posttest scores and experimentation scores. Using descriptive methods, we compared the changes in the percentage of correct answers per condition and question. For all the inferential analyses performed, we used a confidence level of 0.05. Assumptions of all the inferential statistics methods used were tested and meet (e.g., normality, constant variance).

5.6.1 Validity and reliability of the data

The instrument's validity was addressed by face validity and content validity. A multidisciplinary team carried out the development of the materials for the study. Experts in physics, mechanical engineering, computer simulations, education, and design, ensuring that the content was aligned with the physics laws and the technology capabilities (e.g., the haptic device used had three degrees of freedom). The materials were revised on multiple occasions by the design team and external personnel with physics and mechanical engineering knowledge. Questions used in the study were based on the misconceptions reported by Steif and Dantzler (2005).

For assessing the internal consistency reliability, we used the Kuder-Richardson 20 test (KR-20).We used KR-20 because the data obtained is binary (e.g., correct or incorrect). For the calculation of the KR-20, blank answers were considered as incorrect. A value of 0.7 or higher is considered consistent. Lower than 0.6 is considered not consistent. The obtained value of internal consistency for the 16 items included in the pretest and posttest was α = 0.8. For the eight items pretest was α = 0.7, and for the eight items in the posttest was α = 0.8. Regarding CQ1 (role of the objects' weight in friction), the eight items included in the pretest and posttest obtained α = 0.6. For CQ2 (role of the objects' size in friction), the obtained value for the eight items included in the pretest and posttest was α = 0.9.

5.7 Results

The results are presented in two main sections. Section 5.7.1 focused on answer the first research questions regarding the differences in learning friction between interacting with a PMT and a VHS. Section 5.7.2 focused on answering the second research question about the influence of the VHS's visual and haptic feedback on students' conceptual knowledge of friction. Both sections are divided into two parts, corresponding to the conceptual questions (CQ1 and CQ2).

5.7.1 Comparing PMT and VHS for learning friction

This section answers the research question *What are the differences in student's explanations of friction concepts (i.e., role of the object's weight in friction, and role of the object's size in friction) between interacting with a physical manipulative tool (PMT) and a visuohaptic simulation (VHS)?*

5.7.1.1 Role of the object's weight in friction

Table 5.3 shows the descriptive statistics of the scores and the learning gains from pretest to posttest per condition to answer the question for CQ1 (role of the object's weight in friction). The four answers of CQ1 were considered in calculating the pretest and posttest scores (e.g., frictional force, speed, acceleration, and applied force). Pretest scores for CQ1 were found no significant differences in the five conditions at α= 0.95 confidence level $[F(4,201) = 1.031, p = 0.392]$. Thus, all initial conditions were comparable.

Table 5.3. Learning gains for CQ1. Role of the object's weight in friction

Condition	N	Pretest		Posttest		Δ	Paired *t*-test			Effect
		Mean	StDv	Mean	StDv		DF	*t*-value	*p*-value	size
PMT	35	85.00	19.36	82.86	25.56	-2.14	34	0.52	0.61	0.09
Haptic *H*	48	78.65	25.26	86.98	25.78	8.33	47	-1.94	0.06	0.28
Visual *V*	47	79.26	27.25	92.55	15.56	13.30	46	-3.66	<0.001***	0.53
Simultaneous *H*+*V*	22	79.55	22.67	88.64	25.27	9.09	21	-1.24	0.24	0.26
Sequenced: $H \rightarrow H+V$	54	86.11	20.41	92.13	15.22	6.02	53	-2.04	0.04	0.28

Table 5.3 suggested that students did not have problems answering the questions for CQ1 correctly in general. In the pretest, the Visual *V* condition obtained the lowest score (79.26%), while the sequenced condition $H \rightarrow H+V$obtained the highest score (86.11%). The scores of Scenario1 increased from pretest to posttest for all conditions except the PMT condition. Learners from PMT condition decreased their overall score from pretest to posttest by 2.14%. Visual *V* condition had the highest increment in the overall score from pretest to posttest by 13.3%, followed by the simultaneous H+V condition by 9.09%.

Significant learning gains for answering questions regarding CQ1 were found only in Visual V and Sequenced $H \rightarrow H+V$ conditions. In Visual V condition, scores on the pretest $(M = 79.26, SD = 27.25)$ were significantly different from the scores of the posttest $(M = 92.55, SD = 15.56)$ at $t(46) = -3.66, p < 0.001$. In the Sequenced $H \rightarrow H+V$ condition, scores on the pretest $(M = 86.11, SD = 20.41)$ were significantly different from the scores on the posttest $(M = 92.13, SD = 15.22)$ at $t(53) = -2.04, p < 0.05$. The effect size of the Visual V condition was considered moderate while the effect size of the Sequenced $H \rightarrow H+V$ condition was considered weak to moderate.

The analysis of posttest scores for CQ1 (role of the object's weight in friction) suggested no statistically significant differences between condition groups at a 0.95 confidence level $[F(4,201) = 1.47, p = 0.213]$. Figure 5.5 shows the result of the paired-mean comparison using the Tukey method for CQ1.

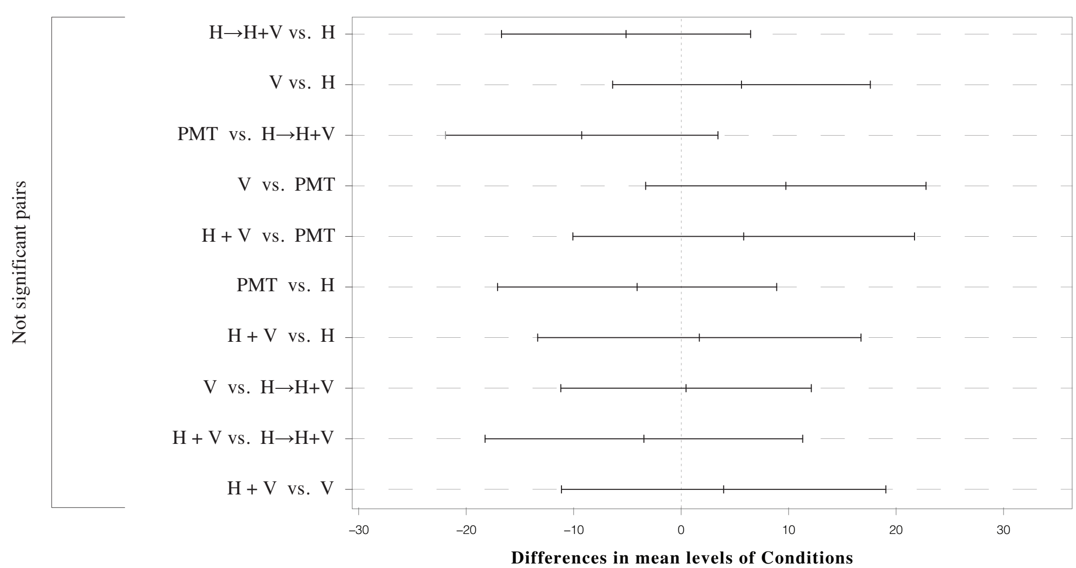


Figure 5.5. Paired-mean comparison of posttest scores for CQ1.

As shown in Figure 5.5, all pairs' gains were not statistically significantly different at $\alpha = 0.05$. The analysis of posttest scores for CQ2 (role of the object's size in friction) suggested statistically significant differences between condition groups at α= 0.05 $[F(4,201) = 5.438, p = 0.0003]$.

Table 5.4 shows the percentage of correct answers in pretest and posttest per concept for answering CQ1 (role of the object's weight in friction).

Table 5.4. Percentage of correct answers for CQ1

Concept	Pretest		Posttest		Δ
	Mean	StdDv	Mean	StdDv	
Frictional force	83.29	5.49	88.36	7.62	5.07
Speed	83.53	6.56	89.12	3.57	5.59
Acceleration	78.50	5.50	87.85	3.71	9.34
Traveled distance	81.20	5.49	89.20	7.71	7.68

As shown in Table 5.4, when comparing cubes of CQ1 (two cubes with the same size but different weight), the acceleration concept had the lowest percentage of correct answers by 78.5%. Contrary, the concept of speed had the highest percentage of correct answers by 83.53%. The four concepts (e.g., frictional force, speed, acceleration, and traveled distance) increased the percentage of correct answers from pretest to posttest (e.g., by 9.34 in the acceleration concept). Table 5.5 shows the percentage of correct, incorrect, and no response answers in the pretest and posttest by physics concept and condition for answering CQ1 (role of the object's weight in friction.

As shown in Table 5.5, in the pretest, the lowest percentage of correct answers was obtained by the participants in the Visual V condition with 72.34% for answering the difference in acceleration between two cubes with the same size but different weight. The highest percentage of correct answers in pretest was obtained by the Sequenced $H \rightarrow H+V$ condition with 92.59% for answering the differences in frictional force for the cubes. In the posttest the lowest percentage of correct answered was provided by the participants in the PMT condition for answering the differences in traveled distance for the cubes by 77.14%, and the highest by the participants in the Sequenced $H \rightarrow H+V$ condition with 98.15% for answering the differences in frictional force. The highest increment in the percentage of

Table 5.5. Type of answer per concept for answering CQ1

Concept	Condition	N	Pretest			Posttest			Δ	Δ
			Correct	Incorrect	NA	Correct	Incorrect	NA	correct	incorrect
Friction force	PMT	35	80.00	17.14	2.86	80.00	14.29	5.71	0.00	-2.86
	Haptic *H*	48	83.33	14.58	2.08	81.25	18.75	0.00	-2.08	4.17
	Visual *V*	47	78.72	17.02	4.26	91.49	8.51	0.00	12.77	-8.51
	Simultaneous H+V	22	81.82	9.09	9.09	90.91	9.09	0.00	9.09	0.00
	Sequenced: $H \rightarrow H+V$	54	92.59	5.56	1.85	98.15	0.00	1.85	5.56	-5.56
Speed	PMT	35	91.43	5.71	2.86	82.86	17.14	0.00	-8.57	11.43
	Haptic *H*	48	77.08	22.92	0.00	89.58	10.42	0.00	12.50	-12.50
	Visual *V*	47	82.98	14.89	2.13	91.49	8.51	0.00	8.51	-6.38
	Simultaneous H+V	22	77.27	22.73	0.00	90.91	9.09	0.00	13.64	-13.64
	Sequenced: $H \rightarrow H+V$	54	88.89	11.11	0.00	90.74	9.26	0.00	1.85	-1.85
Accele-ration	PMT	35	82.86	17.14	0.00	91.43	8.57	0.00	8.57	-8.57
	Haptic *H*	48	81.25	18.75	0.00	89.58	10.42	0.00	8.33	-8.33
	Visual *V*	47	72.34	27.66	0.00	89.36	10.64	0.00	17.02	-17.02
	Simultaneous H+V	22	72.73	27.27	0.00	81.82	18.18	0.00	9.09	-9.09
	Sequenced: $H \rightarrow H+V$	54	83.33	16.67	0.00	87.04	12.96	0.00	3.70	-3.70
Traveled distance	PMT	35	85.71	14.29	0.00	77.14	22.86	0.00	-8.57	8.57
	Haptic *H*	48	72.92	27.08	0.00	87.50	12.50	0.00	14.58	-14.58
	Visual *V*	47	82.98	17.02	0.00	97.87	2.13	0.00	14.89	-14.89
	Simultaneous H+V	22	86.36	13.64	0.00	90.91	9.09	0.00	4.55	-4.55
	Sequenced: $H \rightarrow H+V$	54	79.63	20.37	0.00	92.59	7.41	0.00	12.96	-12.96

correct answers occurred in the Visual *V* condition for answering the question regarding the differences in acceleration for the cubes by 17.02%. Only the PMT and the Haptic *H* conditions increased the percentage of incorrect answers from pretest to posttest. The PMT condition increased from pretest to posttest the percentage of incorrect answers by 11.43% in the concept of speed, and by 8.57% in the concept of traveled distance. The Haptic *H* condition increased from pretest to posttest the percentage of incorrect answers by 4.17% in the concept of friction force.

The Visual *V* condition had the highest increments of correct answers from pretest to posttest in the concepts of friction force (12.77%), acceleration (17.02%), and traveled distance (14.89%). The Haptic *H* condition obtained the highest increment for the concept of speed by 12.5%.

5.7.1.2 Role of the object's size in friction

Table 5.6 shows the descriptive statistics of the scores and the learning gains from pretest to posttest per condition to answer CQ2 (role of the object's size in friction). The four answers of Scenario 2 were considered in the calculation of the pretest and posttest scores (e.g., frictional force, speed, acceleration, and applied force). Pretest scores for questions regarding Scenario 2 were found no significant differences in the conditions at a 0.95 confidence level $[F(4,201) = 0.728, p = 0.574]$. Thus, all initial conditions were comparable.

Table 5.6. Learning gains for CQ2. Role of the object's size in friction

Condition	N	Pretest		Posttest		Δ	Paired *t*-test			Effect size
		Mean	StDv	Mean	StDv		DF	*t*-value	*p*-value	
PMT	35	61.43	43.02	67.14	39.66	5.71	34	-0.84	0.41	0.14
Haptic *H*	48	56.25	41.42	68.75	42.68	12.50	47	-2.29	0.03	0.33
Visual *V*	47	47.34	43.69	89.36	29.83	42.02	46	-6.17	<0.001***	0.90
Simultaneous *H+V*	22	62.50	43.47	96.59	15.99	34.09	21	-3.26	<0.01**	0.70
Sequenced: $H \rightarrow H+V$	54	55.09	44.87	87.96	29.83	32.87	53	-4.72	<0.001***	0.64

Results from Table 5.6 suggested that students had more problems answering CQ2 than CQ1. For instance, the pretest mean of PMT condition was lower by 23.57%, 22.4% in Haptic *H* condition, 31.92% in Visual *V* condition, 17.05% in Simultaneous *H+V* condition, and 31.02% in Sequenced $H \rightarrow H+V$ condition. Posttest scores in CQ2 increased in all the conditions. Visual *V* condition had the highest increment by 42.02%, followed by the Simultaneous *H+V* condition by 34.09%. PMT condition had the lowest increment of 5.71%.

Significant learning gains for answering CQ2 were found in Visual *V*, Simultaneous *H+V*, and Sequenced $H \rightarrow H+V$ conditions. In Visual *V* condition, scores of the pretest $(M = 47.34, SD = 43.69)$ were significantly different from the scores of the posttest $(M = 89.36, SD = 29.83)$ at $t(46) = -6.17, p < 0.001$. In Simultaneous *H+V* condition, scores of the pretest $(M = 62.5, SD = 43.47)$ were significantly different from the scores of the posttest $(M = 96.59, SD = 15.99)$ at $t(21) = -3.26, p < 0.01$. In Sequenced $H \rightarrow H+V$ condition, scores of the pretest $(M = 55.09, SD = 44.87)$ were significantly different from the scores of the posttest $(M = 87.96, SD = 29.83)$ at $t(53) = -4.72, p < 0.001$. The effect size of the Visual V condition was considered strong while the effect size of the Simultaneous H+V condition was considered moderate to strong, and moderate for the Sequenced $H \rightarrow H+V$ condition. The haptic condition obtained a strong effect size considered as weak to moderate.

Figure 5.6 shows the result of the paired-mean comparison using the Tukey method for CQ2 (role of the object's size in friction).

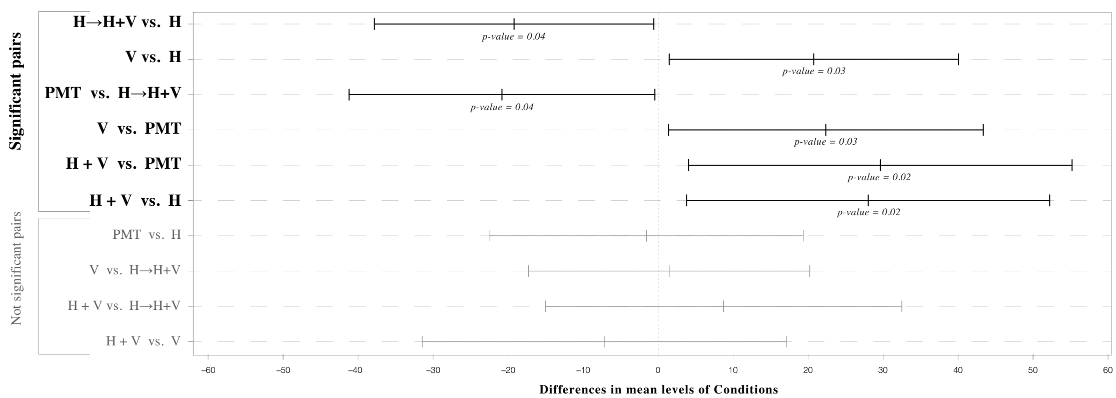


Figure 5.6. Paired-mean comparison of posttest scores for CQ2.

As shown in Figure 5.6, the pairs of means that demonstrated a statistically significant difference at $\alpha = 0.05$ were: (a) the Sequenced $H \rightarrow H+V$ vs. Haptic H, (b) Simultaneous H+V vs. Haptic H, (c) Visual V vs. Haptic H, (d) Sequenced $H \rightarrow H+V$ vs. PMT, (e) Simultaneous H+V vs. PMT, and (f) Visual V vs. PMT. Gains from all other pairs were not statistically significantly different at $\alpha = 0.05$. The PMT condition scores in the posttest were significantly different from all the VHS conditions except for the haptic condition. Visual V, Sequenced $H \rightarrow H+V$ S, and Simultaneous H+V posttest scores were significantly different than the score of the PMT and Haptic H conditions. However, the posttest scores of the Visual V, Sequenced $H \rightarrow H+V$ S, and Simultaneous H+V conditions were not statistically significantly different between each other.

Table 5.7 shows the percentage of correct answers in pretest and posttest per concept for answering CQ2 (role of the object's size in friction).

Table 5.7. Percentage of correct answers for CQ2

Concept	Pretest		Posttest		A
	Mean	StdDv	Mean	StdDv	
Frictional force	51.37	5.87	76.99	18.79	25.63
Speed	56.16	6.16	83.46	11.20	27.30
Acceleration	60.31	10.19	84.52	12.13	24.20
Traveled distance	58.25	10.85	82.88	11.46	24.63

As shown in Table 5.7, in general, the percentage of correct answers in the pretest for answering CQ2 (role of the object's size in friction) was lower than the percentage of correct answers in the pretest for answering CQ1. Increments of correct answers also occurred in CQ2 for all the concepts (e.g., by 27.30% for answering the speed differences between two cubes with the same weight but also different sizes). The friction concept obtained the lowest average percentage of correct answers in the pretest and posttest by 51.37% and 76.99%, respectively, while the concept of acceleration obtained the highest by 60.31% and 84.52%, respectively. Table 5.8 also shows that the standard deviation in all the concepts increased from pretest to posttest, indicating that the answers were more spread in the posttest.

Table 5.8 shows the percentage of correct, incorrect, and no response answers in the pretest and posttest by physics concept for answering CQ2 (role of the object's size in friction). The Visual *V* condition had the highest increment of correct answers from pretest to posttest in the concepts of speed, acceleration, and traveled distance, by 45.45%, 44.68%, and 48.94%, respectively. The Simultaneous *H+V* condition obtained the highest increment for the concepts of frictional force by 45.45%.

Table 5.8. Type of answer per concept for answering CQ2

Concept	Condition	N	Pretest			Posttest			A1	A2
			Correct	Incorrect	NA	Correct	Incorrect	NA	correct	incorret
Friction force	PMT	35	54.29	45.71	0.00	57.14	42.86	0.00	2.85	-88.57
	Haptic *H*	48	41.67	52.08	6.25	56.25	41.67	2.08	14.58	-93.75
	Visual *V*	47	55.32	38.30	6.38	87.23	12.77	0.00	31.91	-51.07
	Simultaneous *H+V*	22	50.00	40.91	9.09	95.45	4.55	0.00	45.45	-45.46
	Sequenced: $H \rightarrow H+V$	54	55.56	38.89	5.56	88.89	9.26	1.85	33.33	-48.15
Speed	PMT	35	62.86	37.14	0.00	68.57	31.43	0.00	5.71	-68.57
	Haptic *H*	48	58.33	41.67	0.00	75.00	25.00	0.00	16.67	-66.67
	Visual *V*	47	46.81	53.19	0.00	89.36	10.64	0.00	42.55	-63.83
	Simultaneous *H+V*	22	59.09	40.91	0.00	95.45	4.55	0.00	36.36	-45.46
	Sequenced: $H \rightarrow H+V$	54	53.70	46.30	0.00	88.89	9.26	1.85	35.19	-55.56
Accele-ration	PMT	35	68.57	31.43	0.00	71.43	28.57	0.00	2.86	-60.00
	Haptic *H*	48	64.58	35.42	0.00	72.92	27.08	0.00	8.34	-62.50
	Visual *V*	47	44.68	55.32	0.00	89.36	10.64	0.00	44.68	-65.96
	Simultaneous *H+V*	22	68.18	31.82	0.00	100.00	0.00	0.00	31.82	-31.82
	Sequenced: $H \rightarrow H+V$	54	55.56	44.44	0.00	88.89	9.26	1.85	33.33	-53.70
Traveled distance	PMT	35	60.00	40.00	0.00	71.43	28.57	0.00	11.43	-68.57
	Haptic *H*	48	60.42	39.58	0.00	70.83	29.17	0.00	10.41	-68.75
	Visual *V*	47	42.55	57.45	0.00	91.49	8.51	0.00	48.94	-65.96
	Simultaneous *H+V*	22	72.73	27.27	0.00	95.45	4.55	0.00	22.72	-31.82
	Sequenced: $H \rightarrow H+V$	54	55.56	44.44	0.00	85.19	12.96	1.85	29.63	-57.40

As shown in Table 5.8, all conditions increased the percentage of correct answers from pretest to posttest. For instance, the Visual *V* had a higher increment of correct answers from pretest to posttest by 48.94% for answering the question regarding the difference in traveled distance between pushing two cubes with the same weight but different size. All conditions decreased the percentage of incorrect answers in all the physics concepts investigated in the study.

5.7.2 Analysis of experimentation answers

This section answers the research question *What is the influence of VHS's visual and haptic feedback on students' conceptual knowledge of the role of the objects' size in friction?*

During the experimentation phase, participants from all conditions recognized the cubes' characteristics (see Section 4.3.3). The cubes' characteristics' recognition was important to determine to further the differences in frictional force, speed, acceleration, and traveled distance between Cube 2 and Cube 3 (CQ2). Participants in the PMT condition used two methods for identifying the similarities and differences of the cubes, the palm-method, and the bag-method (see Figure 4.10).

Results from the recognition stage (e.g., comparing the weight of Cube 2 vs. Cube 3) suggested that students did not have problems identifying that Cube 3 was the smaller cube. Only one student in the Haptic *H* condition incorrectly identified Cube 1 as the smallest cube. The student may had perceptual problems or be distracted while answered the question. Table 5.9 shows the frequency of correct and incorrect answers per condition regarding the differences in weight between the cubes.

Table 5.9. Recognition of the differences between Cube 2 and Cube 3

Condition	N	Correct	Incorrect
PMT-palm*	35	22 (66.86%)	13 (37.14%)
PMT-bag*	35	25 (71.43%)	10 (28.57%)
Haptic *H*	48	41 (85.42%)	7 (14.58%)
Visual *V*	47	45 (95.74%)	2 (4.26%)
Simultaneous H+V	22	21 (95.45%)	1 (4.55%)
Sequenced $H \rightarrow H+V$	54	52 (96.30%)	2 (3.70%)

*methods used in the PMT condition

Table 5.9 suggested that students in the PMT condition had difficulties identifying that Cube 2 and Cube 3 had the same weight but different sizes: 37.14% using the palm-method and 25.57% bag-method. In the PMT-palm method, all the 13 participants indicated that Cube 3 was heavier than Cube 2, in which eight participants also selected the option that Cube 2 was bigger than Cube 3. In the PMT-bag method, only one student indicated that Cube 2 was heavier than Cube 3. The other nine participants that answered incorrectly indicated that Cube 3 was heavier than Cube 2, which six also indicated that Cube 2 was larger than Cube 3.

For identifying the weight difference between Cube 2 and Cube 3, we found consistency in student's answers in the PMT group from one method of identification to the other (from PMT-palm to PMT-bag). That is, 30 out of the 35 students maintained the same answer in both methods: 21 students answered correctly in both methods (the only difference between Cube 2 and Cube 3 is the size). Nine students answered incorrectly in both methods: seven students indicated that Cube 2 was bigger than Cube 3 and that Cube 3 was heavier than Cube 2; and two students indicated that Cube 3 was heavier than Cube 2. We found changes in the answer from one method to the other in five participants: one student answered correctly using the PMT-palm method but in the PMT-bag method indicated that Cube 2 was heavier than Cube 3; four students answered using the PMT-palm method that Cube 3 was heavier than Cube 2 and corrected the answer in the PMT-bag method.

Twelve students in VHS conditions answered the question about the difference between Cube 2 and Cube 3 incorrectly. In the Haptic H condition, two students answered that Cube 2 was heavier than Cube 3 and that Cube 2 was bigger than Cube 3; three students answered that Cube 3 was heavier than Cube 2 and that Cube 2 was bigger than Cube 3; one student answered that Cube 3 was heavier than Cube 2, and one student answered that Cube 3 was bigger than Cube 2. In the Visual V condition, two students answered that Cube 2 was heavier than Cube 3. In the Simultaneous H+V condition, one student answered that Cube 3 was bigger than Cube 2. In the Sequenced $H \rightarrow H+V$ condition, one student answered that Cube 2 was bigger than Cube 3 and Cube 3 was heavier than Cube 2; one student answered that Cube 3 was bigger than Cube 2.

Table 5.10. Scores at the different steps of the study

Condition	N	Pretest scores		Experimentation scores		Posttest scores	
		Mean	StDv	Mean	StDv	Mean	StDv
PMT-2	18	56.94	43.56	43.56	43.06	41.84	58.33
Haptic	48	56.25	41.42	63.54	46.11	68.75	42.68
Visual	47	47.34	43.69	89.89	28.86	89.36	29.83
Simultaneous *H+V*	22	62.50	43.47	89.77	27.45	96.59	15.99
First interaction Sequenced $H \to H+V$	54	55.09	44.87	73.15	40.00	87.96	29.83
Second interaction Sequenced $H \to H+V$				87.04	29.83		

The experimentation performance was compared against the pretest and the posttest scores. Only the students from the spring semester using the PMT were considered in the experimentation stage analysis. We included each interaction with the Sequenced $H \to H+V$ condition separately. The first interaction of the Sequenced $H \to H+V$ had a similar experience as the Haptic *H* condition, while the second interaction had a similar experience as the Simultaneous *H+V*. Table 5.10 shows the scores in pretest, experimentation, and posttest per condition.

Table 5.10 shows that PMT-2 condition was the only group decreasing the mean score from pretest to the experimentation stage by 13.88%. From experimentation to posttest, the Visual *V* was the only group that decreased the scores by 0.53%. Table 5.11 shows the inferential analysis between the pretest scores and the experimentation scores.

Table 5.11. Pretest scores vs. Experimentation scores comparison

Condition	N	Pretest		Experimentation		Δ	Paired *t*-test			Effect size
		Mean	StDv	Mean	StDv		DF	*t*-value	*p*-value	
PMT-2	18	56.94	43.56	43.56	43.06	-13.88	17	1.27	0.221	0.30
Haptic	48	56.25	41.42	63.54	46.11	7.29	47	-1.20	0.237	0.17
Visual	47	47.34	43.69	89.89	28.86	42.55	46	-6.47	<0.001	0.94
Simultaneous	22	62.50	43.47	89.77	27.45	27.27	21	-2.30	0.032	0.49
First interaction Sequenced	54	55.09	44.87	73.15	40.00	-2.21	53	-2.21	0.031	0.30
Second interaction Sequenced	54	55.09	44.87	87.04	29.83	-4.58	53	-4.58	<0.001	0.62

The Haptic H condition had an increment of the mean score from pretest to experimentation by 7.29% but not in a statistically significantly different level (p-value = 0.24). The first interaction with the VHS of the Sequenced $H \rightarrow H+V$ condition were statistically significantly different at (p-value = 0.03). Learners from the Haptic H condition and the first interaction of the Sequenced $H \rightarrow H+V$ condition received haptic feedback and minimal visual cues. Comparison of the pretest scores between the Haptic H and Sequenced $H \rightarrow H+V$ conditions resulted in no statistically significantly differences at $t(100) = 0.135, p\text{–}value = 0.89$. Comparison of the experimentation scores also resulted in no statistically significantly differences at $t(93.7) = 1.12, p\text{–}value = 0.27$. Thus, we merged the scores of the Haptic H and the first interaction with the VHS in the Sequenced $H \rightarrow H+V$ condition and compared the pretest vs. the experimentation scores. The comparison of the pretest scores $(M = 55.64, SD = 43.07)$ vs. experimentation scores $(M = 68.63, SD = 43.04)$ resulted in statistically significantly differences at $t(93.7) = -2.7, p\text{–}value = 0.01$.

The highest increment from pretest to the experimentation stage occurred in the Visual V condition by 42.55%, followed by the Sequenced $H \rightarrow H+V$ condition, after the second interaction (haptic + enhanced visual feedback activated) by 31.95%. The Visual V and the second interaction of Sequenced $H \rightarrow H+V$ condition were statistically significantly different at α = 0.001. The effect size in the Visual V condition was considered strong, while the effect size in the second interaction of Sequenced $H \rightarrow H+V$ condition was considered moderate. The Simultaneous H+V condition, and the first interaction of the Sequenced $H \rightarrow H+V$ condition were statistically significantly different at α = 0.05. The effect size of the Simultaneous H+V condition was considered moderate, while the effect size of the first interaction of Sequenced $H \rightarrow H+V$ condition was considered weak to moderate.

Comparing the scores of the first and second interactions of the Sequenced $H \rightarrow H+V$ resulted in statistically significantly differences at $t(53) = -3.22, p\text{–}value = 0.02$. Students in the second interaction with the VHS in the Sequenced $H \rightarrow H+V$ condition improved their scores from the first interaction. The comparison of the experimentation scores of the Haptic H condition and the second interaction of the Sequenced $H \rightarrow H+V$ condition resulted in statistically significantly differences at $t(78.8) = -3.01, p\text{–}value = 0.003$.

The comparison between experimentation and posttest scores suggested increments in all the conditions except in the Visual V condition, which the mean score decreased by 0.53%. Students receiving the haptic and enhanced visual feedback tended to maintain the scores from experimentation to posttest. Students in the Sequenced $H \rightarrow H+V$, after the second interaction increased only by 0.92% the mean score in the posttest. Students in the Simultaneous H+V condition increased only by 6.82% the mean score in the posttest. Students in the Haptic H and Sequenced $H \rightarrow H+V$ in the first interaction, increased the scores from experimentation to posttest by 5.21% and by 14.81% respectively. Students in the PMT-2 condition increased the mean score from experimentation to posttest by 15.27%.

For comparing the differences among conditions in the experiment scores, we used one-way ANOVA. Only the second interaction score with the VHS in Sequenced $H \rightarrow H+V$ condition was considered because it is the learners' final answer. Results suggested statistically significant differences of the experimentation scores at F (4,184) = 9.183, p-value < 0.001. Similar to the comparison of the posttest scores, the post-hoc analysis using the Tukey HSD method suggested two groups of experimentation scores Group A, PMT and Haptic H, and the Group B in the experimentation scores Visual V, Simultaneous H+V, and Sequenced $H \rightarrow H+V$.

5.8 Chapter summary

This study aimed to investigate the differences in learning between interacting with a PMT and the VHS for learning friction. Furthermore, we aimed to determine the influence of the haptic and visual feedback of the VHS in learning concepts of friction.

We compared the student's performance in friction conceptual questions in the pretest, experimentation, and posttest. The study's conditions were PMT, and four configurations of the visuohaptic simulation, Haptic *H*, Visual *V*, Simultaneous *H*+*V*, and Sequenced $H \rightarrow H+V$. Students in Haptic *H* condition received haptic feedback (force feedback + kinesthetic feedback) and minimal visual information. Students in Visual *V* condition received enhanced visual information and kinesthetic feedback. The simultaneous *H*+*V* received haptic and enhanced visual feedback at the same time, and students in the Sequenced $H \rightarrow H+V$ had two interactions with the VHS. The feedback in the first interaction was haptic and minimal visual information, while in the second interaction, it was haptic and enhanced visual information.

The first research question was, *what are the differences in learning the concept of the role of the objects' size in friction between interacting with a physical manipulative tool PMT and a visuohaptic simulation VHS?* The null hypothesis indicated that students interacting with the PMT and the VHS benefited similarly in conceptual knowledge of friction (PMT = VHS). The alternative hypothesis stated the outperformance of students in the VHS (PMT $<$ VHS). Based on the results from the analysis of learning gains, the analysis of answers per question, and experimentation scores, we rejected the null hypothesis and concluded that students in the VHS conditions outperform students in the PMT condition (PMT $<$ VHS). Furthermore, results suggested that PMT and Haptic *H* conditions performed similarly in the posttest. However, only the Haptic *H* condition had significant learning gains from pretest to posttest, and the performance scores were higher. The visual feedback of the PMT and Haptic *H* conditions was considered minimal, and both conditions provided haptic feedback.

The second research question was, *what is the influence of VHS's visual and haptic feedback on students' conceptual knowledge of the role of the object's size in friction?* Our null hypothesis indicated that haptic and visual feedback influenced the conceptual knowledge of friction (H = V) similarly. We rejected the null hypothesis and concluded that haptic and visual feedback influenced the conceptual knowledge of friction $(H \neq V)$ differently. Enhanced visual feedback was more useful to correct learner's incorrect ideas of friction concepts than haptic feedback. Haptic and visual feedback provided in a Sequenced approach $H \rightarrow H+V$ suggested higher retention of the friction concepts.

Regarding the conceptual questions, students did not have problems answering CQ1 (role of the object's weight in friction). The mean score of the pretest of the conditions was above 79%. Significant learning gains occurred only for the Visual *V* and Sequenced $H \rightarrow H+V$ conditions. The VHS had a higher positive effect on the participants in the Visual *V* condition (e.g., significant learning gains at (p-value $<$0.001, and $|d| = 0.53$, which is considered moderate). However, posttest scores of all the conditions were not statistically significantly different (p-value $<$0.05).

For answering CQ2, the four VHS's conditions had significant learning gains from pretest to posttest; Visual *V*, and Sequenced $H \rightarrow H+V$ at (p-value $<$0.001), Simultaneous *H+V* at (p-value $<$0.01), and Haptic *H* at (p-value $<$0.05). The Visual *V* condition had a strong effect size; Simultaneous *H+V* moderate to strong, and the Sequenced $H \rightarrow H+V$ moderate.

The post-hoc analysis for CQ2 suggested two groups of students' performances in the posttest *Group A*, which included the PMT and the Haptic *H* conditions *Group A*, which included the conditions of Visual V, Simultaneous H + V, and Sequenced HH+V. The difference between *Group A* and *Group B* is the type of visual feedback received. *Group A* received minimal visual feedback, while *Group B* received enhanced visual feedback.

CHAPTER 6. COMPARING SEQUENCED APPROACHES

The second study investigated the students' conceptual explanations of friction concepts before, during, and after the use of the visuohaptic simulation (VHS) in two different sequenced approaches: visual to haptic + visual feedback ($V \rightarrow H+V$) and haptic to visual + haptic feedback ($H \rightarrow H+V$). The participants answered questions regarding two friction concepts (a) role of the object's weight in friction and (b) role of the objects' size in friction. Participants (*n* = 48) interacted with the visuohaptic simulation in a laboratory session of introductory statics during the Spring semester of 2017. For characterizing students' explanations of friction concepts, we used a thematic analysis approach. The results section presents (a) the result of the thematic analysis characterizing the language themes used by the participants for answering the conceptual questions, (b) a comparison of the language themes used by participants on each sequenced approaches (i.e., $V \rightarrow H+V$ vs. $H \rightarrow H+V$), and (c) analysis of the students' language themes by level of performance in the pretest (i.e., low, medium, and high).

6.1 Research questions

The guiding research question of the study was: *What are the differences in students' conceptual explanations before, during, and after interacting with a visuohaptic simulation in two different sequenced approaches such as visual to haptic + visual feedback ($V \rightarrow H+V$), and haptic to visual + haptic + visual feedback ($H \rightarrow H+V$)?*

The sub-questions of the study are:

1. What are the characteristics of student's explanations of friction-related conceptual questions?
2. What are the differences between the conditions of sequenced approaches ($V \rightarrow H+V$ vs. $H \rightarrow H+V$) in student's explanations used to answer the friction-related conceptual questions at the different stages of the study (pretest, interaction 1, midtest, interaction 2, and posttest)?

3. What are the differences between the low-level, medium-level, and high-level performers on each condition of sequenced approaches ($V \rightarrow H+V$ vs. $H \rightarrow H+V$) in student's' explanations used to answer the friction-related conceptual questions at the different stages of the study (pretest, interaction 1, midtest, interaction 2, and posttest)?

For answering the first research question, we used thematic analysis (see Section 6.7.1). For the second research question, we analyzed the changes in students' explanations per sequenced of feedback approach ($V \rightarrow H+V$ and $H \rightarrow H+V$) at the different phases of the study: pretest, interaction 1, midtest, interaction 2, and posttest (see Section 6.7.2). Inferential analysis and descriptive analysis were used for answering the second research question.

For answering the third research question, we categorized the student's pretest answers in three levels of performance (i.e., low-level performers, medium-level performers, and high-level performers) and analyzed the students' explanations for answering the friction conceptual questions at the different stages of the study (see Section 6.7.3). The importance of the change in the unit of analysis of the explanations (i.e., by sequenced of feedbacks approach and by the level of performance in the pretest) is that it allowed us to capture the answers change from the general perspective (condition) to the specific view (participants).

6.2 Participants

Participants (n = 48) were students enrolled in an applied statics course taught during the Spring semester of 2017. The applied statics course consisted of two lectures of one hour each and a laboratory session of two hours per week. The learning experience took place in two different laboratory sessions in the 13th week of the semester. One session followed the first sequenced visual feedback approach to haptic + visual ($V \rightarrow H+V$). The second session followed the second sequenced haptic feedback approach to haptic + visual

($H \rightarrow H+V$). Participants registered for the course and the laboratory session at the beginning of the semester. The researchers did not have control over the course registration process. Table 6.1 shows the treatment conditions and the self-reported characteristics of the participants.

Table 6.1. Participants characteristics

Condition	N	Gender*		Prior experience		Major		Level		
		M	F	HS or college	No courses	Engineering related	Other/ NA	Freshmen	Sopho-more	Other
$V \rightarrow H+V$	24	24	0	23	1	24	0	15	5	4
$H \rightarrow H+V$	24	24	4	23	1	24	0	17	2	6

*not reported by the participants. This number is based on the class list and researcher's notes.

Table 6.1 shows that 91.67% of the participants were male, 95.83% had previous exposure to physics courses at a high school or college level, all the participants were enrolled in a program related to engineering (e.g., mechanical engineering technology, robotics, mechatronics), and the majority of students were freshmen (66.67%), or sophomore (14.83%).

Participants also self-reported their confidence in friction concepts and their knowledge of haptic devices. Participants rated the questions by selecting an option from the Likert-scale. Options were: strongly agreed (SA), agreed (A), neutral (N), disagreed (D), and strongly disagreed (SD). Table 6.2 shows the results for answering the confidence in friction concepts before and after the intervention.

Table 6.2. Question, I feel confident about my understanding of statics friction concepts

Condition	Before the intervention					After the intervention*				
	SA	A	N	D	SD	SA	A	N	D	SD
$V \rightarrow H+V$	0.00	45.83	37.50	16.67	0.00	16.67	66.67	8.33	4.17	0.00
$H \rightarrow H+V$	4.17	58.33	37.50	0.00	0.00	8.33	70.83	16.67	0.00	0.00

*One participant on each condition did not answer the question in the posttest.

Before the intervention participants mainly selected the agreed-option ($V \rightarrow H+V$: 48.83%; $H \rightarrow H+V$: 58.33%), followed by the neutral-option (37.5% on each condition). After the intervention the percentage of participants agreed in reporting higher levels of confidence in friction-related concepts by increasing to 20.84% in $V \rightarrow H+V$ condition and by 12.5% in the $H \rightarrow H+V$ condition. The category of strongly-agreed (SD) increased by 16.67% in the $V \rightarrow H+V$ condition, and 4.16% in the $H \rightarrow H+V$ condition. Table 6.3 shows the results for answering the question about knowledge of haptic technology. Regarding their knowledge about haptic technology before the intervention, participants mainly selected the disagreed-option ($V \rightarrow H+V$: 45.83%; $H \rightarrow H+V$:50%), followed by the strongly-disagreed ($V \rightarrow H+V$: 16.67%; $H \rightarrow H+V$: 20.83%). After the intervention, participants mainly selected the agreed-option ($V \rightarrow H+V$: 58.33%; $H \rightarrow H+V$: 62.5%), followed by the strongly-agreed ($V \rightarrow H+V$: 29.17%; $H \rightarrow H+V$: 29.17%).

Table 6.3. Question, I know about haptic technology

Condition	Before the intervention					After the intervention*				
	SA	A	N	D	SD	SA	A	N	D	SD
$V \rightarrow H+V$	8.33	8.33	20.83	45.83	16.67	29.17	58.33	4.17	4.17	0.00
$H \rightarrow H+V$	0.00	4.17	25.00	50.00	20.83	29.17	62.50	0.00	4.17	0.00

*One participant on each condition did not answer the question in the posttest.

6.3 Context

The study took place in the laboratory session of an introductory statics course. The setting had twenty-nine stations composed of a laptop computer and a haptic device. Upon arrival, each participant sat on a station and completed the study individually. Although discussion among participants occurred during the laboratory session, each participant individually recorded their answers in the worksheets and assessments provided for this study. We did not prohibit and encourage the discussion between participants to maintain normal interaction the laboratory session.

Figure 6.1. Laboratory setting of the VHS stations For the stations' configuration, we only considered space limitations (e.g., doors) and the quantity of equipment available.

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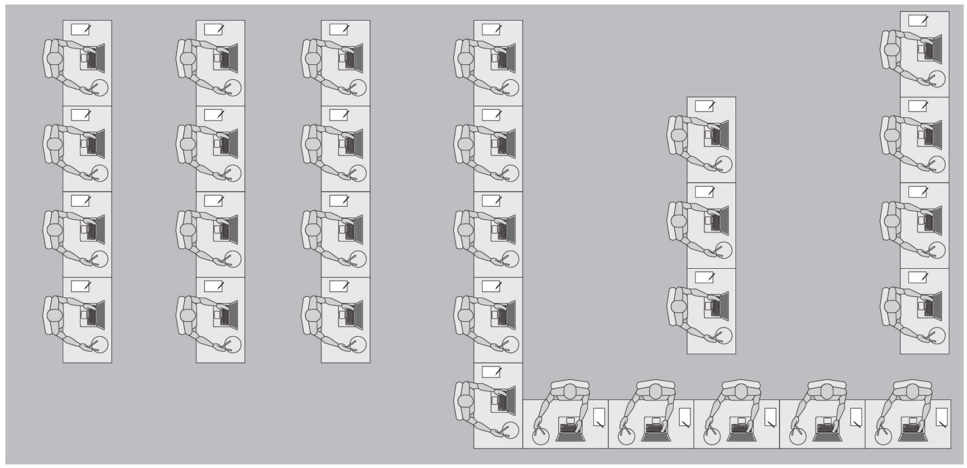

Figure 6.1. Laboratory setting of the VHS stations.

6.4 Research Procedures

Participants completed the study in six steps and had a duration of two days. Each day the session lasted for one hour. Students from both conditions ($H \rightarrow H+V$ and $V \rightarrow H+V$) attended to the laboratory session two days after the lecture. Figure 6.2. shows the procedures pipeline.

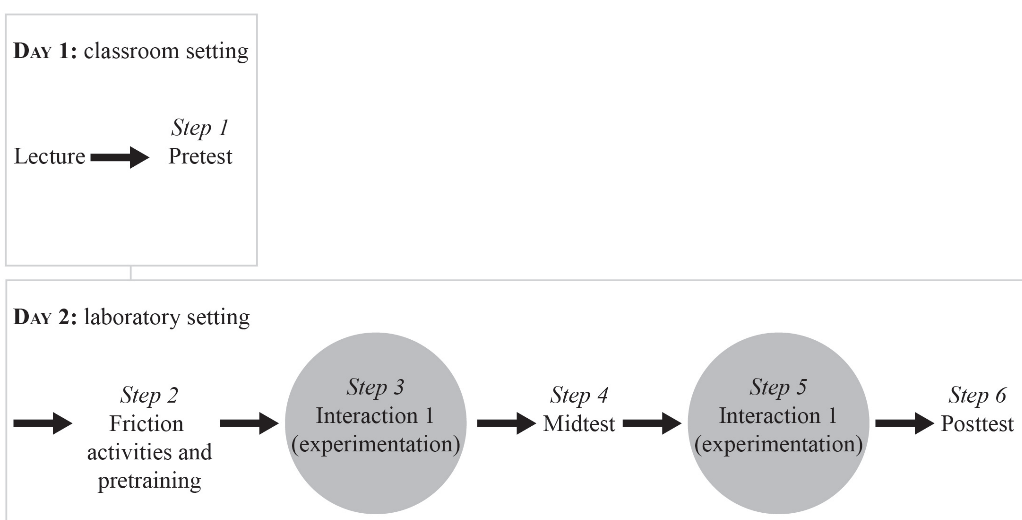

Figure 6.2. Procedures pipeline.

During the first day, participants attended the friction lecture and completed the pretest. Receiving the lecture is important because it enabled all learners to have prior experience in friction. We used the pretest as the baseline for investigating changes in conceptual knowledge through the experiment. In the pretest, participants answered the conceptual, procedural, and representational questions of friction. We only considered the conceptual questions in this study because we analyzed the written explanations. Procedural and representational answers were out of the scope of this study. See Section 6.5. for the questions included in the pretest.

During the second day, participants did friction-related exercises and a pre-training exercise first. In the friction exercises, participants indicated by drawings and written explanations of what forces acted on a cube resting on a surface. In the pre-training, participants learned how to interact with a visuohaptic simulation for learning buoyancy concepts. As part of the simulation, participants submerged a cube with different properties (e.g., weight and density) in a liquid with different densities. A buoyancy experimentation worksheet guided the pre-training activity. In all the studies, all the interactions with the VHS, an experimentation worksheet drove the interaction. The pre-training's importance was that it aimed to reduce the novelty of the technology in the participants (Magana et al., 2017) since they self-reported low knowledge of haptic devices (see Table 6.3).

In Step 3, all the participants interacted with the VHS for learning friction concepts for the first time. Participants experienced the conceptual scenarios using the VHS in a learning activity guided by a worksheet (see Section 6.5.1). In this step, the differentiation between conditions occurred. In the $V \rightarrow H+V$ condition, participants received enhanced visual cues and kinesthetic feedback, while participants in the $H \rightarrow H+V$ condition received haptic feedback and minimal visual feedback. The minimal visual feedback showed spatial information of the cube (e.g., location in the stage), and showed the motion of the cubes (e.g., how fast a cube moved, or the traveled distance after being pushed). The minimal visual feedback did not show numerical values (e.g., speed in numbers). The enhanced visual feedback showed the information provided by the minimal visual feedback and the magnitude (e.g., the numerical value of the force), and direction of the forces (e.g., arrows) acting on the cube while being lifted or pushed (see Figures 4.3, 4.4, and 4.5).

The interaction with the haptic device provided two types of body-related feedback: kinesthetic and haptic. The body movements used for interacting with the virtual environment is the kinesthetic feedback. For instance, for the same force applied to a light cube, and a heavy cube, the participant, could feel their arm moving faster while pushing the light cube. The haptic feedback included the kinesthetic feedback and force feedback. The haptic feedback helped participants feel harder to lift a heavy cube than a light cube. See Section 4.3.1 for more details about the feedback. The importance of Step 3 was that it allowed the comparison of conceptual answers during the interaction with the VHS between the students receiving mainly visual information ($V \rightarrow H+V$ condition) or haptic information ($H \rightarrow H+V$ condition).

After completion of the first interaction with the VHS, participants answered the midtest (Step 4). The midtest answers were used to compare the differences between conditions ($V \rightarrow H+V$ vs. $H \rightarrow H+V$) and changes in the same condition (e.g., changes in answers before and after the use of the VHS). Once finished the midtest, participants interacted with the VHS in a second occasion. In the second interaction, both conditions received enhanced visual cues and haptic feedback. We enabled the haptic feedback to the participants in the $V \rightarrow H+V$ condition, and we enabled the enhanced visual cues to the participants in the $H \rightarrow H+V$ condition. There was no differentiation of feedback received between conditions. Participants revised the answers provided in the worksheet during the first interaction. If the participant considered that the first interaction's answer was incorrect or incomplete, the participant wrote the new observations using a researchers' red pen. We encouraged participants to only used red pen in the worksheets during the second interaction. The second interaction's importance was that we were able to compare the differences between the sequenced approaches. For instance, we recorded how many answers were corrected from the first interaction to each condition's second interaction.

The posttest was the last step of the study. The questions of the posttest were the same as the questions in the pretest. The posttest had the same importance as the midtest, which allowed the comparison between conditions, and allowed the analysis of language change through the study. For instance, in the $V \rightarrow H + V$ condition, allowed the comparison of answers after using the use of the VHS with mainly enhanced visual cues (interaction 1) or with enhanced visual cues and haptic feedback (interaction 2).

All the materials used during the experiment were designed and printed by the author of this dissertation and other researchers involved in the study. Participants received replicates of the study documents (e.g., all students received the same posttest). The author of this dissertation was presented in all the laboratory sessions. Assistants for the data collection (e.g., other researchers in the project and the teacher assistant) were trained to ensure the quality in the study.

6.5 Assessment questions

This study's conceptual questions were designed based on the misconceptions reported on SCI by Steif and Dantzler (2005). A multidisciplinary team composed of professionals in engineering education, physics education, and software development adapted the questions used in the Statics Concept Inventory by Steif and Dantzler (2005). The questions were framed into two conceptual questions: CQ1 focused on the role of the objects' weight in friction, and CQ2 focused on the role of the objects' size in friction. The conceptual questions for CQ1 were:

- Pretest and posttest: What happens when you push two cubes made from the same material and with the same size, but with different weights (one half the weight of the other) on a surface?
- First and second interactions: Are the forces to move Cube 2 different or the same to those you apply to move the Cube 1 when it stands on the cardboard?
- Midtest: What can you tell about the friction force experienced by the Cubes that have the same size but different masses?

The conceptual questions for CQ2 were:

- Pretest and posttest: What happens when you push two cubes made from the same material and with the same weight, but with different size (one half the size of the other) on a surface?
- First and second interactions: Are the forces to move Cube 2 different or the same to those you apply to move the Cube 3 when it stands on the cardboard?
- Midtest: What can you tell about the friction force experienced by the Cubes that have the same mass but different sizes?

The different wording used for asking the conceptual questions for each different step in the study. The conceptual questions focused on prompting students to recall their prior knowledge of friction (i.e., pretest question) or recall prior knowledge and knowledge acquired in the learning experience with the VHS (i.e., midtest and posttest). The midtest questions were phrased so that students focused their observations on the concept of friction. The interaction questions were closely aligned with the experience. For instance, questions focused on the forces felt or saw while sliding the cubes on different surfaces.

6.5.1 Interaction guidance

All the participants followed an experimentation worksheet during the interaction with the VHS. The worksheet had six main parts. Each part had different questions that required the participants to use the VHS for answering them. The parts were: recognition, focusing on Cube 1, focusing on Cube 2, comparing Cube 1 vs. Cube 2, focusing on Cube 3, and comparing Cube 2 vs. Cube 3. For the analysis of the role of the objects' weight in friction, we analyzed the participants answers in the comparison of Cube 1 vs. Cube 2.

In the parts where participants focused on a specific cube (e.g., Focusing on Cube 1), participants slid the cube on the three different surfaces of the virtual environment (i.e., cardboard, fabric, and sandpaper). Participants compared the differences between sliding Cube 1 and Cube 2 on the differences surfaces in the fourth part and compared Cube 2 and Cube 3 on the differences surfaces in the sixth part. The answers provided for the fourth part and the sixth part were used for the analysis of CQ1 and CQ2, respectively. See section 4.3.3 for a complete explanation of each part of the interaction guidance.

6.6 Data analysis

The data analysis consisted of two main parts: (a) analysis of the students' answers per conceptual questions at the different stages of the study, and (b) categorizing students' answers in the pretest based on their performance.

We analyzed a total of 480 answers corresponding to the students' answers ($n = 48$) to the two conceptual questions during the five stages of the study (pretest, interaction 1 and interaction 2, midtest, and posttest). For the data analysis, three trained researchers graded the students' responses. The obtained Cronbach's α to evaluate the scoring process's trustworthiness was within the acceptable range (0.7 for the role of the object weight in friction and 0.6 for the role of the object size). Disagreements were not about the explanation themes or the correctness of the answers. Disagreements were primarily due to the grammar and handwriting of the students. Disagreements between graders were solved by discussion and by creating and applying the rules of grading. The grading rules helped the scoring process by framing and specifying different considerations in students' conceptual answers. For instance, rule 1 and rule 2 defined the statement characteristics, and rule 3 defined how to grade answers that participants considered a smooth surface as frictionless.

We followed the six-phase guide for analyzing the student's answers for conducting thematic analysis as proposed by Braun and Clarke (2006)). The form of thematic analysis used in this study was inductive, to remain as close as possible to the meaning of the data. The phases of the thematic analysis are: become familiar with the data, generate initial codes, search for themes, review themes, define themes, and write up.

During the stage of becoming familiar with the data we noticed that participants used different variables for answering the conceptual questions. Each of the students' responses was divided into statements. The statements were sentences containing one physics variable to answer the question (Rule 1). Details that reinforce the idea were not considered as a statement (e.g., formulas). For example, the student $H \to H+V$: ID9 wrote in the pretest for answering the conceptual question about the role of the weight of the object in friction (CQ1): "Cube 1 (light) will be easier to push + move faster". There are two statements in the student': "Cube 1 (light) be easier to push…" and "…move faster". If two sentences contained the same variable, used in different words, the sentences were considered one statement (Rule 2). For instance, for answering CQ1, participant $V \to H+V$: ID21 indicated that Cube 1 will move from one point to another with little resistance and that Cube 2 will move from one point to another with more resistance. Both sentences were considered as a single statement. Table 6.4 shows the total number of statements provided by the participants on each of the conditions to answer CQ1 (role of the objects' weight in friction) and CQ2 (role of the objects' size in friction).

Table 6.4. Condition, conceptual question, number of statements per study phase.

Condition	Conceptual question	Pretest	Interaction 1	Midtest	Interaction 2	Posttest
$V \to H+V$	CQ1 (weight)	44	30	25	30	36
	CQ2 (size)	28	31	24	29	28
$H \to H+V$	CQ1 (weight)	36	30	30	31	34
	CQ2 (size)	23	22	23	24	28

Students wrote 586 statements for answering CQ1 and CQ2 at the different phases of the study. Students provided 131 statements in the pretest, 113 in the first interaction, 102 in the midtest, 114 statements in the second interaction, and 126 statements in the posttest. For CQ1, students provided 326 statements, and for answering CQ2, students provided 260 statements. Changes from the first interaction to the second interaction with the VHS occurred when participants changed the answer during the second interaction. If a participant did not change the second interaction answer, the first and second interaction's answer was the same (Rule 3). Section 6.7.3 provides a detailed description of the changes that occurred from the first interaction to the second interaction.

During the second phase of the thematic analysis, generate initial codes, we classified the statements based on the variable used and whether they used the variable correctly or incorrectly. We found multiple codes: hard and easy, applied force, frictional force, speed, traveled distance, acceleration, time, resistance, and glide. During the revision of the codes we defined six themes, hard and easy (HE), applied force (Fa), frictional force (Ff), speed (S), traveled distance (TD), and others (O). We also defined if students used the variable in a correct or in an incorrect way. Table 6.6. shows the revised codes obtained from the students' explanations.

The themes obtained from the initial codes were haptically-oriented and visually-oriented themes. Haptically-oriented and Visually-oriented concepts could be perceived through visual imagery or by the sensorimotor capabilities of the learners.

Haptically-oriented themes referred to the human's actions needed to make the cubes start to move. Human's actions were directly related to the force feedback and kinesthetic feedback. Students acquired movement information through the sense of touch. For instance, students may have felt harder to slide a heavy cube than a lighter cube. The Haptically-oriented themes were hard/easy, applied force, and frictional force.

The themes considered **Visually-oriented** referred to the cube's motion as a consequence of human action. Students acquired the movement information through the sense of sight. For instance, students may have seen the light cube moving faster than the heavy cube on a smooth surface. The Visually-oriented themes were speed, traveled distance, and other variable statements (e.g., acceleration). Table 6.7 and Table 6.8 shows the percentage of haptically-oriented and visually-oriented themes per stage in the study per conceptual question.

The second part of the data analysis consisted of categorizing students' pretest answers for CQ1 and CQ2 in high-level, medium-level, and low-level performance. High-level performance is a student's answers that only included correct statements. Low-level performance is a student's answers that only included incorrect statements. Medium-level performance is answers that combined correct and incorrect statements. The classification of the student's answers for CQ1 and CQ2 was independent. For instance, the participant $V \rightarrow H+V$: ID8 provided a pretest answer categorized as high-level for CQ1, and low-level for CQ2. Once we categorized the pretest answers, we analyzed the explanations themes used for answering the conceptual questions at the different stages of the study.

6.6.1 Frictionless assumption

During the thematic analysis stage of becoming familiar with the data, we noticed that a group of students considered frictionless the smooth surface. The frictionless assumption was not stated in the worksheets. Because the study's goal is not to identify misconceptions in student's answers, we created a grading rule (Rule 4) to analyze the student's explanations themes used to answer the conceptual questions. Rule 4 stated that if the student stated the assumption correctly, the answer was considered correct. For instance, for answering CQ1, the participant $V \rightarrow H+V$: ID16 wrote in the posttest "If the friction is frictionless, the cubes should behave in the same manner."The answer was considered correct. We found in the pretest, ten students assuming that the smooth surface was frictionless ($V \rightarrow H+V$: six; $H \rightarrow H+V$: four), one in the midtest ($V \rightarrow H+V$: one), and five in the posttest ($V \rightarrow H+V$: three; $H \rightarrow H+V$: two). Only one participant in the $V \rightarrow H+V$ stated the pretest and posttest's frictionless assumption. All other participants indicated the frictionless assumption in only one test. For answering CQ2, four participants stated the frictionless assumption in the pretest ($V \rightarrow H+V$: three; $H \rightarrow H+V$: one), and three in the posttest ($V \rightarrow H+V$: one; $H \rightarrow H+V$: two).

We recognized answers for CQ2 that did not explicitly stated the frictionless assumption but left room for questioning if the participant did or not the assumption (e.g., Cube 2 and Cube 3 will behave the same). We carefully revised each case but could not identify with certainty if the student assumed a frictionless surface. To minimize the effect of the frictionless assumption in CQ2, we identified the student's answers in Section 6.7.3, which analyzed the changes per study phase.

6.6.2 Positionality and reflexivity of the author in the research

The author's background in engineering design and visual communication, and her interest in the impact of technology in learnin, may have influenced the data analysis and interpretation of the results, compromising the results' trustworthiness. For instance, during the stage of becoming familiar with the data in the thematic analysis (Braun & Clarke, 2006), the author focused on differences in the students' variables to answer the conceptual questions. The author did not consider important aspects in physics (e.g., if friction force was considered a property of the cubes or a resultant force from the interaction between the cube and the surface) as part of this analysis. Differences in student's explanations found in the data were aligned with prior research (e.g., Minogue & Borland, 2016), suggesting a promising direction for the investigation of the influence of visuohaptic simulations in students' conceptual knowledge.

To minimize the research bias, the author was first aware of her influence in the data analysis. The selected inductive method of analysis helped the author to maintain a neutral position during the data analysis. Secondly, investigator triangulation was considered in the process of grading student's answers (Carter, Bryant-Lukosius, Dicenso, Blythe, & Neville, 2014). The author trained two graders and together analyzed the data set. Graders created a rubric, following an inductive process that required constant revisions and agreement among graders. Each grader analyzed students' answers independently. The author compiled the results and analyzed the results from the condition's perspective (Section 6.7.2) and the participant (Section 6.7.3). For presenting the results, quantitative and qualitative methods were used.

6.7 Results

This section summarize the results of the data used for answering the research questions. Section 6.7.1 answered the first research questions about the differences in students' explanations for answering the research questions. Section 6.7.2. compared the student's explanations per condition and Section 6.7.3 compared the students' explanations per participant.

6.7.1 Themes in student's explanations

We classified the student's statements according to the variable used to answer the conceptual questions. Table 6.5 presents the codes and examples of answers provided by the participants to answer conceptual question 1 (CQ1) and the conceptual question 2 (CQ2).

Table 6.5. Codes definition and examples

Codes	Definition	Correct answer	Incorrect answer
Hard or easy (HE)	Participants make a reference to how difficult would be to push the cubes. Common words: easy, hard, and effort.	CQ1. The lighter cube is easier to move… CQ2. The small and big cube are equally harder to move…	CQ1. Both cubes are equally easy to slide. CQ2. The small cube would move easier than the big cube…

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Table 6.5 continued from previous page

Explanation themes	Definition	Correct answer	Incorrect answer
Applied Force (Fa)	Participants make a reference to the magnitude of the force required to push the cubes. Common words: applied force, forces needed to push the cubes.	CQ1. Light cube will require less force to start motion… CQ2. The small and big cube are equally harder to move…	CQ1. The heavy cube requires more force for being pushed… CQ2. Small cube requires more force applied than the big cube…
Friction Force (Ff)	Participants make a reference to the opposite force of the force being applied. Common words: friction force, and resistance.	CQ1. Less weight means less friction CQ2. Both cubes have the same weight and the same friction force.	CQ1. Cubes experience no friction because the surface is smooth. CQ2. The big cube will come to rest quicker because friction is coming into contact with more surface.

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Table 6.5 continued from previous page

Explanation themes	Definition	Correct answer	Incorrect answer
Traveled distance (TD)	Participants make a reference to the distance traveled by the cubes when are sliding on the surface and the distance. Common words used: distance, farther, shorter distance, long distance.	CQ1. If you apply the same force, the light cube will move further. CQ2. Both cubes (small and big) slides the same distance.	Q1. Both cubes travel the same distance. CQ2. Assuming the same force is applied to both cubes, the heavy cube would travel farther.
Speed (S)	Participants make a reference to the speed the cubes would slide. Common words used: speed, fast, slow, rapidly, and less rapidly.	CQ1. The light cube moves further and faster if pushed with the same force. CQ2. Same speed for both cubes	CQ1. The heavy cube would move faster. CQ2. The big cube will move faster.

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Table 6.5 continued from previous page

Explanation themes	Definition	Correct answer	Incorrect answer
Other variable statements (O)	Participants make a reference to different variables such as acceleration, beat, time, and inertia.	CQ1. Light cube requires less effort. CQ2. Same acceleration for both cubes (small and big).	CQ1. Light cube will stop sooner. CQ2. If you apply the same force, the light cube accelerates less.

Hard or easy (HE), applied force (Fa), and Friction force (Ff) are haptically-oriented themes or body-based actions. Speed (S), traveled distance (TD) and others (O) are visually-oriented themes that refers to the cube's motion on the virtual environment.

6.7.2 Haptically-oriented and Visually-oriented language per condition

Table 6.6 shows the variation of the themes per condition for answering the CQ1 (role of the object's weight in friction).

Table 6.6. Percentage of statements for answering CQ1.

Condition	Type of answer	Themes	Pretest	Int 1	Midtest	Int2*	Posttest
$V \to H+V$	Correct	Haptically-oriented	45.5	83.3	88.0	83.3	58.3
		Visually-oriented	40.9	10.0	12.0	10.0	33.3
	Incorrect	Haptically-oriented	0.0	0.0	0.0	0.0	5.6
		Visually-oriented	13.6	6.7	0.0	6.7	2.8
$H \to H+V$	Correct	Haptically-oriented	36.1	83.3	96.7	83.9	82.4
		Visually-oriented	47.2	10.0	0.0	9.7	8.8
	Incorrect	Haptically-oriented	2.8	3.3	3.3	3.2	8.8
		Visually-oriented	13.9	3.3	0.0	3.2	0.0

*Interaction 2 results reflect the changes made by participants during the second interaction.

Table 6.6 shows that students provided mainly correct statements for answering CQ1 in the pretest ($V \to H+V$: 86.4%; $H \to H+V$: 83.3%). Only in $H \to H+V$'s pretest condition were the Visually-oriented themes more used than Haptically-oriented themes by 11.1%. Visually-oriented themes decreased from pretest to the others' study stages. For instance, from pretest to the first interaction, the $V \to H+V$ condition decreased the percentage of Visually-oriented themes by 30.9%, while the $H \to H+V$ condition decreased by 37.2%.

From pretest to the first interaction with the VHS, there was an increment of incorrect Haptically-oriented themes ($V \to H+V$: by 3.2%; $H \to H+V$: 4.6%). Only one changed occurred from the first interaction to the second interaction; a participant in the $H \to H+V$ condition added a statement categorized as correct Applied force's theme (CFa).

From pretest to posttest, there was an increment of correct Haptically-oriented themes ($V \to H+V$: by 12.9%; $H \to H+V$: 46.2%). The decrement of correct Visually-oriented themes from pretest to posttest was by 7.6% in the $V \to H+V$ condition, and 38.4% in the $H \to H+V$ condition.

Appendix A shows the percentage of explanations themes used for answering CQ1 in both conditions. Figure 6.3 summarized the results presented in Appendix A.

During the interactions with the VHS, the correct Applied force (CFa) was the most common correct Haptically-oriented theme ($V \rightarrow H+V$: 70%; $H \rightarrow H+V$: 50%). The themes of correct Friction force (CFf), and correct Hard or easy (CHE) were used in 13.3% of the statement in the $V \rightarrow H+V$ condition, and in 33.3% of the statement in the $H \rightarrow H+V$ condition. The midtest results suggested a dominance of the correct friction force theme ($V \rightarrow H+V$: 72%; $H \rightarrow H+V$: 76.7%). Also, students provided 16% of the statements using the correct Hard or easy (CHE) and correct Applied Force (CFa) themes in the $V \rightarrow H+V$ condition and 20% in the $H \rightarrow H+V$ condition. The posttest results suggested that students in the $H \rightarrow H+V$ condition used 82.4% of Haptically-oriented themes for answering CQ1, which corresponded to 35.3% correct Hard or easy (CHE), 29.4% correct Applied Force (CFa), and 17.6% correct Friction force (CFf). For the $V \rightarrow H+V$ condition, the most common explanations themes were correct Applied force (CFa) by 33.3%, followed by the Visually-oriented theme of correct other (CO) by 19.44%. Table 6.6 shows the variation of the themes per condition for answering the CQ2 (the role of the object's size in friction).

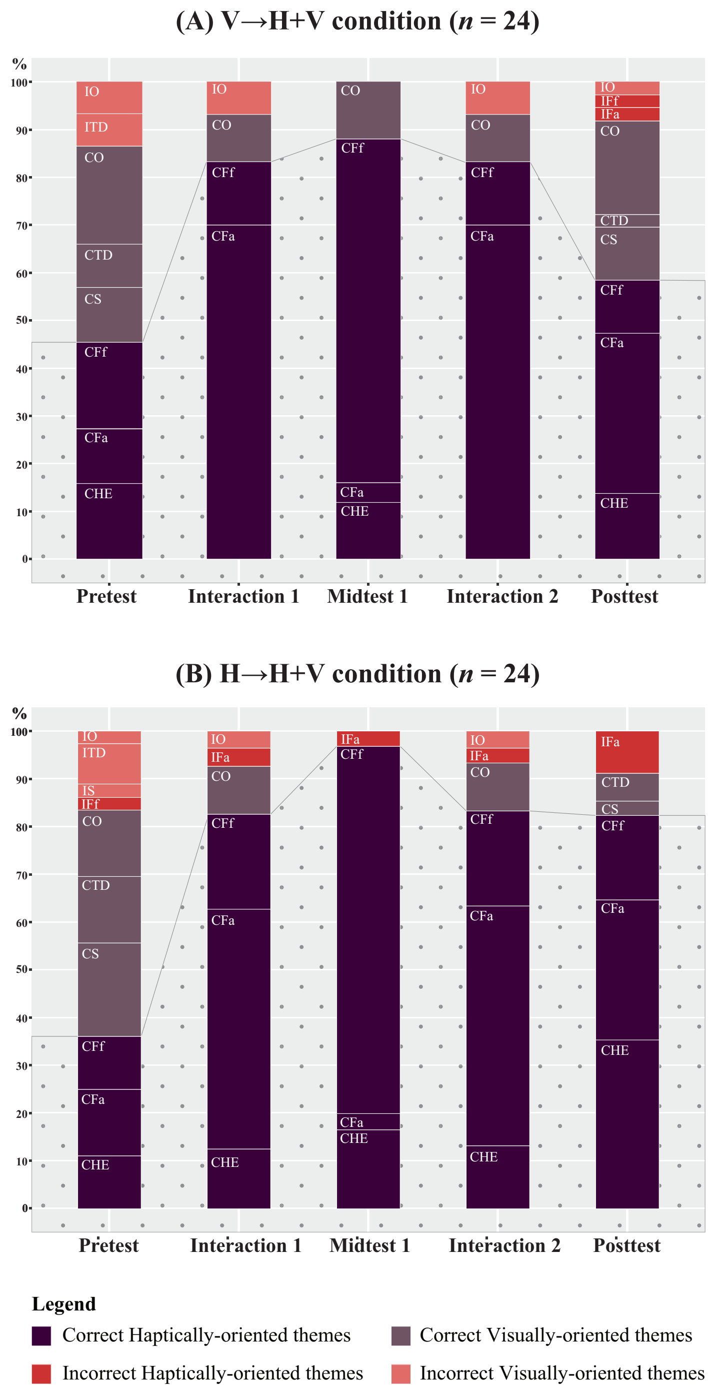

Figure 6.3. Changes in the explanations themes per condition for answering CQ1. Legend:CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other, IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer.

During the interactions with the VHS, the correct Applied force (CFa) was the most common correct Haptically-oriented theme ($V \rightarrow H+V$: 70%; $H \rightarrow H+V$: 50%). The themes of correct Friction force (CFf), and correct Hard or easy (CHE) were used in 13.3% of the statement in the $V \rightarrow H+V$ condition, and in 33.3% of the statement in the $H \rightarrow H+V$ condition. The midtest results suggested a dominance of the correct friction force theme ($V \rightarrow H+V$: 72%; $H \rightarrow H+V$: 76.7%). Also, students provided 16% of the statements using the correct Hard or easy (CHE) and correct Applied Force (CFa) themes in the $V \rightarrow H+V$ condition and 20% in the $H \rightarrow H+V$ condition. The posttest results suggested that students in the $H \rightarrow H+V$ condition used 82.4% of Haptically-oriented themes for answering CQ1, which corresponded to 35.3% correct Hard or easy (CHE), 29.4% correct Applied Force (CFa), and 17.6% correct Friction force (CFf). For the $V \rightarrow H+V$ condition, the most common explanations themes were correct Applied force (CFa) by 33.3%, followed by the Visually-oriented theme of correct other (CO) by 19.44%. Table 6.7 shows the variation of the themes per condition for answering the CQ2 (the role of the object's size in friction).

Table 6.7. Percentage of statements for answering CQ2.

Condition	Type	Themes	Pretest	Int 1	Midtest	Int2	Posttest
$V \rightarrow H+V$	Correct	Haptically-oriented	14.3	80.6	54.2	79.3	64.3
		Visually-oriented	39.3	0.0	20.8	0.0	32.1
	Incorrect	Haptically-oriented	35.7	19.4	16.7	20.7	3.6
		Visually-oriented	10.7	0.0	8.3	0.0	0.0
$H \rightarrow H+V$	Correct	Haptically-oriented	17.4	63.6	34.8	83.3	71.4
		Visually-oriented	47.8	4.5	13.0	4.2	14.3
	Incorrect	Haptically-oriented	30.4	31.8	47.8	12.5	14.3
		Visually-oriented	4.3	0.0	4.3	0.0	0.0

*Interaction 2 results reflect the changes made by participants during the second interaction.

As shown in Table 6.7, in the pretest, 41.2% of the student's statements from both conditions were incorrect ($V \rightarrow H+V$: 46.4%; $H \rightarrow H+V$: 34.8%). Also, in the pretest, students used a higher percentage of correct Visually-oriented themes than correct Haptically-oriented themes ($V \rightarrow H+V$: difference by 25%; $H \rightarrow H+V$: difference by 30.4%). However, the distribution of correct Haptically-oriented and Visually-oriented themes changed after the pretest. Students used more Haptically-oriented themes than

Visually-oriented themes for answering CQ2 in all the study stages except for the pretest. For instance, from pretest to posttest, students in the $V \rightarrow H+V$ condition increased the use of correct Haptically-oriented themes 50% and decreased the use of correct Visually-oriented themes by 7.1%. The $H \rightarrow H+V$ condition increased the use of correct Haptically-oriented themes by 54% and decreased the use of correct Visually-oriented themes by 33.5%.

Regarding the use of incorrect statements, results suggest that the visuohaptic simulation helped correct the student's misconceptions in the $V \rightarrow H+V$ condition more than the students in the $H \rightarrow H+V$ condition. In the $V \rightarrow H+V$ condition, only 3.6% of the statements provided in the posttest were incorrect, while students in the $H \rightarrow H+V$ condition provided 14.3% of incorrect statements. During the interactions with the VHS, participants did not provide statements using incorrect Visually-oriented themes. From pretest to the first interaction, the decrement of incorrect Haptically-oriented themes was 16.4% in the $V \rightarrow H+V$ condition and 1.4% in the $H \rightarrow H+V$ condition. During the second interaction with the VHS, there was an increment of incorrect Haptically-oriented themes in the $V \rightarrow H+V$ condition by 1.3%. Students in the $V \rightarrow H+V$ condition reduced the incorrect Haptically-oriented themes when received enhanced visual feedback but increased when receiving haptic feedback in the second interaction. There was a decrement of incorrect Haptically-oriented themes from the first interaction to the second interaction by 19.3% in the H V+H condition. Hence, enhanced visual feedback helped students to transition from incorrect statements to correct statements. In the posttest, the higher percentage of statements were categorized as Haptically-oriented ($V \rightarrow H+V$: 64.29%; $H \rightarrow H+V$: 71.43%). Appendix A shows the percentage of explanations themes used for answering CQ2. Figure 6.4 summarized the results presented in Appendix A.

The higher percentage of pretest statements were categorized as correct-Other (CO) in the $V \rightarrow H+V$ condition with 25%, and correct Traveled distance (CTD) in the $H \rightarrow H+V$ condition with 26.09%. During the first interaction with the VHS, the higher percentage of statements were categorized as correct Applied force (CFa) in both conditions ($V \rightarrow H+V$: 61.29%; $H \rightarrow H+V$: 54.55%). The most common theme used in the midtest was the correct Friction force theme (CFf) by 54.17% in the $V \to H+V$ condition and 34.78% in the $H \to H+V$ condition. Furthermore, the $H \to H+V$ condition incorrectly used the friction force theme (IFf) by 30.43%. The correct Visually-oriented theme of other statements (CO) was the second most used theme in the $V \to H+V$ condition by 20.83%.

Regarding the changes from the first interaction to the second interaction with the VHS, the $V \to H+V$ condition's greater change occurred in the percentage of correct Friction force statements (CFf), which decreased by 2.11%. In the $H \to H+V$ condition, there was an increment of correct Applied force (CFa) statements by 20.45%.

In the posttest, the higher percentage of statements were categorized as correct Haptically-oriented. Specifically, for the $V \to H+V$ condition, the correct Friction force (CFf) was used in 35.71% of the posttest statements and correct Applied force (CFa) in 28.57% of the statements. Correct Hard or easy (CHE)statements were not provided in the posttest by the $V \to H+V$ condition participants. In the $H \to H+V$ condition, the correct Applied force (CFa) was used in 46.43% of the statements, followed by correct Hard or easy (CHE) by 14.29% and correct Friction force (CFf) by 10.71%. However, the correct Other (CO) represented 25% of the posttest statements in the $V \to H+V$ condition, indicating a higher use of correct Visually-oriented themes in the $V \to H+V$ condition than in the $H \to H+V$ condition 17.86%.

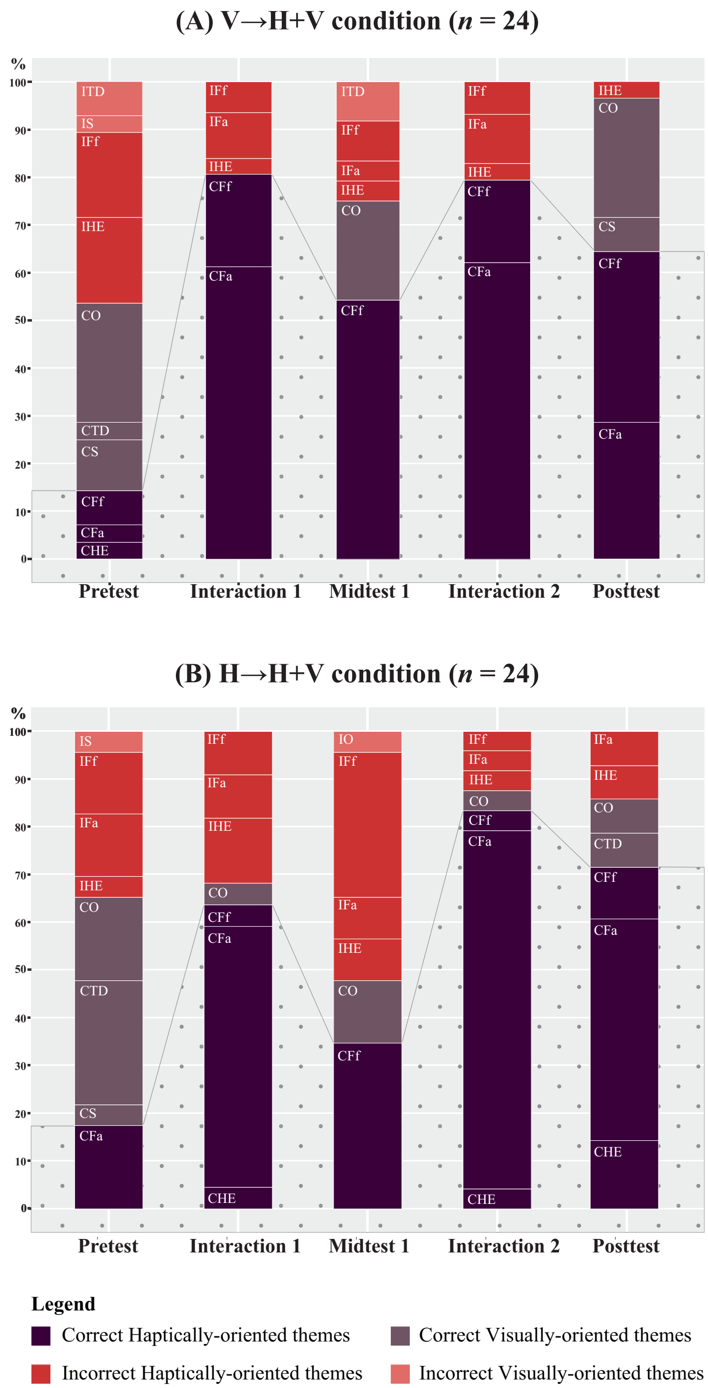

Figure 6.4. Changes in the explanations themes per condition for answering CQ2. Legend: CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other,IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer.

6.7.3 Haptically-oriented and Visually-oriented language used per student on each condition

This section focuses on answering the third research question of the study. The third research question focused on comparing the explanations themes for answering the conceptual questions at the different stages of the study per student. The pretest answers were categorized in low-level (incorrect statements), medium-level (correct statement and incorrect statements), and high-level (correct statements) to analyze performance per student on each conceptual question. Table 6.8 shows the number of students on each performance level per conceptual question.

Table 6.8. Number of students per performance level.

Condition	Conceptual question	Low	Medium	High
$V \rightarrow H+V$	CQ1 (weight)	4	3	17
(*n*=24)	CQ2 (size)	12	0	12
$H \rightarrow H+V$	CQ1 (weight)	2	5	17
(*n*=24)	CQ2 (size)	10	3	11

As shown in Table 6.8, most student's answers were categorized as high-performance for answering CQ1 ($V \rightarrow H+V$: 17; $H \rightarrow H+V$: 17). For answering CQ2, there was a higher number of low-level answers ($V \rightarrow H+V$: 12; $H \rightarrow H+V$: 10), indicating that students had problems identifying the role of the objects' size in friction. Figure 6.5 shows the improvement of the low-performers through the different phases of the study for answering CQ1. Also, figure 6.5 shows the changes in the student's explanations through the study. For instance, a participant in the $V \rightarrow H+V$ condition provided an answer using the code of incorrect traveled distance (ITD) in the pretest, and provided an answer in the first interaction using the code of correct Applied force (CFa). Appendix B shows the categorization of student's explanations per phase for CQ1 and CQ2

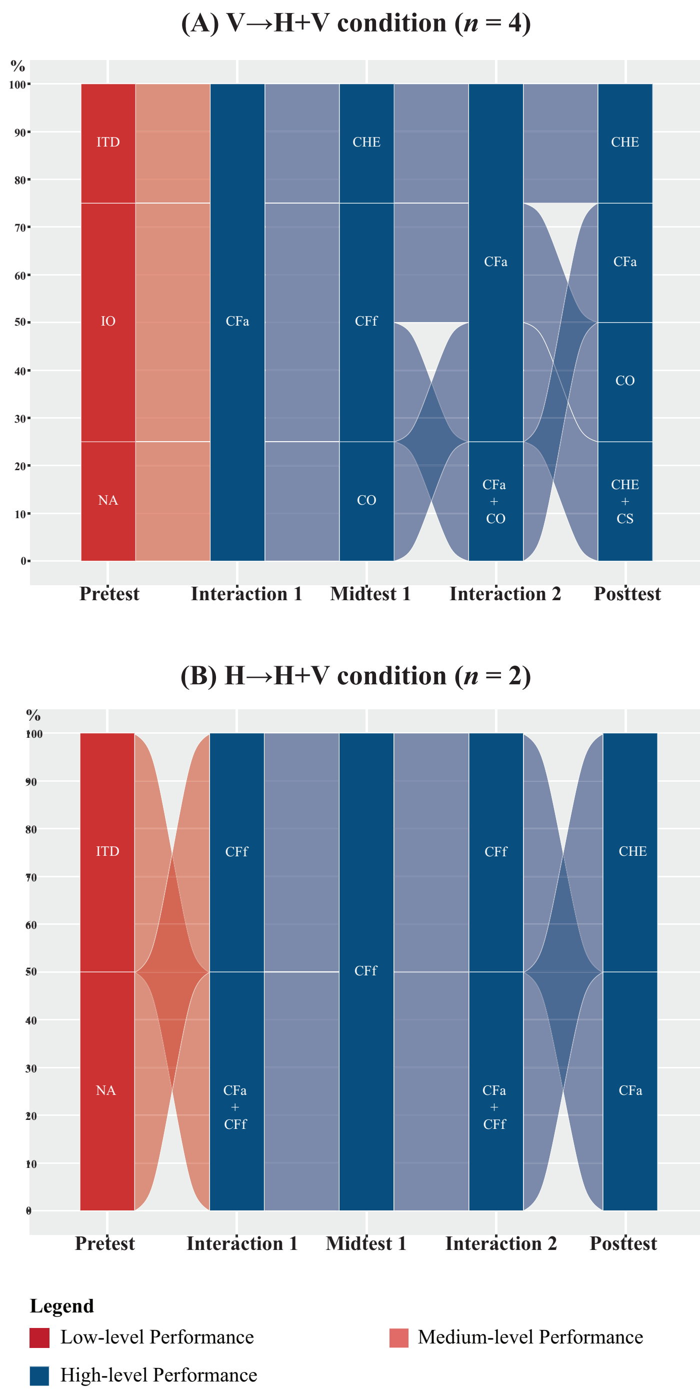

Figure 6.5. Explanation's change in pretest low-level performers for answering CQ1.Legend:CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CO: correct Other,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer

Figure 6.5 suggests that enhanced visual feedback and haptic feedback helped students to correct their answers regarding the role of the objects' weight in friction. All the $V \rightarrow H+V$'s participants provided a correct Applied force (CFa) during the first interaction with the VHS. Participants in the $H \rightarrow H+V$ condition provided correct Applied force (CFa) and correct Friction force (CFf) statements. All participants continued providing high-level answers after the pretest. For instance, during the pretest, participant $H \rightarrow H+V$: ID12 used incorrect Traveled distance statements (i.e., Cube 2 will travel farther) and in the interaction phases indicated that Cube 2 required a higher force for being pushed on a smooth surface than Cube 1. Participant $V \rightarrow H+V$: ID23 indicated in the pretest that for the same applied force, the heavy cube would travel a longer distance. Participant $V \rightarrow H+V$: ID14 indicated that the forces required to push Cube 1 and Cube 2 were the same. See Appendix C for examples of the student's answers to CQ1. Figure 6.6 shows the improvement of the medium-performers through the different phases of the study.

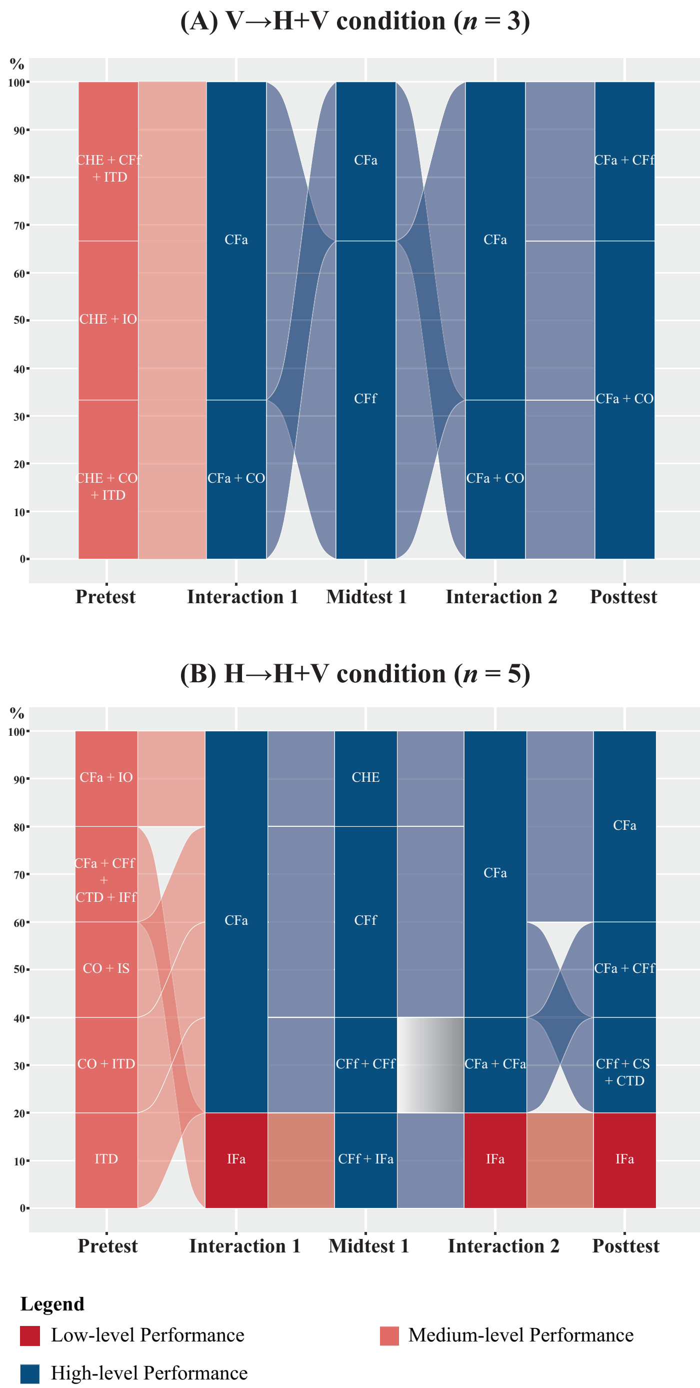

Figure 6.6. Explanation's change in pretest medium-level performers for answering CQ1. Legend: CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other,IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer

Figure 6.6 suggests two main patterns: (a) the VHS helped medium-performers to correct their answers, (b) the majority of correct answers included at least one correct Haptically-oriented statements, and (c) incorrect Visually-oriented themes were most common than incorrect Haptically-oriented themes. Seven out of eight participants that provided a medium-level answer in the pretest provided a high-level answer in the posttest. Only one participant did not answer correctly CQ1 in the posttest. The participant $H \rightarrow H+V$: ID8 felt that Cube 1 had the same weight of Cube 2, resulting in an incorrect perception of the force required to push the objects. The participant might assume that a smooth surface was frictionless in the posttest, but the assumption was not completed, resulting in categorizing the statement in incorrect Applied force (IFa).

During the interaction phases with the VHS, all medium-level performers included at least one correct Haptically-oriented theme in their answer. Furthermore, during the first interaction, the correct Applied Force (CFa) was used in six out of eight participants. For instance, $H \rightarrow H+V$: ID18, and $H \rightarrow H+V$: ID22 indicated that the forces of Cube 2 were greater than the forces of Cube 1 in all the surfaces. Students who provided medium-level answers in the pretest used seven times incorrect Visually-oriented themes and incorrect Haptically-oriented themes. The most common incorrect language theme was Traveled distance (e.g., $H \rightarrow H+V$: ID12, and $H \rightarrow H+V$: ID22 indicated in the pretest that Cube 2 would travel farther than Cube 1). Figure 6.7 shows the answers of the high-performers through the different phases of the study.

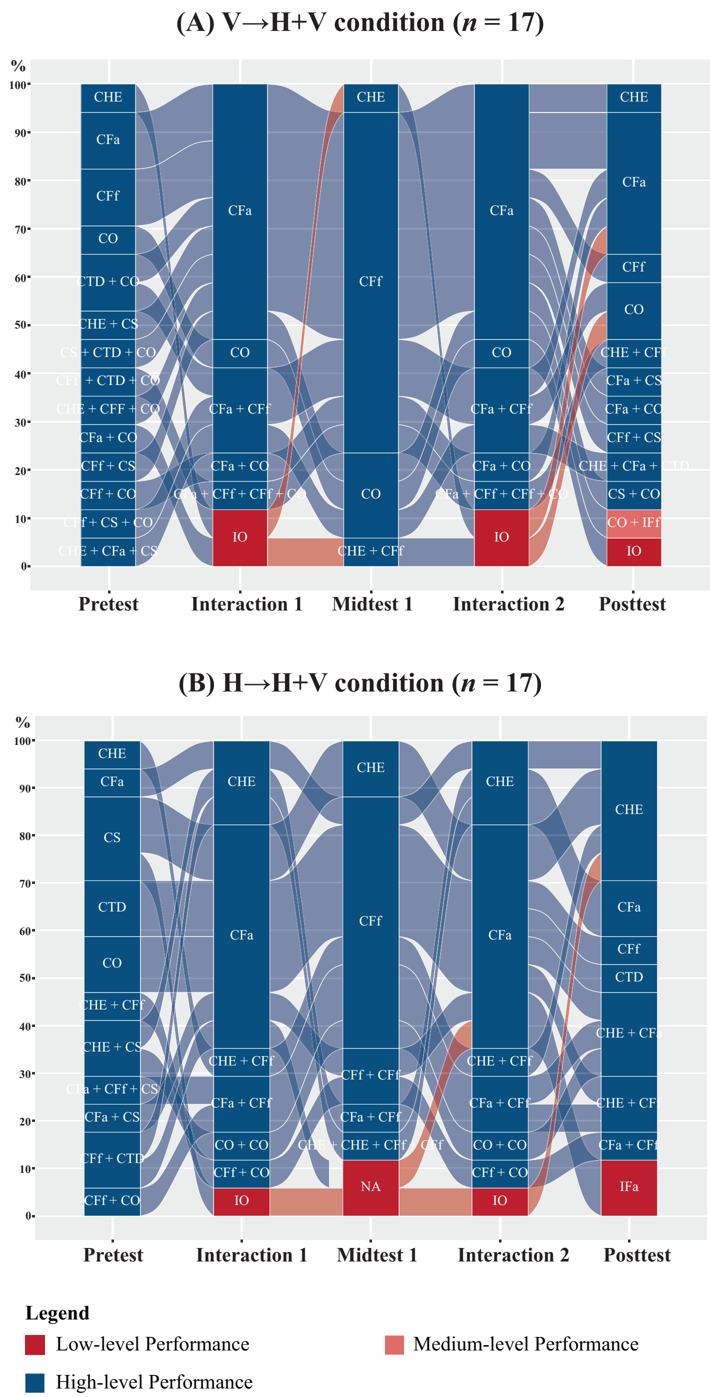

Figure 6.7. Explanation's change in pretest high-level performers for answering CQ1.Legend: CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other,IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer

Figure 6.7 suggests three main patterns: (a) the majority of students reinforced their knowledge using the VHS; (b) during the interactions, high-level performers (n = 4) used incorrect statements for answering CQ1; and (c) correct Haptically-oriented themes were more common than correct Visually-oriented themes.

The use of the visuohaptic simulation helped high-level performers to reinforce their correct conceptual knowledge. Twenty-five students answered CQ1 using only correct statements in all the study ($V \rightarrow H+V$: 12 students, $H \rightarrow H+V$: 13 students). Examples of correct answer in all the study phases were provided by the participants $V \rightarrow H+V$-ID2, $V \rightarrow H+V$-ID18, $H \rightarrow H+V$-ID1, $H \rightarrow H+V$-ID5, and $H \rightarrow H+V$-ID7 (see Appendix C). During the interactions, four students provided an incorrect answer for CQ1. For instance, participant $V \rightarrow H+V$: ID4, participant $V \rightarrow H+V$: ID14, and participant $H \rightarrow H+V$: ID11 indicated that Cube 1 and Cube 2 were the same. The answers were categorized as incorrect Other (IO). Participants corrected their answers in the posttest. Incorrect answers in the first interaction with the VHS did not change during the second interaction.

Incorrect answers using the Applied force language theme (IFa), stated that Cube 1 and Cube 2 required the same force for being pushed (e.g., $H \rightarrow H+V$: ID6, $H \rightarrow H+V$: ID8, $H \rightarrow H+V$: ID19). Participants did not state the frictionless assumption; hence, the answer was considered incorrect. The third pattern was that correct Haptically-oriented themes were more common than correct Visually-oriented themes. For instance, high-performers provided 235 statements for answering CQ1, which only 63 were using Visually-oriented themes ($V \rightarrow H+V$: 40 statements, $H \rightarrow H+V$: 23 statements). All other statements were Haptically-oriented. The most common Haptically-oriented theme was correct Applied force (CFa), followed by correct Friction force (CFf) with 70 statements and 62 statements, respectively. Figure 6.8 shows the improvement of the low-performers through the different phases of the study for answering CQ2.

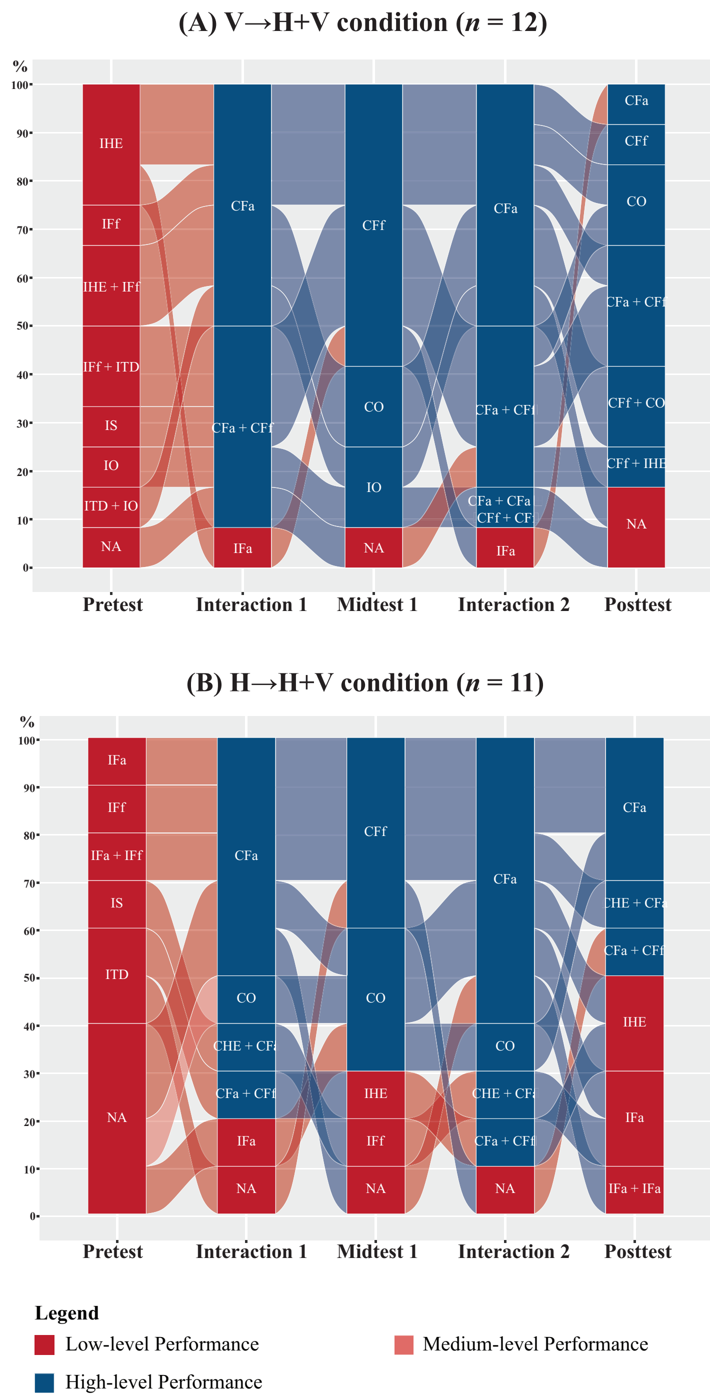

Figure 6.8. Explanation change in pretest low-level performers for answering CQ2. Legend: CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other,IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer.

Figure 6.8 suggests that the VHS helped low-level performers to correct their knowledge about the role of the objects' size in friction. For instance, at least half of the participants who provided a low-level answer in the pretest provided a high-level answer in the posttest (e.g., $V \rightarrow H+V$: ID2, and $V \rightarrow H+V$: ID18). Student $H \rightarrow H+V$: ID7 indicated in the pretest that Cube 2, with a larger surface area, will require more force for being pushed than Cube. During the interaction phase, the participant corrected their answer and indicated that they felt the forces acting on Cube 2 and Cube 3 very similar. We considered "very similar" as a correct answer because the participant did not have access to enhanced visual information. The participant made a correct interpretation of their haptic feedback. Appendix C showed examples of answers provided by the participants for answering CQ2.

During the first interaction with the VHS, 16 participants incorrectly answered CQ2 ($V \rightarrow H+V$: five students, and $H \rightarrow H+V$: eleven students). Students incorrectly indicated that the force required for moving Cube 2 was different from the force required to move Cube 3. For instance, participant $V \rightarrow H+V$: ID14 indicated that Cube 2 is harder to push because the weight was distributed in a larger area. During the second interaction, in the $H \rightarrow H+V$ condition, five out of eleven participants that provided an incorrect answer during the first interaction with the VHS corrected their answers. For instance, in the first interaction, participant $H \rightarrow H+V$- ID15 indicated that Cube 3 required more force than Cube 2 for being pushed on a smooth surface. The second interaction answer indicated that the force required for pushing Cube 2 and Cube 3 on a smooth surface was the same. Participants in the $V \rightarrow H+V$ condition did not correct their answers during the second interaction with the VHS. Figure 6.9 shows the improvement of the medium-performers through the different phases of the study for answering CQ2.

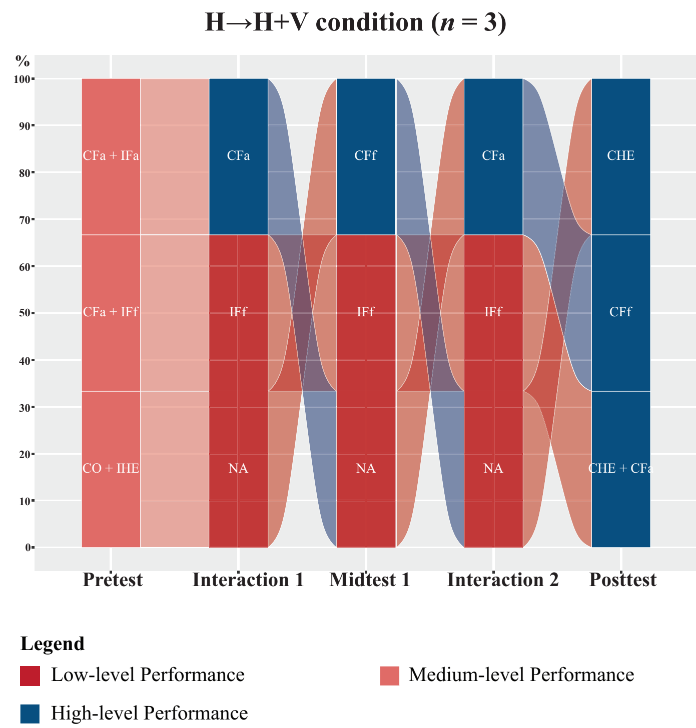

Figure 6.9. Language change in pretest medium-level performers for answering CQ2.Legend: CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other,IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer.

Only three pretest answers in the $H \rightarrow H+V$ condition were categorized as a medium-level. Medium-level answers suggested a disassociation between the applied force and the frictional force in student's answers. For instance, $H \rightarrow H+V$-ID8 indicated that the force required for pushing Cube 2 and Cube 3 was the same, but the friction force of Cube 3 was smaller than the friction force of Cube 2. During the interactions, the participant provided an incorrect answer, indicating that Cube 3 required more force for being pushed. In the posttest, the participant corrected the answer. All three participants provided a correct answer in the posttest. Correct answers in the posttest used only correct Haptically-oriented themes (e.g., CHE). Figure 6.10 shows the improvement of the high-performers through the different phases of the study for answering CQ2.

Figure 6.10 shows that four participants incorrectly answered CQ2 during the interaction phases. Participants did not change the answer when the haptic feedback was activated during the second interaction. Participant $V \rightarrow H+V$-ID9 indicated that Cube 2 required less force for being push on a smooth surface because it experienced less frictional force (IFa + IFf). Participant $V \rightarrow H+V$-ID15 indicated that Cube 2 required more force for being push on a smooth surface because it experienced more frictional force (IFa + IFf). Participant $V \rightarrow H+V$-ID14 indicated that Cube 3 was easier to push than Cube 2 on a smooth surface. Participants explained that the difference between cubes was due to the difference in sizes.

In the $H \rightarrow H+V$ condition, seven participants answered incorrectly CQ2 during the first interaction. Five participants felt that Cube 3 was heavier than Cube 2; hence, Cube 3 required more force for being pushed than Cube 2. The other two participants indicated that forces required to push Cube 2 and Cube 3 were not equal but did not explain why. Five participants corrected their answer during the second interaction with the enhanced visual cues activated. For instance, $H \rightarrow H+V$-ID16 indicated that Cube 3 was harder to move because it was heavier. During the second interaction with the enhanced visual cues activated, the participant saw the forces' magnitude's numerical values and changed the answer to correct (i.e., Cube 3 and Cube 2 required the same force for being pushed because cubes had the same weight).

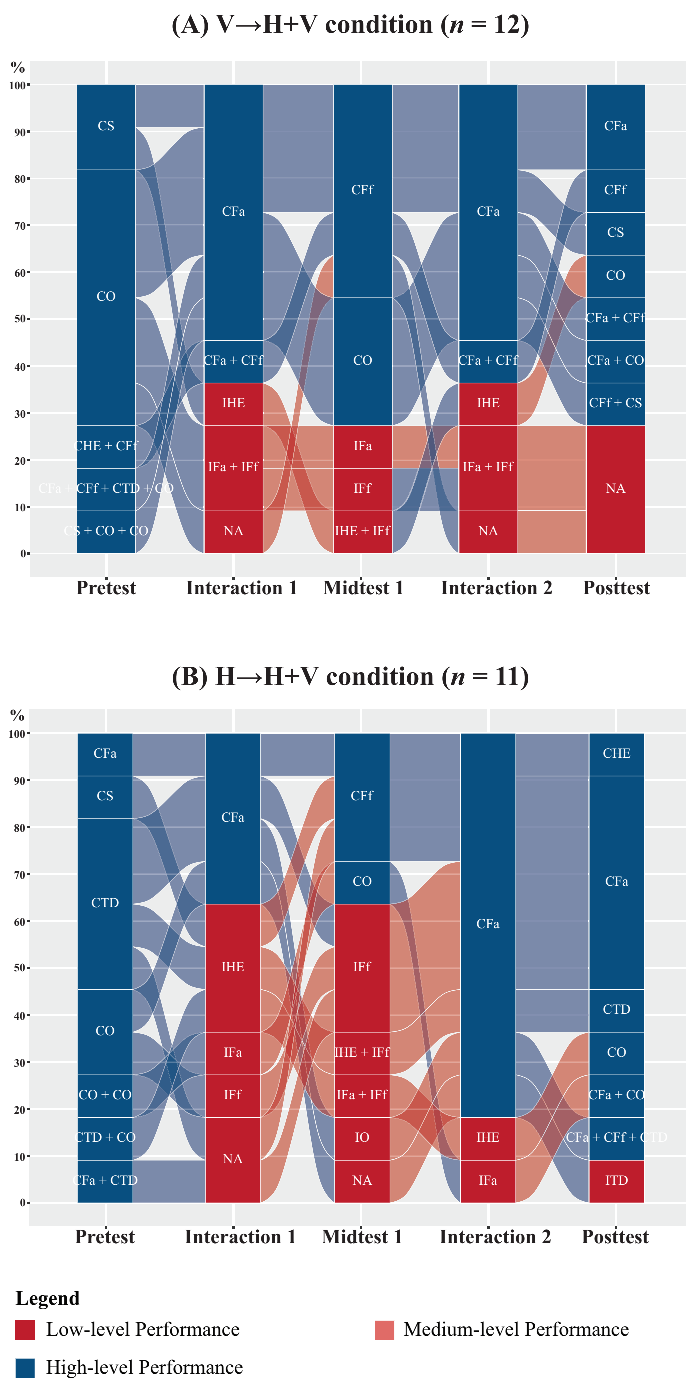

Figure 6.10. Language change in pretest high-level performers for answering CQ2.Legend: CHE: correct Hard or easy, CFa: correct Applied force, CFf: correct Friction force, CS: correct Speed, CTD: correct traveled distance, CO: correct Other, IHE: incorrect Hard or easy, IFa: incorrect Applied force, IFf: incorrect Friction force, IS: incorrect Speed,ITD: incorrect traveled distance, IO: incorrect Other, NA: no answer

6.7.4 Chapter summary

The first research question focused on identifying the explanations themes used for answering conceptual questions of friction (CQ1: role of the objects' weight in friction, and CQ2, role of the objects' size in friction). Results of the thematic analysis suggest six main explanations themes used in a correct and incorrect form. Explanations themes were categorized into Haptically-oriented and Visually-oriented themes. Figure 6.11 summarized the results of the thematic analysis.

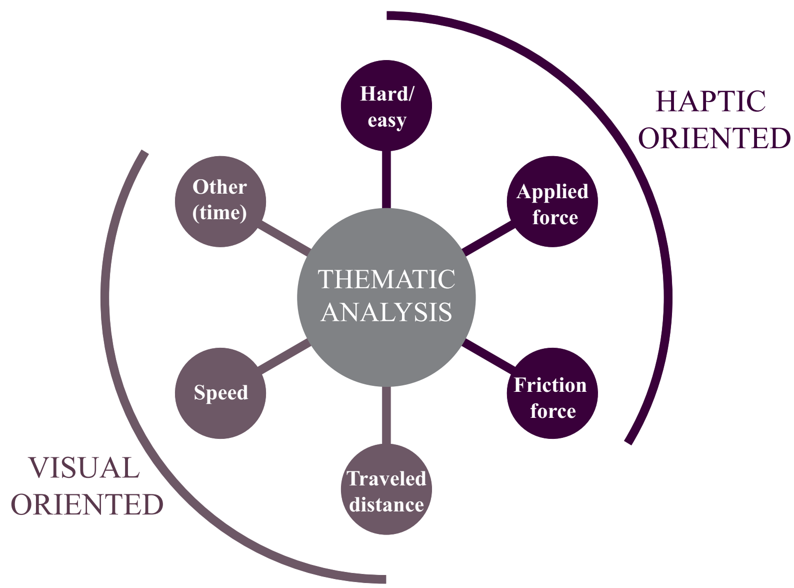

Figure 6.11. Explanations themes used for answering CQ1 and CQ2.

The second research question focused on the student's differences in explanations themes in the $V \rightarrow H+V$ condition vs. the $H \rightarrow H+V$ condition. We identified that participants in the $H \rightarrow H+V$ condition tended to have a higher increment of Haptically-oriented themes than participants in the $V \rightarrow H+V$ condition (e.g., the increment of correct Haptically-oriented themes from pretest to posttest in the $V \rightarrow H+V$ condition was by 12.8% and 46.24% in the $H \rightarrow H+V$ condition).

For answering CQ1, participants from both conditions provided a higher percentage of correct statements than incorrect statements. The interaction with the visuohaptic simulation helped students to consider the coefficient of friction of a smooth surface when they pushed the cubes. For instance, participants correctly indicated that Cube 2 (heavy) and Cube 1 (light) experienced different forces while being pushed on a smooth surface.

For answering CQ2, conditions had different results in the interaction phases with the VHS. Incorrect answers in the $V \rightarrow H+V$ condition were accompanied by the statements that size influenced the cubes' friction force. Hence, cubes with the same weight but different sizes experienced a different magnitude in the frictional force. Incorrect answers in the $H \rightarrow H+V$ occurred when participants could not identify that Cube 2 and Cube 3 had the same weight. Due to the differences in weight, cubes experienced different magnitude in the frictional force. Participants in the $H \rightarrow H+V$ condition benefited by activating the enhanced visual feedback by correcting their answer. Participants corrected their answers by identifying that cubes had the same weight. Participants in the $V \rightarrow H+V$ condition did not correct their answers during the second interaction with the VHS. The haptic feedback did not help participants in the $V \rightarrow H+V$ condition correct their answers. Posttest results of CQ2 suggested that participants in the $V \rightarrow H+V$ condition had a higher decrement of incorrect statements than participants in the $H \rightarrow H+V$ condition.

The third research question focused on the difference between low-level, medium-level, and high-level performers in the pretest at the different study stages. For answering CQ1, low-level performers from both conditions benefited by the interaction with the VHS. Improvement in participants' answers suggested that participants assumed that a smooth surface was frictionless in the pretest but did not explicitly state the answers' assumption. For answering CQ2, results suggested that an incorrect perception of the haptic feedback affected student's answers from all levels (i.e., low-level, medium-level, and high-level). For instance, if the participants felt that Cube 3 was heavier than Cube 2, the answer for CQ2 was incorrect during the interactions.

CHAPTER 7. STUDY RESULTS AND EMBODIED LEARNING

The goal of the studies presented in this dissertation was to identify the *value of adding the haptic feedback in a virtual environment for learning fiction concepts*. Table 7.1 summarizes the result of the studies presented in Chapter 5 (PMT vs VHS), and Chapter 6 (comparing sequenced approaches).

Table 7.1. What is the value of adding haptic feedback in a virtual environment?

Research question	CQ	Main results
Study 1. Hands-on tools: PMT vs. VHS		
Research question 1. Differences in student's explanations. PMT vs. VHS	CQ1	Students did not have problems for answering CQ1. Significant learning gains in the Visual V and Sequenced $H \rightarrow H+V$ conditions
	CQ2	Performance of PMT $<$VHS, Haptic H $>$PMT Group A $<$Group B Group A: Haptic H $>$PMT Group B: Visual V, Simultaneous H+V, and Sequenced $H \rightarrow H+V$
Research question 2. Influence of haptic and	CQ1	No major findings. Students did not have problems for answering CQ1

continued on next page

Table 7.1 continued from previous page

Research question	CQ	Main results
visual feedback in learning for students using VHS	CQ2	- Pretest vs. Posttest: Visual V performed better than Sequenced $H \rightarrow H+V$, and Simultaneous H+V - Experimentation: results suggested higher retention in the Sequenced $H \rightarrow H+V$ and Simultaneous H+V conditions
Study 2. Comparing sequenced approaches		
Research question 1. Explanation's themes for answering the conceptual questions	CQ1 and CQ2	Six themes, used in correct and incorrect forms. Haptically-oriented themes: Hard or easy, Applied force, Friction force. Visually-oriented themes: Speed, Traveled distance, and Other.
Research question 2. Students explanations $V \rightarrow H+V$ vs $H \rightarrow H+V$	CQ1	Use of themes Haptically-oriented $>$ Visually-oriented
	CQ2	- Use of themes Haptically-oriented $>$ Visually-oriented by 7.1% - Visually-oriented themes $H \rightarrow H+V > H \rightarrow H+V$ by 17.8% - Incorrect answers $H \rightarrow H+V > V \rightarrow H+V$

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Table 7.1 continued from previous page

Research question	CQ	Main results
Research question 3. Students explanations in per performance level (i.e., low, medium, high)	CQ1	- Use of themes in all the levels: Haptically-oriented > Visually-oriented - High-performance provided incorrect answers in the posttest.
	CQ2	-Incorrect answers $H \rightarrow H+V > V \rightarrow H+V$ - Participants that provided an incorrect answer in the $V \rightarrow H+V$ used size as a variable affecting friction - Participants that provided an incorrect answer in the $H \rightarrow H+V$ indicated that the weight of Cube 2 was different than the weight of Cube 3.

CHAPTER 8. DISCUSSION

For answering the guiding research question of the value of the visual and haptic feedback in virtual environments, we designed the learning tools presented in Chapter 4 and the studies presented in Chapter 5 and Chapter 6. The hands-on learning tools were a physical manipulative tool (PMT) and a visuohaptic simulation (VHS). The study's participants were undergraduate students of a technology program that answered friction conceptual questions before, during, and after using a hands-on learning tool. The conceptual questions focused on the role of the object's weight in friction (CQ1) and the role of the object's size in friction (CQ2).

The first study, presented in Chapter 5, aimed to answer two research questions related to the value of enhanced visual and haptic feedback in virtual environments. Data analysis of the first study used quantitative methods. Moreover, the first research question compared the differences in learning friction between interacting with a physical manipulative tool (PMT) and a visuohaptic simulation (VHS) used in different visual and haptic feedback configurations. Prior research suggested a positive impact in the comprehension of science concepts after interacting with PMT and VHS (e.g. Bivall et al., 2011; D'Angelo et al., 2014; de Jong et al., 2013; Höst et al., 2013; Yuksel et al., 2019; Zacharia & Olympiou, 2011). However, to the best of our knowledge, we are not aware of a study that compares the benefits of learning with PMT and VHS.

Learners interacted with the VHS in four different configurations, Haptic *H*, Visual *V*, Simultaneous *H*+*V*, and Sequenced $H \rightarrow H+V$. The VHS configurations were differentiated by the type of feedback received and the sequenced feedback (see Figure 5.4). The Haptic *H* and the first interaction with the VHS in the Sequenced $H \rightarrow H+V$ condition received haptic feedback and minimal visual feedback. The Visual *V* received enhanced visual feedback and kinesthetic feedback. The Simultaneous *H*+*V* and second interaction with the VHS of the Sequenced $H \rightarrow H+V$ condition received enhanced visual feedback and haptic feedback. The second research question focused on the benefits of the visual and haptic feedback for learning during the interaction phases with the learning tools between conditions (i.e., PMT, Haptic *H*, Visual *V*, Simultaneous *H*+*V*, and Sequenced $H \rightarrow H+V$).

The second study contributed to answering the guiding research question of the value of enhanced visual and haptic feedback in virtual environments by investigating students' conceptual explanations of friction. The data analysis of the students' explanations followed qualitative methods. Participants interacted with the VHS in two different sequenced approaches $H \rightarrow H+V$ and $V \rightarrow H+V$ (see Figure 6.2). During the first interaction, participants in the $V \rightarrow H+V$ condition received enhanced visual feedback + kinesthetic feedback. Participants in the second condition, $H \rightarrow H+V$, received haptic feedback and minimal visual cues. During the second interaction, both conditions received enhanced visual feedback + haptic feedback. Enhanced visual feedback included minimal visual cues + non-visible information of the forces (e.g., the numerical value of the magnitude of the force, direction, and location of the force). Haptic feedback included kinesthetic feedback and force feedback.

Results from our studies suggest that the use of visuohaptic simulations for learning purposes promoted the conceptual knowledge of forces acting on in-movement objects. These positive effects regarding the VHS in learning align with prior findings in other STEM domains (e.g. Han & Black, 2011; Höst et al., 2013; Magana & Balachandran, 2017; Magana et al., 2017, 2019), and with the findings reported in our prior studies in the statics domain in Walsh et al. (2020) and Yuksel et al. (2019).

The forces acting on in-movement objects are a hard concept for teaching and learning in STEM as reported by the Force Concept Inventory (FCI) by Hestenes et al. (1992), the Statics Concept Inventory (SCI) by Steif and Dantzler (2005), and other studies using different learning tools (e.g. Dollar & Steif, 2006; Steif & Dollar, 2003). The advantages of providing enhanced visual and haptic feedback support Brooks, Ming, Batter, and Kilpatrick (1990), Höst et al. (2013) and Rieber et al. (2004)'s studies that indicated that haptic and visual information improved the conceptual understanding by enhancing the visual information and providing haptic information of the active forces.

Moreover, the studies presented in this dissertation suggest that learners exposed to enhanced visual feedback and haptic feedback used two different mechanisms for improving friction conceptual knowledge. When enhanced visual feedback was activated, learners read the cubes' forces from the computer screen for correcting their answer or reinforce their correct knowledge. When haptic feedback was activated, learners inferred about the cubes' forces from the haptic feedback for correcting their answer or reinforce their correct knowledge. The majority of participants exposed to enhanced visual feedback improved their conceptual answers. The improvements due to haptic feedback depended on the learners' capacity to characterize its haptic perception, and explanations provided were more stable than the enhanced visual feedback improvements.

The enhanced visual feedback showed learners the characteristics of the forces acting on the cubes in the virtual environment (e.g., force magnitude and direction, Figure 4.4). Learners read the force's characteristics from the computer screen, which may have repaired fragmented ideas of friction and reinforced correct friction ideas. Improvements due to the exposure to enhanced visual feedback impacted the majority of learners. For instance, for answering CQ2, the Visual *V* condition improved the mean score from pretest to the experimentation phase by 42.55%, and the mean comparison suggested statistically significant differences at $t(46) = -6.47, p < 0.001$ with a strong effect size. Learners that provided an incorrect answer in the pretest might observe in the VHS that the values of the forces of Cube 2 and Cube 3 were the same. Results from the Simultaneous *H+V* also suggest increments in the mean score from pretest to the experimentation phase at $t(21) = -2.30, p = 0.032$ (see Table 5.10). As well, results from the second study, support the positive impact of the enhanced visual feedback in friction conceptual learning. Enhanced visual feedback promoted a decrement of incorrect answers and promoted the use of correct haptically-oriented explanations of friction concepts (see Table 6.6 and Table 6.7).

Haptic feedback provided learners with information about the forces by force and kinesthetic feedback. Learners perceived feedback and built their conceptual knowledge based on their interpretation. Compared with the enhanced visual feedback, the scores after exposure to the haptic feedback, had a smaller effect size and were significantly different at a higher *p*-values. For instance, comparison of the pretest and posttest scores of CQ2 were significantly different for the Visual *V* condition at $t(46) = -6.17, p < 0.001$, while the Haptic *H* condition had significant differences at $t(47) = -2.29, p = 0.03$. The value of the effect size of the Haptic *H* condition was weak to moderate, while the effect size of the

Visual V condition was strong. Furthermore, score comparisons between the first and second interaction with the VHS in the Sequenced $H \rightarrow H+V$ condition suggest significant improvements in the second interaction at $t(53) = -3.22, p = 0.02$ when the enhanced visual feedback was activated.

The lower impact in conceptual knowledge by the haptic feedback can be related to the learners' capacity to characterize its haptic perception. For instance, before interacting with the VHS, high performers in the $H \rightarrow H+V$ condition knew that cube's forces were not affected by the size. However, during the interaction, 65% of the high-performed answered CQ2 incorrectly (see Figure 6.10). In all the cases, learners indicated that the forces of Cube 2 and Cube 3 were different because the cubes' weight was different. Hence, high-performers in the $H \rightarrow H+V$ condition provided correct conceptual answers using false perceptual evidence. Learners correctly indicated that weight differences affected the friction force and the force required to push the cubes. However, the answer was considered incorrect because the weight of Cube 2 was the same as the weight of Cube 3.

Figure 6.10 also showed that 35% of the high-performers in the $V \rightarrow H+V$ condition decreased their performance level in the first interaction with the VHS. Participants indicated that the cube's forces' differences were due to their size (e.g., Cube 2 bigger than Cube 3). We hypothesized two possible explanations for the decrement in students' performance in the $V \rightarrow H+V$ condition. First, learners may have assumed that the smooth surface was frictionless, resulting in no differences in the cubes' forces. If students did not explicitly stated the assumption, scorers could no determine if the assumption was made or not. Once the friction coefficient was not negligible in the VHS, learners provided answers that incorrectly identified the object's size as a variable affecting the cubes' forces.

The second explanation is that students may have experienced the size-weight illusion (Murray et al., 1999; Wolf et al., 2018). The size-weight illusion could explain this finding by arguing that humans' perception of the object's weight could have been influenced by the object's size and the pressure and muscles involved in lifting the objects.

Hence, high-performers in the $V \rightarrow H+V$ condition provided incorrect conceptual answers using false perceptual evidence. Furthermore, changes in conceptual answers based on the environment's affordances support the notion that conceptual knowledge has intrinsic dynamism and is embedded in the context (Brown Hammer, 2013).

The illusion of the size-weight effect was found in the PMT condition. The size-weight illusion might explain the failure of the PMT for learning friction concepts. Even when students used the scale to determine the weight of Cube 2 and Cube 3 in the PMT condition, students may have experienced a false perception through the entire interaction with the learning tool. More research is needed to test the hypothesis that students (a) carry incorrect perceptions through the entire learning activity, (b) identify which factor influenced more the students' perceptions, and (c) find a way to overcome this perceptual problem.

8.1 Increments in haptically-oriented themes

The analysis of explanation themes' suggest that learners from both conditions increased the use of haptically-oriented themes after the pretest (see Table 6.6 and Table 6.7). Haptically-oriented themes included answers that explained the friction concepts in terms of applied force, friction force, and how hard or easy it was to push the cubes. Hence, students moved from explanations using macroscropic variables (e.g., visually-oriented themes) to the use of invisible concepts to explain scientific phenomena. The change towards haptically-oriented themes, instead of symbols or physical entities, suggests knowledge growth (Vosniadou, 2013b), and the differentiation between novices and experts (Chi, Feltovich, & Glaser, 1981), (e.g., focusing on the forces acting on the objects instead of how fast an object moves after being pushed).

The $H \rightarrow H+V$ condition had a higher increment in haptically-oriented themes than the $V \rightarrow H+V$ condition. The increment from pretest to posttest of the haptically-oriented themes for answering CQ1 was by 12.8% in the $V \rightarrow H+V$ condition and by 46.3% in the $H \rightarrow H+V$ condition (see Table 6.6). For CQ2, the increments were by 50% and 54%, respectively.

Once the students changed their conceptual answers from visually-oriented to haptically-oriented themes, students in the $H \rightarrow H + V$ condition tended to maintain the explanation themes in a higher percentage than the students in the $V \rightarrow H + V$ condition. For instance, the percentage drop of haptically-oriented themes from the second interaction with the VHS to the posttest for answering CQ1 in the $V \rightarrow H + V$ condition was 25%, while the $H \rightarrow H + V$ condition decreased was by 1.5%. For CQ2, the decrements were 15% and 11.4%, respectively.

Stability in the students' explanations was positive suggesting that learners considered the same variables for answering the conceptual questions in different environments. Stability differences may be attributed to the process of gathering evidence to answer the conceptual questions. In the case of learners exposed to the enhanced visual feedback, results suggested that learners understood the visual information and used it for answering the conceptual questions. Learners exposed to the haptic feedback built the forces' abstract information based on haptic information (e.g., force magnitude and force direction). Results suggest that experiencing the haptic feedback with minimal visual cues increased the sense of immersion in learners (Fritz & Barner, 1999), and promoted the students' reasoning for connecting perception with content knowledge.

Another example of this explanation occurred in the midtest results. The correct Friction force theme (CFf) increased from pretest to midtest in both sequenced conditions. Learners in the $V \rightarrow H + V$ condition identified the friction force in the visual cues. Learners in the $H \rightarrow H + V$ condition connected the friction concepts with the haptic feedback (e.g., by connecting that the harder they pushed, the higher the friction force). Prior studies support this finding. For instance, Abrahamson and Lindgren (2014) indicated that the body has everything to do with learning, including abstract concepts (e.g., friction). Han and Black (2011) found that rooted bodily experiences can be a cognitive ground for reaching the conceptual level of comprehension. (Schönborn, Bivall, & Tibell, 2011) found that students in the haptic condition produced better positions for the molecules and proteins in a biomolecular model than students in the non-haptic condition.

8.2 Comparing order for presenting visual and haptic feedback

We found differences in students' answers by conditions of haptic and enhanced visual feedback. When learners received simultaneous haptic feedback and enhanced visual feedback (H+V), results suggest that enhanced visual feedback overpowered the haptic feedback. When learners interacted with the VHS using the Sequenced $H \rightarrow H+V$ approach, enhanced visual feedback supplemented the learners embodied experience.

Comparing Visual *V* and Simultaneous *H+V* conditions, results do not suggest a clear advantage of the haptic feedback. First, the post-hoc analysis of the posttest scores and experimentation scores suggest no statistically significant differences between the Visual *V* and Simultaneous *H+V* conditions (e.g., both conditions belong to *Group B*). Secondly, learning gains of the Visual *V* condition were statistically significantly different in CQ1 and CQ2, while the Simultaneous *H+V* only obtained significant differences in CQ2. However, learners in the Simultaneous *H+V* condition had a higher mean score in pretest and posttest than the Visual *V* condition. The mean score of the experimentation phase of the conditions was similar (difference by 0.12% in favor of Visual *V* condition). When haptic feedback was activated after the enhanced visual feedback (e.g., second interaction of the $V \rightarrow H+V$ condition), learners did not change their incorrect answers. Hence, learners might only use visual information for providing conceptual answers, and haptic feedback was not valuable for learners after observing the enhanced visual information.

Prior studies have found that when presented together, visual information may dominate the haptic information (e.g., Magana et al., 2019). One of the reasons why visual information often dominates the kinesthetic information is that the visual sense is easier to perceive and comprehend than the tactile information (Fritz & Barner, 1999). Visual information can enhance performance during the action phases (e.g., interaction phases), but the performance gains may decrease in the retention tests (Sigrist, Rauter, Riener, & Wolf, 2013).

Haptic feedback and minimal visual feedback promoted the reasoning of the forces acting on in-movement objects. However, the perception of the cubes' characteristics affected the conceptual answers (e.g., indicating that Cube 2 and Cube 3 experienced different frictional force because they had different weights). By activating the enhanced visual feedback in the second interaction in the $H \rightarrow H+V$ condition, learners corrected their knowledge and analyzed the visual information (e.g., answers categorized as low-performance in the interaction phase changed to high performance in the second interaction, see Figure 6.10).

8.3 Evidence of embodied learning

The results from our studies suggest that adding haptic feedback to a virtual manipulative environment, in the form of visuohaptic simulation, is beneficial for learning friction concepts. Learners increased the conceptual knowledge of friction concepts due to a good orchestration between haptic and visual feedback and the learning guidance in the VHS's learning experience.

Embodied learning activities provided learners the possibility to experience abstract concepts and contextualize the knowledge with real-life experiences. Furthermore, Abrahamson and Lindgren (2014) suggested that embodied design is committed with the hypothesis that content knowledge from science and mathematics is not abstract – content knowledge in science and mathematics "is deeply somatic, kinesthetic and imagistic" (Abrahamson & Lindgren, 2014, p.11). Results from our studies support this non-abstract view in science and mathematics for embodied learning design. Through enhanced visual feedback, the virtual environment crossed the boundaries of real-life environments and allowed learners to observe invisible phenomena. The haptic feedback rooted the learning experience to the body to promote the learners' consideration of prior experiences and prior knowledge in constructing new experiences linked with content knowledge of forces. Learners increased the conceptual knowledge of friction concepts due to a good orchestration between haptic and visual feedback in the VHS's learning experience.

The good orchestration between haptic and visual feedback may be due to the consideration and integration of embodied learning guidelines provided by Abrahamson and Lindgren (2014), the considerations of the embodied learning taxonomy by Johnson-Glenberg (2018), the affordances of the physical manipulatives and virtual manipulatives for learning sciences by Zacharia and Michael (2016), and the considerations of the differences between haptic and visual perception (Fritz & Barner, 1999). Hence, successful, embodied learning design requires considering the learners' characteristics, technology, materials, and content knowledge.

8.3.1 Evidence of embodied learning

Our results suggest that cognition is situated and that the environment is part of the cognitive system (M. Wilson, 2002). None of the learners from the second study ($n = 49$) provided the same answer in all of the stages of the study (i.e., pretest, interaction, midtest, and posttest). Moreover, the pretest analysis of explanation themes showed that learners used multiple explanations themes to answer the questions. We hypothesize that conceptual questions asked to learners in the pretest promoted the use of mental imagery for recalling prior experiences stored in the long-term memory (Brookes & Etkina, 2007; S. Brown & Salter, 2010; Cattaneo & Silvanto, 2015; Kosslyn, 1994; Rinck & Denis, 2004). For instance, a learner may have had imagined the cubes moving faster on a surface, while another learner may have focused on the cubes' distance traveled.

During the interaction phases, body actions worked as the perceptual input for answering the questions. For learners that experienced haptic feedback, the input was rooted in the body's actions. For learners who experienced enhanced visual feedback, the input was rooted in the cubes' forces acting' visual perception. Haptic and enhanced visual feedback promoted visual imagery and spatial imagery for a significant link between body experience and content knowledge (Kosslyn, 1994; Rieber et al., 2004). To answer the midtest and posttest, learners used the information stored in the short-term memory from the VHS's learning experience.

After the pretest, learners increased the haptically-oriented explanations and decreased visually-oriented explanations. Haptically-oriented explanations referred to the human's actions needed to make the cubes move. Haptically-oriented explanations included the term force (e.g., applied force and friction force). Visually-oriented explanations referred to the motion of the cube as a consequence of human action. Visually-oriented themes included the explanations that used the terms speed, traveled distance, and others, such as acceleration and time. The increment of haptically-oriented themes provided evidence that the VHS's learning experience promoted the knowledge of the abstract concept of friction, as suggested by Höst et al. (2013). Results are aligned with Chi et al. (1981), Härtig et al. (2020), and Vosniadou (2013b)'s studies that suggested providing explanations of scientific concepts using invisible concepts is evidence of knowledge growth.

The manipulation of the virtual environment through the haptic device provided a sense of immersion and presence in the learning active (Johnson-Glenberg, 2018), and an active transfer of information in a two-way path (Fritz & Barner, 1999). First, learners manipulated the haptic device to modify the virtual environment, and the virtual environment provided information to the forces acting on the cubes. For instance, a learner increased the force required to push the cubes based on the weight simulated in the virtual environment.

The experimentation and observation worksheet guided learners to perform specific actions to acquire knowledge in friction concepts. Learners unfold the conceptual information through body actions (Abrahamson & Lindgren, 2014). The VHS had perceptual affordances that facilitate the comprehension of the friction concepts and the performance of actions to interact with the virtual environment. The enhanced visual feedback (e.g., force magnitude and direction) provided easy to understand information by the learners (Fritz & Barner, 1999). Learners that interacted with the VHS with haptic feedback, and minimal visual cues, had problems identifying that Cube 2 and Cube 3 had the same weight. The result suggests that haptic feedback for the recognition of the cube's weight is a hidden affordance. Furthermore, the PMT condition obtained a higher percentage of incorrect answers in the recognition phase, suggesting that the learners' haptic feedback is hard to characterize.

Walsh et al. (2017) suggested using a method of recognition for the object's weight, which does not require active touch (e.g., holding the object in the palm). In this study, learners from the PMT condition used two methods for recognizing that Cube 2 and Cube 3 had the same weight, the palm-method and the bag-method (Figure 4.10). 37.14% of the learners using the palm-method incorrectly indicated that Cube 2 and Cube 3's weight was different—the percentage decrease by 8.7% using the bag-method. Furthermore, the Haptic *H* condition that used the haptic device for recognizing the cube's weight provided a 14.58% of incorrect answers. We conclude that recognizing the object's weight was hard for the learners, whether there was an element of active touch or passive touch.

The size-weight illusion may explain the problem of recognizing the weight of objects with different sizes (Murray et al., 1999; Wolf et al., 2018). The size-weight illusion explained that humans expect larger objects to be heavier than smaller objects and that perception of weight depends on the pressure and muscles involved (Wolf et al., 2018). We found both effects in our results (e.g., Cube 2, larger, is heavier than Cube 3, and that Cube 3, denser, was heavier than Cube 2). More research is needed to confirm how learners' interpretations of the haptic feedback are affected by the size-weight illusion.

CHAPTER 9. IMPLICATIONS OF THE STUDY

This study investigated the use of two hands-on tools for learning friction in a laboratory session of an introductory physics course. The hands-on learning tools were a physical manipulative tool (PMT) and a visuohaptic simulation (VHS). The study's results suggested that (a) our PMT did not promote conceptual knowledge in friction, (b) VHS had a positive impact on students' conceptual knowledge of friction, (c) learners exposed to haptic and visual feedback used a different mechanism for improving conceptual knowledge. With enhanced visual feedback, learners read the information provided by the computer screen, while with haptic feedback, learners inferred about the cubes' forces characteristics, and (d) learners in the sequenced approach condition of $H \rightarrow H+V$ obtained the benefits of the haptic and visual feedback. This study also identified that (i) the findings of the studies were possible through quantitative and qualitative methods of data analysis, and (ii) including the analysis of students' answers in the experimentation phases with the hands-on tools allowed identifying the challenges learners faced when perceiving visual and haptic feedback.

In the following section, we now discuss the implications for teaching and learning (section 9.1), implications for learning design (section 9.2), and implications research in embodied learning (section 9.3).

9.1 Implications for teaching and learning

Research in teaching science concepts linked the quality of the education with active learning experiences that enhance the comprehension of science concepts (Al Azawi et al., 2019; Cimer, 2007; National Research Council, 2012). The study's results suggest a positive impact of the VHS in laboratory settings in the comprehension of friction concepts.

The VHS complemented the learning of friction previously taught during the lecture. The lecture and the laboratory session provided different learning experiences to students. The lecture exposed learners to conceptual, representational, and procedural knowledge of friction. However, the instruction was not enough for learners to comprehend friction. Pretest results from our studies showed that students held incorrect conceptions of the role of the object's weight and the role of the object's size in friction after instruction (e.g. Dollar & Steif, 2005, 2006).

The VHS provided a learning environment that linked the conceptual learning of friction with real-life experiences (Al Azawi et al., 2019; Höst et al., 2013; Marshall & Young, 2006; Minstrell, 1984; Winn et al., 2006). The connection between the learning experience and real-life experiences were also promoted by the pedagogical approach of the three phases (White & Gunstone, 1992). The three-phases approach guided the learning experience and promoted the reasoning of friction concepts before, during, and after the interaction with the VHS. In the first phase, learners predicted the outcome of sliding cubes with different characteristics on a surface. Learners used prior experiences (e.g., sliding objects in real-life) and prior knowledge (e.g., lecture content) for creating the predictions. Learners used the VHS to test their predictions and observed the friction phenomena. The experimentation worksheet guided the observation of the friction phenomena with the VHS. Steps of the experimentation worksheet guided learners to perform meaningful interactions to test their predictions and construct knowledge in friction. The confirmation worksheet helped learners to reflect on their prior knowledge and the learning experience with the VHS.

The haptic and visual feedback configuration that enhanced the learning experience was the sequenced $H \rightarrow H+V$ approach. Learners in the $H \rightarrow H+V$ condition benefited from two interactions with the VHS. In the first interaction, learners received haptic feedback and minimal visual cues while pushing the cubes across the surface. The haptic feedback increased the sense of immersion and presence in the learning activity. However, the haptic feedback was not easy to interpret by the learners. Results suggested that incorrect answers in the experimentation worksheet occurred when learners did not correctly identify the cube's weight (e.g., learners that identified Cube 3 heavier than Cube 2).

During the second interaction, learners received enhanced visual cues. Enhanced visual cues showed learners the force acting on the cubes and its characteristics (e.g., magnitude and direction). Learners that incorrectly characterize the cube's weight in the first interaction with the VHS tended to correct their answers with the enhanced visual feedback. Finally, posttest results suggest that learners retained their correct conceptual answers after using the VHS when receiving haptic and enhanced visual feedback.

Regarding the method for evaluating the VHS experiences, results suggest that standard tests (e.g., multiple-choice) do not fully assess aspects of the embodied experience (Johnson-Glenberg et al., 2014). Open-ended questions, interviews, and discussions may require learners to build their knowledge based on the embodied experience and state the assumptions made for answering the conceptual questions (e.g., frictionless assumption). For instance, in the first study, the Visual V condition outperformed the Sequenced $H \rightarrow H+V$ and Simultaneous H+V conditions (e.g., higher learning gains). In the second study, the qualitative analysis of students' explanations found an increment of the haptically-oriented themes after the first interaction with the VHS in the $H \rightarrow H+V$ condition. Increments in the haptically-oriented themes are related to learning growth (Chi et al., 1981; Vosniadou, 2013b). Furthermore, analysis of the experimentation answers, instead of a pre-post comparison, provided a better sense of the student's challenges while learning friction with a VHS. Finally, the PMT use for learning friction concepts did not provide a learning advantage to students. Students showed incorrect conceptual knowledge and difficulties in the perception of the tactile feedback during the learning experience. We do not recommend implementing the PMT in the learning context before re-designing the tool based on our findings.

9.2 Implications for learning design

The design of visuohaptic simulations and physical manipulative tools must consider the physical and virtual manipulatives' affordances and the use of the sense of touch and vision for learning. In this study, we evaluated the conditions of the first study according to the affordances provided by Zacharia and Michael (2016) and Fritz and Barner (1999). Depending on the studies' results, we classified the condition's impact on the affordance into four categories: high, medium, low, and none value categories. High impact indicates that results suggested a positive and high impact of the condition in the affordance. The low category indicates that results suggest a low impact of the condition in the affordance. Figure 9.1 summarized the results. High-impact level are shown with three green circles. Medium-impact level with two orange circles, and low-impact level with one red circle. No impact level had no circles.

Affordance	**PMT**	**H**	**V**	**H+V**	**H→H+V**
1. Conducting experiments	●●	●●	●●	●●	●●●
2. Manipulations	●●	●	●	●●	●●
3. Observation	●	●●	●●	●●●	●●●
4. Participation in science	●●●	●●●	●●●	●●●	●●●
5. Multisensory feedback	●	●	●	●●●	●●●
6. Psychomotor skills					
7. Use body for learning	●	●	●	●●	●●
8. Modify variables					
9. Multiple linked representations			●●●	●●●	●●●
10. Minimized errors		●●●	●●●	●●●	●●●
11. Real-time feedback	●●	●●	●●	●●●	●●●
12. Observable outcomes	●	●	●●	●●●	●●●
13. Safe environment	●●●	●●●	●●●	●●●	●●●

Figure 9.1. Evaluation of the affordances for learning of each condition.

The affordances described in Figure 9.1 are elaborated below for each of the interventions of this study:

Affordance 1. Exposed students to experimentation skills (e.g., testing hypothesis).

- PMT: Medium-impact level. Learners experienced the concept of the role of the object's size in friction using the PMT. Learners tested the hypothesis stated during the pretest using the PMT. There was no limitation of trials for testing. The PMT provided the same feedback in all the trial.

- Haptic H, Visual V, Simultaneous $H+V$: Medium-impact level. Learners experienced the concept of the role of the object's size in friction using the VHS. Learners tested the hypothesis stated during the pretest using the VHS. There was no limitation of trials for testing. The VHS provided the same feedback in all the trials.

- Sequenced $H \rightarrow H+V$: High-impact level. Learners experienced the concept of the role of the object's size in friction using the VHS. Learners tested the hypothesis stated during the pretest using the VHS. There was no limitation of trials for testing, but the condition required at least two trials. Learners tested the hypothesis stated during the pretest using the VHS first with haptic feedback and secondly with haptic and enhanced visual feedback.

Affordance 2. Allowed learners the manipulation of the learning materials.

- PMT: Medium-impact level. There was no limitation for manipulating the learning materials (e.g., learners grab and move the cubes freely). Recognition phase results suggested that learners had problems identifying the similarity in weight between the cubes (e.g., experienced the size-weight illusion).

- Haptic H: Low-impact level. Learners manipulated the cubes using the haptic device. Exploration of the materials and cube's characteristics were limited to its weight only by haptic feedback. Recognition phase results suggested that learners had problems identifying the similarity in weight between the cubes (e.g., experienced the size-weight illusion).

- Visual V: Low-impact level. Learners manipulated the cubes using the haptic device. Exploration of the materials and cube's characteristics were limited to its weight by enhanced visual feedback only.
- Simultaneous H+V, and Sequenced $H \rightarrow H+V$: Medium-impact level. Learners manipulated the cubes using the haptic device. Exploring the materials and cube's characteristics was limited to its weight only by enhanced visual feedback and haptic feedback. Learners could not feel the characteristics of the material.

Affordance 3. Allowed learners the direct observation of the phenomena.

- PMT: Low-impact level. Learners inferred the friction phenomenon. Learners felt the cubes and saw the cube's movement. Comparison of the learning gains and pretest vs. experimentation scores suggested no statistically significant difference.
- Haptic H: Medium-impact level. Learners inferred the friction phenomenon. Learners felt the cubes and saw the cube's movement. A comparison of the pretest vs. experimentation scores suggested a statistically significant difference.
- Visual V: Medium-impact level. Learners observed the friction phenomenon. Learners saw all the forces acting on the cubes while being pushed or slid. Learning gains changes in the percentage of correct answer per question, recognition phase, and experimentation scores suggested a positive result of the Visual V condition. Learners did not feel the cube's forces.
- Simultaneous H+V, and Sequenced $H \rightarrow H+V$: High-impact level. Learners observed and felt the friction force. Speed, acceleration was only observed. The traveled distance was observed and felt. Learners saw all the forces acting on the cubes while being pushed or slid. Learning gains changes in the percentage of correct answer per question, recognition phase, and experimentation scores suggested a positive result of the Simultaneous Simultaneous H+V, and Sequenced $H \rightarrow H+V$.

Affordance 4. Promoted the participation in science instruction.

- All condition: High-impact level. PMT and VHS are considered an active learning tool. is considered an active learning tool.

Affordance 5. Allowed learners to have multiple sensory feedback.

- PMT: Low-impact level. Despite learners having multiple sensory feedback, results suggested that multi-sensory feedback was not beneficial for learning the friction concepts. For instance, the recognition phase suggested that learners experienced the size-weight illusion.

- Haptic H: Low-impact level. Results suggested that learners obtained the information mainly from the haptic feedback (e.g., sense of touch). For instance, the recognition phase suggested that learners experienced the size-weight illusion.

- Visual V: Low-impact level. Results suggested that learners obtained the information mainly from the enhanced visual feedback (e.g., vision sense).

- Simultaneous H+V: High-impact level. The VHS allows learners to feel the friction force and see the friction force's direction and magnitude. Experimentation scores increased from pretest to the experimentation phase.

- Sequenced $H \rightarrow H+V$: High-impact level. The VHS allows learners to feel the friction force and see the friction force's direction and magnitude. Experimentation scores increased from pretest to the experimentation phase. Learners experienced the haptic and the enhanced visual feedback at different interactions with the VHS.

Affordance 6. Promoted the development of psychomotor skills.

- All conditions: Not applicable for this study. Psychomotor skills were not evaluated.

Affordance 7. Allowed learners to use the body for learning.

- PMT: Low-impact level. The PMT promoted the upper body's use for interaction with the learning material, but there was no movement limitation. However not all movements were goal-direct, increasing the difficulty with the learning material.

- Haptic H: Low-impact level. The VHS limited the interaction to the upper body. Only by hand, learners manipulated the virtual environment; however, no enhanced visual feedback was provided, limiting the acquisition of information to the sense of touch.

- Visual V: Low-impact level. The VHS limited the interaction to the upper body. Only by hand, learners manipulated the virtual environment; however, no haptic feedback was provided, limiting the acquisition of information to the kinesthetic and visual feedback.

- Simultaneous H+V: Medium-impact level. The VHS limited the interaction to the upper body. Only by hand, learners manipulated the virtual environment. The VHS promoted the use of the sense of touch, and the sense of sight was used for learning.

- Sequenced $H \rightarrow H+V$: Medium-impact level. The VHS limited the interaction to the upper body. Only by hand, learners manipulated the virtual environment. The VHS promoted the use of the sense of touch, and the sense of sight was used for learning.

Affordance 8. Allowed the modification of variables that are hard to modify in real life.

- All conditions: None. Variables were fixed in the experiment.

Affordance 9. Allowed the use of multiple linked representations.

- PMT, and Haptic H: None. No representations of the phenomenon were provided to the learners.

- Visual V, Simultaneous H+V,Sequenced $H \rightarrow H+V$: High-impact level. Through the enhanced visual cues, learners observed information not available in the real world. Results suggested a positive influence in the learning of the enhanced visual feedback

Affordance 10. Errors were minimized in the environment to improve the comprehension of the concept.

- PMT: None. The scientific phenomenon was presented as it is. PMT does not limit the presence of error (e.g., rotation of the cubes while being pushed).

- Haptic H, Visual V, Simultaneous H+V,Sequenced $H \rightarrow H+V$: High-impact level. The VHS constrained the rotation of the cubes and did not provide information about the cube's material. Walsh et al. (2017), in a prior study, found that the cubes' rotation prevented learners from focusing on the differences between cubes while sliding. Determining the characteristics of the materials of the cubes was also another distraction for learning

Affordance 11. Provided real-time feedback.

- PMT: Medium-impact level. Haptic and visual feedback of the PMT was provided in real-time. No enhanced visual information.

- Haptic H: Medium-impact level. There was no enhanced visual feedback. The haptic feedback of the VHS was provided in real-time.

- Visual V: Medium-impact level. There was no haptic feedback. The enhanced visual feedback of the VHS was provided in real-time.

- Simultaneous H+V, and Sequenced $H \rightarrow H+V$: High-impact level. Haptic and visual feedback of the VHS was provided in real-time.

Affordance 12. Provided observable outcomes, no matter the complexity of the concepts.

- PMT: Low-impact level. The learners inferred outcomes (e.g., the higher the friction force, the lower the speed). Experimentation scores and learning gains were low and not statistically significantly different.

- Haptic H: Low-impact level. The learners inferred outcomes (e.g., the higher the friction force, the lower the speed). Scores of the Haptic H condition were the lower of all VHS conditions.

- Visual V: Medium-impact level. Enhanced visual feedback showed the value of the forces. Experimentation scores and learning gains were statistically significantly different.

- Simultaneous H+V, and Sequenced $H \rightarrow H+V$: High-impact level. Force feedback allowed learners to feel the forces. Enhanced visual feedback showed the value of the forces. Experimentation scores and learning gains were statistically significantly different.

Affordance 13. Experiments were performed in a safe environment for the students.

- All conditions: High. The PMT and the VHS do not represent a risk for the learners.

9.2.1 Improvements for the hands-on tools

The studies' results and the researchers' experimentation notes during the data collection suggested hindrances of the learning experiences afforded by the hands-on tools that need to be considered in future embodied learning designs. For the learning experience with the PMT, we identified two main hindrances. First, the PMT did not provide information about the forces acting on cubes in stationary and in-movement conditions. Second, learners required more scaffolding to guide the exploration of the cube's properties through tactile feedback.

In the PMT condition, learners did no have visual information about the forces acting on the cubes. All information on the forces relied on tactile perception. The tactile perception may be affected by the size-weight illusion (Murray et al., 1999; Wolf et al., 2018), or by the difficulty of identifying the force required to push objects. More research is needed to identify the problems faced by learners while lifting and pushing the objects. The studies' results suggest a positive impact in students' conceptual learning by showing the forces' abstract information to students (e.g., enhanced visual feedback in the VHS).

During the stages of recognizing the cubes' characteristics, learners required a scaffolding that guided them to differentiate between density and weight. Our studies' scaffolding was not enough to help learners correctly identify the cube's weight. Confusion of the density and weight might be carried through the learning activity. One available technology for overcoming the hindrances of not showing abstract information is Augmented reality. Combining Augmented reality with the PMT may enhance the learning experience by providing haptic and enhanced visual information.

For the visuohaptic simulation, we identified that learners required more scaffolding to take advantage of all the enhanced visual cues' information. For instance, most participants may not recognize the differences between the static and kinetic friction forces. Also, even when the force's magnitude was available, learners tended not to include the force's magnitude's numerical value in their answers. The results may suggest that learners focused just on the friction force and did not take advantage of other visual information for constructing their answers.

Adding more explicit feedback to the visuohaptic simulations may improve learning (e.g., a virtual tutor, a pop-out showing information). Rieber et al. (2004) found that students who had exposure to explicit feedback in the form of graphics while interacting with a simulation had higher learning gains in the posttest than students who did not have access to the explicit feedback.

Another improvement for the VHS is to include more scenarios to teach friction. For example, Besson et al. (2007) proposed teaching infriction using vertical scenarios to increase the knowledge about the role of the normal force and the role of the weight of the object in the in-movement objects. Other scenarios can include incline planes that require the decomposition of forces. By including more scenarios, instructors can observe changes in student's answers based on the context. If the core concepts of friction change based on the context, instructors may guide learners to consider core concepts in their answers and improve scientific knowledge.

CHAPTER 10. CONCLUSIONS, LIMITATIONS AND FUTURE WORK

The goal of this work was to investigate the value of haptic feedback for learning friction concepts. For that, the first study focused on comparing two hands-on tools for learning friction, a physical manipulative tool (PMT) and a visuohaptic simulation (VHS) with different configurations of haptic and visual feedback. The second study focused on the explanation themes students used to answer the conceptual questions throughout the study's different stages (i.e., pretest, interaction 1, midtest, interaction 2, and posttest). Results from our studies allow us to make eight conclusions.

The first conclusion of this work is that hands-on tools had a different impact on students' conceptual learning of friction concepts than the VHS. The PMT did not promote a correct conceptual knowledge of friction concepts, while the VHS promoted a correct conceptual knowledge of friction concepts. All VHS conditions outperformed the PMT condition in answering the friction conceptual knowledge. Furthermore, comparing the PMT and Haptic *H* conditions, which provided similar visual and haptic feedback but in two different environments (i.e., physical or virtual), the use of the VHS resulted in a higher positive impact on learning friction than the PMT (e.g., higher increments in the mean from pretest to posttest).

The second conclusion is that visual and haptic feedback promoted conceptual knowledge through two different mechanisms. Enhanced visual feedback promoted the conceptual knowledge of friction by correcting fragmented ideas and reinforcing correct ideas through visual information meaningful for learners. The haptic feedback promoted conceptual knowledge by providing an embodied learning experience that contributed to the comprehension of forces.

The third conclusion is that the concept of the role of the object's size in friction is counter-intuitive for learners. After a formal lecture and the laboratory session with the hands-on tools, learners provided incorrect explanations about the forces acting on cubes with the same weight and a different size. Moreover, learners faced challenges associated with the size-weight illusion while learning about the role of the object's size in friction.

The fourth conclusion relates to the importance of a pedagogical approach to promote the formulating hypotheses before experiencing the embodied environment. Formulating hypotheses allowed learners to consider their prior knowledge and prior experiences to construct scientific knowledge. The pedagogical approach must guide learners meaningfully throughout the steps of the interactions with the hands-on tool to construct the knowledge accurately.

The fifth conclusion expands on the importance of the experimentation worksheet. Students' answers during the experimentation with the learning tools must be considered in analyzing the value of the tactile feedback for conceptual learning. Student's answers provide clues about learners' perceptions, challenges faced by learners, and affordances of the tools that helped learners construct knowledge.

The sixth conclusion is that using multiple-choice and selecting one question assessments does not capture the haptic feedback value in learning environments. Furthermore, only using quantitative methods of data analysis is not recommended for analyzing learning in embodied environments. We recommended using qualitative methods of analysis and questions that require learners to construct their answers (e.g., open-ended questions, representations) in the form of explanations.

Regarding the use of the haptic feedback for learning, we conclude that linking visual information to haptic feedback is required to understand forces (seventh conclusion). Learners faced challenges during the interpretation of haptic feedback that might lead to incorrect conceptions of the characteristics of the forces acting on the stationary and in-movement objects, when provided alone.

Finally, the eighth conclusion is that virtual environments can provide multiple information at the same time. Educational designers should be careful in using them. Human's capacities for process visual information for learning are limited. Furthermore, experiences must be guided with a pedagogical approach to obtain positive results in learning.

10.1 Limitations

The study has six main limitations. First, the study focused on conceptual learning promoted by the physical manipulative tool and the visuohaptic simulations. Other forms of knowledge, such as representations and procedural knowledge, were not explored in the study. Secondly, the concepts investigated were related to friction but, depending on the program, can be part of statics or dynamics courses. Physics programs combine statics and dynamics courses while engineering programs separate the content in different courses. For instance, students in a physics program learned about friction, acceleration, and traveled distance in a single course. Engineering students tend to learn about the forces acting on a stationary object in one course (e.g., friction and applied force) and forces acting on an in-movement object in the following course (e.g., acceleration and travel distance). Future research may investigate which form is better for construction physic's conceptual knowledge in students.

The third limitation is that the studies were performed on learners that meet specific characteristics (e.g., undergraduate students in a technology o engineering program). For extending the conclusions and findings, studies with participants with other characteristics are needed (e.g., high-school students, non-engineering students). The fourth limitation is that other abilities related to learners' performance in virtual environments (e.g., spatial abilities) were not investigated in the study. The fifth limitation is that we did not consider time on task as a variable of learning. Students in the $H \rightarrow H+V$ may have used the visuohaptic simulation for a longer time than the other conditions. Findings of the $H \rightarrow H+V$ might have been enhanced by the time on task.

The sixth limitation is that cognitive offloading was not investigated in the study. We hypothesized that the congruence of gestures benefited the visuohaptic simulation's embodiment and the physical manipulative tool. In this study, we did not consider gestures as a way of conceptual communication knowledge.

10.2 Future work

Based on the study results, conclusion, and limitations, we provide the following research question for future studies.

- What forms of interaction with hands-on tools result in correct scientific knowledge of statics concepts?
- What is the effect of the hands-on tools (visuohaptic simulation and the physical manipulative tool) in the gestures used by the participant to answer the conceptual questions of friction?
- What is the effect of the hands-on tools (visuohaptic simulation and the physical manipulative tool) in the relationship of explanation-gestures used by the participant to answer the conceptual questions of friction?
- What is the effect of the hands-on tools (visuohaptic simulation and the physical manipulative tool) in the participants' friction procedural knowledge?
- What is the effect of the hands-on tools (visuohaptic simulation and the physical manipulative tool) in the participants' friction representational knowledge?

This investigation focused on investigating the role of the visual and haptic feedback in learning friction concepts. The investigation was grounded in theories of embodied cognition and framed in the use of a simulation and the interaction with the haptic device. Results from our studies suggested a positive impact of adding haptic feedback in virtual environments, along with a detailed account of the affordances of visual feedback in combination of haptic feedback. Therefore, this study fills an important gap in the literature about how embodied learning can be promoted with technology. Future work in this line may focus on the value of haptic feedback in other virtual environments such as virtual reality environments and augmented reality environments. The research question is

- What is the effect of adding haptic feedback in virtual reality environments and augmented reality environments?

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APPENDIX A. EXPLANATION'S THEMES PER CONCEPTUAL QUESTION

Table A.1. Percentage of explanation's themes used for answering CQ1

Condition	Category	Explanation theme	Pre (98)	Int1 (58)	Mid (55)	Int2* (60)	Post (70)
$V \rightarrow H+V$	Correct Haptically -oriented	Hard/easy	15.91	0.00	12.00	0.00	13.89
		Applied force	11.36	70.00	4.00	70.00	33.33
		Friction force	18.18	13.33	72.00	13.33	11.11
	Correct Visually -oriented	Speed	11.36	0.00	0.00	0.00	11.11
		Traveled distance	9.09	0.00	0.00	0.00	2.78
		Other	20.45	10.00	12.00	10.00	19.44
	Incorrect Haptically -oriented	Hard/easy	0.00	0.00	0.00	0.00	0.00
		Applied force	0.00	0.00	0.00	0.00	2.78
		Friction force	0.00	0.00	0.00	0.00	2.78
	Incorrect Visually -oriented	Speed	0.00	0.00	0.00	0.00	0.00
		Traveled distance	6.82	0.00	0.00	0.00	0.00
		Other	6.82	6.67	0.00	6.67	2.78
$H \rightarrow H+V$	Correct Haptically -oriented	Hard/easy	11.11	13.33	16.67	13.33	35.29
		Applied force	13.89	50.00	3.33	50.00	29.41
		Friction force	11.11	20.00	76.67	20.00	17.65
	Correct Visually -oriented	Speed	19.44	0.00	0.00	0.00	2.94
		Traveled distance	13.89	0.00	0.00	0.00	5.88
		Other	13.89	10.00	0.00	10.00	0.00
	Incorrect Haptically -oriented	Hard/easy	0.00	0.00	0.00	0.00	0.00
		Applied force	0.00	3.33	3.33	3.33	8.82
		Friction force	2.78	0.00	0.00	0.00	0.00
	Incorrect Visually -oriented	Speed	2.78	0.00	0.00	0.00	0.00
		Traveled distance	8.33	0.00	0.00	0.00	0.00
		Other	2.78	3.33	0.00	3.33	0.00

Table A.2. Percentage of explanation's themes used for answering CQ2

Condition	Category	Explanation theme	Pre (98)	Int1 (58)	Mid (55)	Int2* (60)	Post (70)
$V \rightarrow H+V$	Correct Haptically -oriented	Hard/easy	3.57	0.00	0.00	0.00	0.00
		Applied force	3.57	61.29	0.00	62.07	28.57
		Friction force	7.14	19.35	54.17	17.24	35.71
	Correct Visually -oriented	Speed	10.71	0.00	0.00	0.00	7.14
		Traveled distance	3.57	0.00	0.00	0.00	0.00
		Other	25.00	0.00	20.83	0.00	25.00
	Incorrect Haptically -oriented	Hard/easy	17.86	3.23	4.17	3.45	3.57
		Applied force	0.00	9.68	4.17	10.34	0.00
		Friction force	17.86	6.45	8.33	6.90	0.00
	Incorrect Visually -oriented	Speed	3.57	0.00	0.00	0.00	0.00
		Traveled distance	0.00	0.00	0.00	0.00	0.00
		Other	7.14	0.00	8.33	0.00	0.00
$H \rightarrow H+V$	Correct Haptically -oriented	Hard/easy	0.00	4.55	0.00	4.17	14.29
		Applied force	17.39	54.55	0.00	75.00	46.43
		Friction force	0.00	4.55	34.78	4.17	10.71
	Correct Visually -oriented	Speed	4.35	0.00	0.00	0.00	0.00
		Traveled distance	26.09	0.00	0.00	0.00	7.14
		Other	17.39	4.55	13.04	4.17	7.14
	Incorrect Haptically -oriented	Hard/easy	4.35	13.64	8.70	4.17	7.14
		Applied force	13.04	9.09	8.70	4.17	7.14
		Friction force	13.04	9.09	30.43	4.17	0.00
	Incorrect Visually -oriented	Speed	4.35	0.00	0.00	0.00	0.00
		Traveled distance	0.00	0.00	0.00	0.00	0.00
		Other	0.00	0.00	4.35	0.00	0.00

APPENDIX B. CATEGORIZATION OF THE EXPLANATION'S THEMES

Table B.1. $V \rightarrow H + V$ condition. Explanation's themes for answering CQ1

	Pretest	Interaction 1	Midtest	Interaction 2	Posttest
ID8	CO	CO	CO	CO	IO
ID10	CS + CTD + CO	CFa	CFf	CFa	CFa
ID1	CFf + CO	CFa + CO	CFf	CFa + CO	CFa
ID17	CHE + CFa + CS	CFa + CFf	CFf	CFa + CFf	CFa
ID18	CFf + CS	CFa	CO	CFa	CFf + CS
ID20	CHE + CS	CFa	CFf	CFa	CHE
ID21	CFf	CFa	CFf	CFa	CFa
ID22	CFf	CFa	CFf	CFa	CFf
ID3	CTD + CO	CFa	CFf	CFa	CS + CO
ID4	CFa + CO	IO	CHE + CFf	IO	CFa
ID5	CHE + CFF + CO	CFa	CFf	CFa	CFa + CO
ID7	CFf + CS + CO	CFa + CFf	CO	CFa + CFf	CO
ID2	CTD + CO	CFa + CFf	CFf	CFa + CFf	CHE + CFa + CTD
ID6	CFa	CFa	CFf	CFa	CFa + CS
ID14	CHE	IO	CHE	IO	CO
ID19	CFa	CFa	CFf	CFa	CO + IFf
ID13	CFf + CTD + CO	CFa + CFf+ CFf + CO	CFf	CFa + CFf + CFf + CO	CHE + CFf
ID9	IO	CFa	CFf	CFa + CO	CFa
ID12	IO	CFa	CFf	CFa	CHE + CS
ID16	NA	CFa	CO	CFa	CO
ID23	ITD	CFa	CHE	CFa	CHE
ID11	CHE + CFf + ITD	CFa	CFf	CFa	CFa + CFf
ID15	CHE + IO	CFa	CFf	CFa	CFa + CO
ID24	CHE + CO + ITD	CFa + CO	CFa	CFa + CO	CFa + CO

Table B.2. $H \rightarrow H+V$ condition. Explanation's themes for answering CQ1

	Pretest	Interaction 1	Midtest	Interaction 2	Posttest
ID7	CFa + CFf + CS	CFa + CFf	CFf	CFa + CFf	CHE + CFa
ID18	CO	CFa	CFf	CFa	CHE + CFf
ID9	CHE + CS	CHE	CFf	CHE	CFa
ID10	CTD	CFa	NA	CFa	CHE
ID11	CS	IO	NA	IO	CHE
ID1	CHE	CHE + CFf	CFf	CHE + CFf	CHE
ID16	CS	CFa	CFf + CFf	CFa	CHE
ID17	CTD	CFa	CHE	CFa	CTD
ID19	CFf + CTD	CFa	CHE	CFa	IFa
ID20	CHE + CFf	CFf + CO	CFf + CFf	CFf + CO	CFa + CFf
ID23	CS	CFa	CFf	CFa	CHE + CFa
ID2	CFa	CHE	CFa + CFf	CHE	CFa
ID24	CHE + CS	CO + CO	CFf	CO + CO	CHE + CFa
ID3	CFf + CTD	CHE	CHE + CFf	CHE	CHE
ID5	CFf + CO	CFa + CFf	CFf	CFa + CFf	CHE + CFf
ID6	CFa + CS	CFa	CFf	CFa	IFa
ID4	CO	CFa	CFf	CFa	CFf
ID13	ITD	CFa	CFf	CFa	CFa
ID14	CFa + IO	CFa	CHE	CFa	CFa
ID15	CO + IS	CFa	CFf + CFf	CFa + CFa	CFa + CFf
ID8	CFa + CFf + CTD + IFf	IFa	CFf + IFa	IFa	IFa
ID22	CO + ITD	CFa	CFf	CFa	CFf + CS + CTD
ID12	ITD	CFa + CFf	CFf	CFa + CFf	CHE
ID21	NA	CFf	CFf	CFf	CFa

Table B.3. $V \rightarrow H + V$ condition. Explanation's themes for answering CQ2

	Pretest	Interaction 1	Midtest	Interaction 2	Posttest
ID8	IO	CFa + CFf	CFf	CFa + CFf	CO
ID10	IHE + IFf	CFa	CFf	CFa	CFf + CO
ID11	IFf + ITD	CFa + CFf	CFf	CFa + CFf	CFf + IHE
ID17	IHE	IFa	CFf	IFa	CFa
ID21	IHE + IFf	CFa	CO	CFa	CFa + CFf
ID22	IHE	CFa	CO	CFa	CFf + CO
ID2	IFf + ITD	CFa + CFf	CFf	CFa + CFf	CFa + CFf
ID24	ITD + IO	CFa	CFf	CFa	CO
ID4	IHE	CFa	IO	CFa	NA
ID5	IFf	CFa	CFf	CFa	CFf
ID6	IS	CFa + CFf	IO	CFa + CFa + CFf + CFf	NA
ID7	NA	CFa + CFf	NA	CFa + CFf	CFa + CFf
ID20	NA	CFa	CFf	CFa	CO
ID9	CO	IFa + IFf	IFa	IFa + IFf	NA
ID12	CO	CFa	CFf	CFa	CFa + CO
ID13	CFa + CFf + CTD + CO	CFa	CFf	CFa	CFa + CFf
ID14	CS	IHE	IHE + IFf	IHE	CO
ID1	CHE + CFf	CFa + CFf	CFf	CFa + CFf	CFf
ID15	CO	IFa + IFf	IFf	IFa + IFf	NA
ID16	CO	NA	CFf	NA	NA
ID18	CS	CFa	CFf	CFa	CFf + CS
ID19	CO	CFa	CO	CFa	CFa
ID23	CO	CFa	CO	CFa	CS
ID3	CS + CO + CO	CFa	CO	CFa	CFa

Table B.4. $H \rightarrow H+V$ condition. Explanation's themes for answering CQ2

	Pretest	Interaction 1	Midtest	Interaction 2	Posttest
ID7	IFa + IFf	CFa	CFf	CFa	CHE + CFa
ID9	IS	CHE + CFa	IFf	CHE + CFa	IFa
ID11	NA	CFa	NA	CFa	IHE
ID14	IFf	CFa	CFf	CFa	IFa + IFa
ID18	IFa	CFa	CFf	CFa	CFa
ID19	ITD	CFa + CFf	IHE	CFa + CFf	IHE
ID21	NA	CO	CO	CO	CFa
ID23	ITD	NA	CFf	NA	CFa + CFf
ID2	NA	CFa	CO	CFa	CFa
ID6	NA	IFa	CO	CFa	IFa
ID8	CFa + IFf	IFf	IFf	IFf	CHE + CFa
ID3	CFa + IFa	CFa	NA	CFa	CFf
ID4	CO + IHE	NA	CFf	NA	CHE
ID10	CTD + CO	IHE	IFa + IFf	IHE	CO
ID12	CTD	CFa	IO	CFa	CFa
ID13	CTD	NA	IFf	CFa	CFa
ID1	CO	CFa	NA	CFa	CFa
ID15	CO	IFf	IFf	CFa	CFa
ID16	CS	IHE	CFf	CFa	CHE
ID17	CTD	CFa	IFf	CFa	CTD
ID20	CFa	CFa	CFf	CFa	CFa
ID22	CFa + CTD	NA	CFf	CFa	CFa + CFf + CTD
ID24	CO + CO	IFa	CO	IFa	CFa + CO
ID5	CTD	IHE	IHE + IFf	CFa	ITD

APPENDIX C. EXAMPLES OF STUDENT'S ANSWERS

Examples for CQ1 (role of the object's weight in friction

$V \rightarrow H+V$:ID2 (high-level performer).

- Pretest: "*Will keep accelerating. According Newton Second Law F=ma. The "a" in heavier is smaller than that of the lighter one. So, the second one would be slower*"
- Interaction 1: "*Yes, the force 2 applied to move Cube 2 is larger than that of Cube 1*"
- Midtest: "*Will keep accelerating. According Newton Second Law F=ma. The "a" in heavier is smaller than that of the lighter one. So, the second one would be slower"*
- Interaction 2: "*Will keep accelerating. According Newton Second Law F=ma. The "a" in heavier is smaller than that of the lighter one. So, the second one would be slower"*
- Posttest: "*Will keep accelerating. According Newton Second Law F=ma. The "a" in heavier is smaller than that of the lighter one. So, the second one would be slower"*

$V \rightarrow H+V$:ID3 (high-level performer).

- Pretest: "*When you push Cube 1 it will easily glide on the smooth surface from one point to another. Cube 2 will require more force to push it from one point to another, and will glide less easily than Cube* "
- Interaction 1: "*They are the same*"
- Midtest: "*There is more friction acting on the block with the heavier mass, but they still slide relatively easy (the heavier one did require more force to be able to slide*"
- Interaction 2: "*They are the same*"
- Posttest: "*Cube 1 would glide across a smooth surface easily with a little force. Cube 2 would be able to glide as well, but with more force applied than Cube 1*"

$V \rightarrow H+V$:ID9 (low-level performer).

- Pretest: "*would be the same*"

- Interaction 1: "*No, the forces are not the same applied to Cube 2 as Cube 1. Across the board there is an increase in force used to slide Cube 2. Increase become clearer with foam and fabric surfaces*"
- Midtest: "*Cubes that have the same sizes, the cube with the greatest mass tends to have the greater friction force*"
- Interaction 2: "*No, the forces are not the same applied to Cube 2 as Cube 1. Across the board there is an increase in force used to slide Cube 2. Increase become clearer with foam and fabric surfaces. They are indeed different*"
- Posttest: "*You probably noticed any difference at all. Due to smooth surface, the difference in force required is negligible*"

$V \rightarrow H+V$:ID11 (medium-level performer).

- Pretest: "*Cube 1 would travel more easily because the friction acting on it is less than that of Cube 2. It would take Cube 2 longer to stop though because the greater weight helps maintain its motion after the force is not applied longer*"
- Interaction 1: "*The force applied to Cube 2 are more than that of Cube 1 for all surfaces*"
- Midtest: "*A cube with less mass requires less friction force than a Cube with greater mass*"
- Interaction 2: "*The force applied to Cube 2 are more than that of Cube 1 for all surfaces*"
- Posttest: "*Cube 1 will need less force for it to move across the same surface as Cube 2. Cube 2 will see greater effects from friction*"

$V \rightarrow H+V$:ID17 (high-level performer).

- Pretest: "*Cube 1 would move easier than Cube 2. Cube 1 would take less force to start moving than Cube 2. Cube 2 will stop moving faster than Cube 1*"
- Interaction 1: "*The forces on Cube 2 are greater than Cube 1 forces on all 3 surfaces*"
- Midtest: "*The friction force (of the Cubes) are different*"

- Interaction 2: "*The forces on Cube 2 are greater than Cube 1 forces on all 3 surfaces. The forces are the same*"
- Posttest: "*Cube 2 will take more force to move compared to Cube 1*"

$H \rightarrow H+V$:ID1 (high-level performer).

- Pretest: "*It would be more difficult to push Cube 2*"
- Interaction 1: "*They are different because Cube 2 is heavier. The force of friction is greater making it harder to move*"
- Midtest: "*The friction force is less for Cube 1 than Cube 2 because they have different masses even though they are the same size*"
- Interaction 2: "*They are different because Cube 2 is heavier. The force of friction is greater making it harder to move*"
- Posttest: "*Cube 1 would be easier to push than Cube 2 because it has a mass less than that in Cube 2*"

$H \rightarrow H+V$:ID12 (low-level performer).

- Pretest: "*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 farther and a longer period of time because it will have a larger momentum (caused by weight)*"
- Interaction 1: "*The forces needed to move Cube 2 were much larger than that of Cube 1, when it was on any of the surfaces*"
- Midtest: "*Size does not really matter. The mass multiplied by gravity and mu are the only factors to the equation. Meaning, the change in mass and surface material is everything*"
- Interaction 2: "*The forces needed to move Cube 2 were much larger than that of Cube 1, when it was on any of the surfaces*"
- Posttest: "*Cube 1 since is lighter than Cube 2, the friction would be less, allowing the cube to move further and faster if pushed with the same force*"

$H \rightarrow H + V$:ID22 (medium-level performer).

- Pretest: "*Assuming the force same force is applied to both, Cube 2 would travel farther*"
- Interaction 1: "*Same forces but with a greater magnitude*"
- Midtest: "*Friction force is affected by weight (mass x gravity)*"
- Interaction 2: "*Same forces but with a greater magnitude*"
- Posttest: "*Cube 1 would be easier to push than Cube 2*"

Examples for CQ2 (role of the object's size in friction

$V \rightarrow H + V$:ID1 (high-level performer).

- Pretest: "*Cube 3 would be equally hard to push as Cube 2 because it has the same amount of friction. This is because the cube is pressing down with the same amount of force simply over a lesser surface area*"
- Interaction 1: "*The forces required to move Cube 2 and 3 were the same. The equations for force due to friction do not require surface area, only the mass of the object. Cubes 2 and 3 are still encountering the same overall reaction from... Cube 3 simply exerts a greater force per unit area, while Cube 2 exerts a lesser force per unit over a greater area. This results in the same friction even with different object sizes while on a flat, smooth surface*"
- Midtest: "*The friction between the cubes with different sizes but the same mass is the same*"
- Interaction 2: "*The forces required to move Cube 2 and 3 were the same. The equations for force due to friction do not require surface area, only the mass of the object. Cubes 2 and 3 are still encountering the same overall reaction from... Cube 3 simply exerts a greater force per unit area, while Cube 2 exerts a lesser force per unit over a greater area. This results in the same friction even with different object sizes while on a flat, smooth surface*"
- Posttest: "*Cubes 2 and 3 will have the same resistance due to friction while moving from one point to another*"

$V \rightarrow H + V$:ID2 (low-level performer).

- Pretest: "*If friction is negligible, they would move the same distance, acceleration in the same way and force is constant*"
- Interaction 1: "*The same. Cube 3 and 2 have the same mass. The pushing force depends solely on the friction, and the friction depends on both. The normal force and coefficient of friction. The normal force depends on weight which depends on mass. Since both are on the same surface and have the same mass, then the pushing force is the same for both*"
- Midtest: "*Same friction*"
- Interaction 2: "*The same. Cube 3 and 2 have the same mass. The pushing force depends solely on the friction, and the friction depends on both. The normal force and coefficient of friction. The normal force depends on weight which depends on mass. Since both are on the same surface and have the same mass, then the pushing force is the same for both*"
- Posttest: "*Assuming the force is ¿f, they will move on and will have equal friction forces because they weight the same*"

$V \rightarrow H + V$:ID6 (low-level performer).

- Pretest: "*Cube 2 would move slower*"
- Interaction 1: "*They were the same as the friction coefficient were equal on all material*"
- Midtest: "*The friction force is based on the surface material in each case, the object mass does not affect the friction, so the mass does not matter, only the force the moves it*"
- Interaction 2: "*This is because the mass of Cube 3 and Cube 2 were the same*"
- Posttest: "*They will both slide and require the same force since they are both the same weight*"

$V \rightarrow H + V$:ID11 (low-level performer).

- Pretest: "*Cube 2 will come to rest quicker because friction is coming into contact with more surface*"
- Interaction 1: "*The forces to move Cube 2 and Cube 3 were very close. This is because they have the same mass. The only small difference in force were a result of the bottom of the object* "
- Midtest: "*The friction force experienced by the cubes are very similar. Friction seems to act on them the same*"
- Interaction 2: "*The forces to move Cube 2 and Cube 3 were very close. This is because they have the same mass. The only small difference in force were a result of the bottom of the object* "
- Posttest: "*The cubes should experience similar forces and similar friction. I did not observe much differences between the cubes*"

$V \rightarrow H+V$:ID14 (high-level performer).

- Pretest: "*If the surface is smooth then friction is negligible. If friction is negligible and they weight the same, then the surface area won't make an impact. Therefore, they will move at the same rate*"
- Interaction 1: "*They are different from the most part. Here is a smaller surface area to distribute the force of friction in Cube 3. Therefore, it was more difficult to move Cube 2*"
- Midtest: "*The surface area of the object shows over what size to friction will be distributed, and what size the force will be distributed. Harder to move the smaller object*"
- Interaction 2: "*They are different from the most part. Here is a smaller surface area to distribute the force of friction in Cube 3. Therefore, it was more difficult to move Cube 2*"
- Posttest: "*Should move about the same because the friction is near zero*"

$V \rightarrow H+V$:ID21 (low-level performer).

- Pretest: "*Cube 2 will be easier to push than Cube 3 because there is more surface area which allows the load to be distributed more easily than Cube 3*"
- Interaction 1: "*They were the same because they had the same mass*"
- Midtest: "*The forces were the same*"
- Interaction 2: "*They were the same because they had the same mass*"
- Posttest: "*Cube 1 would slide across with little resistance cube 2 would slide across but with a very light amount of resistance*"

$H \to H + V$:ID7 (low-level performer).

- Pretest: "*Because Cube 2 has more surface area than Cube 3 contacting the floor, it is going to take more foce to move it*"
- Interaction 1: "*The forces of Cube 2 and Cube 3 were very similar and pretty much the same. This could be due to the cubes having a similar weight*"
- Midtest: "*The friction force of cubes with the same mass are similar if not the same*"
- Interaction 2: "*The forces of Cube 2 and Cube 3 were very similar and pretty much the same. This could be due to the cubes having a similar weight*"
- Posttest: "*Both are going to be fairly easy to move across a smooth surface and since they have the same weight it will be very similar forces*"

APPENDIX D. IRB DOCUMENTATION

Exemption Granted on 27-FEB-2018

Revised Oct 12, 2017

EXEMPTION DETERMINATION FORM
Purdue University, Institutional Review Board

Currently, federal regulations recognize six categories of research that are exempt from IRB review. However, in an ironic twist, the IRB must determine if your research fits one of these "exempt from IRB review" categories. Having fun yet? We are, too! Below you will find questions that will help us determine if your research project is exempt from *further* IRB review. Note that research activities may not be implemented until the investigator receives written notification from IRB that an exemption from IRB review has been granted for a particular research project.

Does your research involve prisoners? If so, you can stop completing this form now, as such research is almost never exempt and requires IRB review.

Does your research involve the collection of "identifiable information," defined as information by which a subject can be identified directly (e.g., name, PU ID number, SS number, email address, etc.), indirectly by triangulating multiple variables, (i.e., age, sex, race, profession, etc.), or through codes with links to the identity of a subject? If so, you can stop completing this form now, as such research is almost never exempt and requires IRB review.

Check the category (or categories) below that you believe correspond(s) to your research project:

X	*Category 1*: Research conducted in established or commonly accepted educational settings, involving normal educational practices, such as (i) research on regular and special educational instructional strategies, or (ii) research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.
☐	*Categories 2/3*: Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless all of the following are true: (i) information obtained is recorded in such a manner that the human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, insurability, or reputation. **NOTE: This exemption DOES NOT APPLY to research involving survey or interview**
☐	*Category 4*: Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, if these sources are publicly available or if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects.
☐	*Category 5*: Research and demonstration projects which are conducted by or subject to the approval of department or agency heads, and which are designed to study, evaluate, or otherwise examine: (a) public benefit or service programs; (b) procedures for obtaining benefits or services under those programs; (c) possible changes in or alternatives to those programs or procedures; or (d) possible changes in methods or levels of payment for benefits or services under those programs.
☐	*Category 6*: Taste and food quality evaluation and consumer acceptance studies, (a) if wholesome foods without additives are consumed; or (b) if a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural, chemical, or environmental contaminant at or below the level found to be safe, by the Food and Drug Administration or approved by the Environmental Protection Agency or the Food Safety and Inspection Service of the U.S.

Protocol #:	1802020277 **(Exempt)**	**Expiration Date:**	
Investigator:	MAGANA DELEON, ALEJANDRA J	**Last Approval Date:**	
Title:	In-Class Haptic-Based Learning Experiences as Cognitive Media...		

List of Investigators / Study Personnel: **Send Notification**

Person Name	Department	Lead Unit	Role	Affilate	Training
MAGANA DELEON, ALEJANDRA J	• PWL Computer Information Technology	☑	Principal Investigator	Faculty	✗
BENES, BEDRICH			PROFESSOR OF CGT	Key Personnel	✗
BERGER, EDWARD J			ASSOCIATE PROFESSOR OF EN	Key Personnel	✗
COUTINHO, GENISSON S			LASPAU - LATIN AMERICAN	Key Personnel	✗
EFENDY, EDDY			ASSISTANT PROFESSOR OF PR	Key Personnel	✗
NGAMBEKI, BUSIIME IDA			ASSISTANT PROFESSOR OF CI	Key Personnel	✗
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Education

- 2016-2020 – Doctoral studies. Technology Program at Polytechnic School, Purdue University Dissertation title: Improving conceptual understanding of statics concepts through tactile feedback tools.
- 2014-2015 – Master studies Computer and Information Technology at Polytechnic School, Purdue University. Master thesis title: Multimedia learning for increasing knowledge on energy efficiency and promotion of pro-environmental behavior: a study of undergraduate students in Costa Rica".
- 2012-2013 – Undergraduate studies Specialization on Visual Communication Design at Industrial Design School, Costa Rica Institute of Technology. Project title: Information architecture and usability analysis of the digital version of the national newspaper La Nacion (www.nacion.com).
- 2005-2010 – Bachelor degree on Industrial Design Engineering at Industrial Design School, Costa Rica Institute of Technology. Project title: Foliage: a green outdoor study space design

Work Experience

- 2014-2020 – Research Assisstant Research on Computing in Engineering and Technology Education at Purdue University http://web.ics.purdue.edu/ admagana/

- 2014 -2017 – Graduate assistant Information Technology at Purdue University Teaching and Learning with Technology team http://www.itap.purdue.edu/learning/ Role: Multimedia Designer, UI/UX
- 2012-2013 – Researcher Costa Rica Institute of Technology http://www.tec.ac.cr/ Role: Design of an application for Android mobile devices, where users can learn about the physical and meteorological variables i.e. latitude, weather conditions, house construction, that can influence the performance of photovoltaic panels.
- 2012-2013 – Product Designer Costa Rica Institute of Technology http://www.tec.ac.cr/ Role: Design of sustainable energy products. The most important design was Foliage, a sustainable outdoor study space. Design of promotional material for the promotion of renewable energy for Costa Rica and other countries.
- 2010-2013 – UI/UX Designer for learning environments TEC-Digital at Costa Rica Institute of Technology http://tecdigital.tec.ac.cr/ Role: User interface / user experience designer, multimedia learning designer, course designer.

Publications

- Walsh, Y., Magana, A.J., Will, H., Yuksel, T., Bryan, L., Berger, E., Benes, B. (submitted). A learner-centered approach for designing visuohaptic simulations for conceptual understanding of truss structures. *Computer Applications in Engineering Education.*
- Walsh, Y., Magana, A.J. Feng, S. (2020). Investigating students' explanations about friction concepts after interacting with a visuohaptic simulation with two different sequenced approaches. *J Sci Educ Technol.* https://doi.org/10.1007/s10956-020-09829-5
- Yuksel, T., Walsh, Y., Magana, A.J., Nova, N., Krs, V., Ngambeki, I., Berger, E., Benes, B. (2019). Visuohaptic experiments:Exploring the effects of visual and haptic feedback on students' learning of friction concepts. *Computer Applications in Engineering Education, 27(6), 1376-1401.* https://doi.org/10.1002/cae.22157

- Walsh, Y., Magana, A. J., Quintana, J. P., Krs, V., Coutinho, G. S., Berger, E. J., . . . Benes, B. (2018). Designing a visuohaptic simulations to promote graphical representations and conceptual understanding of structural analysis. *In 2018 IEEE Frontiers in Education Conference (FIE).* San Jose, California.
- Neri, L., Magana, A., Noguez, J., Walsh, Y.,Gonzalez-Nucamendi, A., Victor, R.-R., Benes, B. (2018). Visuo-haptic simulations to improve students' understanding of friction concepts. In *2018 IEEE Frontiers in Education Conference (FIE).* San Jose, California.
- Walsh, Y., Meza, C., Magana, A. (2018). Perceptions about causes and ways to mitigate Climate change and its relationship with energy consumption in the residential sector. In *Congreso Iberoamericano de Ciudades Inteligentes* (pp. 1–14). Soria, España: Springer.
- Walsh, Y., Magana, A. J., Yuksel, T., Krs, V., Ngambeki, I. B., Berger, E. J., Benes, B. (2017). Identifying affordances of physical manipulatives tools for the design of visuo-haptic simulations. In *ASEE 124rd Annual Conference and Exposition.* Columbus, Ohio.
- Yuksel, T., Walsh, Y., Ngambeki, I. B., Berger, E. J., Magana, A. J. (2017). Exploration of affordances of visuo-haptic simulations to learn the concept of friction. In *2017 IEEE Frontiers in Education Conference (FIE)* (pp.1-9). Indianapolis: IEEE. https://doi.org/10.1109/FIE.2017.8190471

Graduate courses

Experimental Statistic I and III, Quantitative Data Analysis in Technology, Human Factors in Engineering, Cyberlearning Research and Development, Introduction to innovation studies, Applied perceptualization, Design theory and technology, Design and evaluation of tactile learning, Cognition and Technology, Cyber-physical systems for learning, The development of Graphics in Technology, Introduction to Educational Research I: Methodology, Interaction Design Studies, Analysis of research in industry and technology, Qualitative Research Methods in Education, Behavioral Analytics, Technology from a global perspective