Combining Physical and Virtual Laboratories:

Effects of Perceptual Features of

Science Laboratory Environments on Learners' Conceptions

By

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Abstract

This study explores the ways in which the unique perceptual-motor features of science laboratory environments can affect students' learning. Drawing from research on embodied cognition highlighting the influence of perception and action on conceptual processes, prior studies comparing and combining physical and virtual science laboratories, and technological breakthroughs in "mixed reality" technologies that combine physical objects and actions with digital media, the study attempts to address how the unique perceptual-motor features of physical, virtual and combined physical-virtual laboratory environments shape learners' understanding of physics concepts.

Working in dyads, participants in the study were asked to complete two inclined plane experiments, investigating how the length and height of an inclined plane affect particular physics concepts when lifting an object up the inclined plane. The study consisted of four experimental conditions, corresponding to four different laboratory environments: physical-only, virtual-only, sequential physical-virtual, and integrated physical-virtual. This study employed several different measures to answer the research questions, including concept tests and interviews. The findings indicated that the perceptual-motor features of science laboratory environments did indeed shape learners' understanding of the underlying science concepts, and because of this, there were unique advantages and disadvantages to different forms of laboratory environments based on their perceptual-motor features. Further, participants gestured differently after engaging with the different laboratory environments, indicating that they internalized specific perceptual-motor features of the environment. This research significantly contributes to the literature by examining more deeply how the perceptual-motor aspects of science

learning environments influence student learning and illustrates advantages and disadvantages of different combinations of physical and virtual laboratory environments.

Chapter 1: Introduction

Laboratories have a long tradition within science classrooms, both within K-12 and higher education settings. They have been used to help students with any combination of the three major goals of science classrooms: learning science (developing conceptual knowledge), learning about science (building an understanding of the nature and methods of science), and doing science (engaging in scientific inquiry) (Hodson, 1996). Physical laboratory environments, which consist of real-world materials and equipment, and computer simulations – digital, dynamic, interactive representations of a phenomena or process – each have a long history within classroom science laboratories (Hodson, 1996). Over the past few decades, several research studies have attempted to investigate the value of using physical laboratory environments and virtual laboratory environments within science classrooms to support students' conceptual understanding (Olympiou & Zacharia, 2012). Though much of the research on physical and virtual science investigations has treated physical experimentation and computer simulations as competing methods in science classrooms (Jaakola & Nurmi, 2008), recent research suggests that virtual and physical laboratories each have unique but somewhat overlapping affordances for learning and several authors are beginning to suggest that a combination of physical and virtual laboratories should be considered in science classrooms (Olympiou & Zacharia, 2012). Still, it is not yet clear in this long line of research exactly when to provide what form of laboratory environment, as empirical results of studies comparing physical and virtual experiments, as well as to sequential combinations of the two, have been somewhat mixed (Olympiou & Zacharia, 2012).

In this dissertation, I suggest that there have been two important pieces missing from the discussion on physical and virtual science laboratories in classrooms: one theoretical, the other technological. First, very little of the research on physical and virtual science laboratories has paid much attention to the specific perceptual-motor features of these learning environments, which may significantly affect students' learning. Second, with emerging technologies that allow new links between physical and virtual elements, there may be new ways to combine physical and virtual laboratories that go beyond offering a sequence of separate physical laboratories and computer simulations.

There is mounting evidence that our sensorimotor system affects cognition and learning in complex ways (Wilson, 2002). According to theories of embodied cognition, our body's interaction in the world shapes how we think and learn, and even abstract conceptual understanding is grounded in perception and action (Barsalou, 2009). As such, the particular perceptual-motor aspects of science laboratory environments may shape how students think and learn about the underlying science in important ways, and analyzing physical and virtual laboratory environments in terms of their perceptual-motor features may offer insights into how best to design laboratory environments to support student learning. In terms of their perceptual-motor features, computer simulations can "make the invisible visible", offering students multiple, dynamic, linked representations of the underlying science variables, including variables that cannot be measured directly in the physical world (Hofstein & Lunetta, 2004). Physical laboratory environments, on the other hand, are unique in that they can incorporate haptic, as well as (limited) visual, feedback within the learning environment.

There may also be additional benefits of *directly coupling* the haptic feedback offered by actions on physical materials with the rich, dynamic visual feedback provided in simulation environments. Our experience in the world is inherently multimodal – combining visual, auditory and haptic information – and mental representation itself may be multimodal as well (Barsalou, 1999). As such, the specific perceptual *combinations* of modalities utilized in interacting within a learning environment can also play an important role in conceptual understanding.

A class of "mixed reality" technologies is emerging that combines physical objects, actions and environments with digital representations, either through augmenting the physical world with digital attributes or by augmenting a digital environment with aspects of the physical world (Milgram, Takemura, Utsumi, & Kishino, 1994). By integrating physical actions and objects with digital representations, mixed reality learning environments can expand upon the range of possible actions and sensory-motor experiences within the learning environment. Some authors suggest that these technologies can bridge the "abstraction gap" between everyday experience and abstract understanding (Zufferey, Jermann, Do Lenh & Dillenbourg, 2009) by creating a controlled context for physical interaction with content from which abstract concepts can be built (Lindgren & Johnson-Glenberg, 2013).

The use of mixed reality laboratory environments may be especially useful in physics contexts, where the digital representations can be used to shape how students interpret the physical world. Despite a substantial body of empirical research, physics remains difficult to teach and to learn, and many students perceive physics as overly abstract and complex (Duit, Niedderer & Schecker, 2007). In an inherently physical and spatial domain such as physics, the specifics of students' perception and action may be an essential component of how they develop formal understanding of the domain. Being that mixed reality laboratory environments may be especially effective in physics contexts, this study focused on learning from combinations of physical and virtual experiments within classical mechanics.

Building upon emerging research on how perceptual processes affect conceptual understanding, prior studies on physical and virtual science laboratory environments, and emerging technologies that combine physical and virtual elements in new ways, the study described in this dissertation attempted to explore how the perceptual-motor features of physics laboratory environments – including physical, virtual, sequential combinations of physical and virtual, and mixed-reality laboratory environments – influence learners' conceptual understanding.

Chapter 2: Review of the Literature

The following study brings together three threads of research that have been largely distinct from each other to this point. The first thread of research is that of embodied cognition and learning, namely that cognitive processing is deeply grounded in perception and action, and that perception influences conception in complex and sometimes surprising ways. The second is a fairly long line of research that explores the affordances of physical and virtual laboratories in science classrooms as well as combinations of the two. Applying ideas about embodied cognition and learning to the study of physical and virtual science laboratory environments may yield new insights to this line of research. Finally, in addition to applying theoretical underpinnings of embodiment to science education conversations on physical and virtual laboratories, this study also intends to explore the ways that emerging mixed reality technologies – which combine physical and virtual elements in new ways – may allow for new opportunities for science laboratory environments beyond more traditional physical laboratories, computer simulations, or sequential combinations of the two. The following sections describe these three research traditions as well as areas for further study where intersections of these three threads may be particularly productive.

Embodiment and Learning: Perceptual Influences on Conceptual Processes

There is mounting evidence that our sensorimotor system affects cognition and learning in complex ways (Wilson, 2002; Barsalou, 2009). According to theories of embodied cognition, learning and cognition is deeply rooted in our body's interaction with the world (Wilson, 2002). The ways in which we manipulate objects, perform actions and gestures, and otherwise interact with the physical environment can have profound and surprising effects on the way we learn (e.g., Glenberg & Kashak, 2002; Glenberg, Havas, Becker & Rinck, 2005; Glenberg et al., 2004; Smith, 2005; Glenberg, Brown & Levin, 2007; Thomas & Lleras, 2009; Goldin-Meadow & Beilock, 2010). Further, the particular perceptual-motor features of learning environments, such as the combination of perceptual modalities available, the concreteness or abstraction of visual representations and even the spatial layout of visual representations can influence learning and cognition (Goldstone & Son, 2005; Landy & Goldstone, 2007; Bivall, Ainsworth & Tibell, 2011).

Many researchers suggest that even abstract conceptual understanding is grounded in our perception and action in the world and built upon a foundation of perceptually-based internal representations (Goldstone, Landy & Son, 2008; Barsalou, 2009). In a recent summary of research on embodiment and learning, Abrahamson & Lindgren (in press) argue that, "conceptual reasoning originates in physical interaction and becomes internalized as simulated actions" (p. 4). Barsalou (1999; 2008; 2009) offers a theoretical account of how conceptual processing is built upon simulated actions. In constructing conceptual understanding, rather than concepts being built entirely on amodal symbols, modality-specific representations are used to reenact prior perception and action. These modality-specific reenactments are then integrated into multimodal representations (Barsalou, 2009). These multimodal representations can themselves be reenacted through mental simulation, and a fully functional conceptual system can be built upon these reenactment mechanisms (Barsalou, 1999, 2003, 2009; Barsalou et al., 2003). Thus, Barsalou claims, "abstract concepts are perceptual, being grounded in temporally extended simulations of external and internal events" (Barsalou, 1999, p. 603).

Other popular models of cognition that claim that abstract concepts are built upon sensorimotor experience include the cognitive semantics theory of conceptual metaphor (Lakoff & Johnson, 1980). This model posits that all human reasoning is grounded in *image schemas*, "patterns of bodily orientations, movements and interaction … imaginatively developed to structure our abstract inferences." (p. 90)

Beyond these theoretical accounts, there is mounting evidence that abstract concepts are indeed perceptual and built upon simulated actions and events. Some such evidence comes from neuroscience research: There is growing neurophysiological evidence on the importance of action and motor simulation in cognitive processes (Garbarini & Adenzato, 2004; Just, 2008; Simmons et al., 2008). For example, neural signatures from fMRI studies indicate that in at least some cases, perceptual and motor representations are activated during processing that is primarily conceptual (Just, 2008). In addition to neurophysiological evidence, gesture is also often taken as evidence of the embodiment of language and cognition (McNeill, 2008; Hostetter & Alibali, 2008). Hostetter & Alibali (2008) further claim that, "gestures occur as the result of simulated action and perception, which are the bases of mental imagery and language production" (p. 511) Thus gesture can be considered in part an outward representation of internal simulated action and perception.

Due to the mounting evidence that conceptual processes are grounded in our perception and action in the world and built upon perceptually-based internal representations, scholars have begun to consider the pedagogical implications of such findings. Some researchers recommend that, rather than focusing solely on "abstract" knowledge, as often occurs in classrooms, students should be offered opportunities to co-opt perceptual processes to aid in tasks that require abstract reasoning. Goldstone, Landy & Son (2010), for example, suggest that scientific and mathematical reasoning is grounded in perceptual processing and curricula should be aimed at guiding students toward adapting their perception to support abstract reasoning:

> "For both science and mathematics, relatively sophisticated performance is achieved not by ignoring perceptual features in favor of deep conceptual features, but rather by adapting perceptual processing so as to conform with and support formally sanctioned processes." (Goldstone, Landy & Son, 2010).

A key component to leveraging perceptual processes to support learning is to offer opportunities for students to "actively interpret perceptually present situations" in order to train their perceptual systems (Goldstone, Landy & Son, 2010).

Such pedagogical approaches that focus on grounding understanding of abstract concepts in perception and action may be especially successful in science classrooms. Lindrgen & Abrahamson (in press) argue that learning, particularly in STEM disciplines, involves coordinating two cognitive systems: the primitive and the formal, and that deep understanding of formal analysis (as is typically the goal in classrooms) is "grounded in unmediated interactions with the physical world". (p. 2) Thus, embodied learning, by building upon our interactions with the physical world, can serve to ground abstract conceptual understanding. One key context for such a process in learning science is in the classroom science laboratory, where students often attempt to coordinate the formal knowledge of the domain with their intuitive understanding of the physical world.

Laboratory Environments in Science Classrooms

Laboratories have played a prominent role in science classrooms for several decades, used to help students with any combination of the three major goals of science classrooms: learning science (developing conceptual knowledge), learning about science (building an understanding of the nature and methods of science), and doing science (engaging in scientific inquiry) (Hodson, 1996). Physical laboratory environments, which consist of real-world materials and equipment, and computer simulations – digital, dynamic, interactive representations of a phenomena or process – each have a long history within classroom science laboratories, both in K-12 and higher education settings (Hodson, 1996).

Over the past few decades, several research studies have attempted to investigate the value of using physical laboratory environments and virtual laboratory environments within science classrooms to support student learning (Olympiou & Zacharia, 2012). Though much of the research on physical and virtual science investigations has treated physical experimentation and computer simulations as competing methods in science classrooms (Jaakola & Nurmi, 2008), recent research suggests that virtual and physical experimentation each have unique but somewhat overlapping affordances for learning (Olympiou & Zacharia, 2012) and several authors are beginning to suggest that a combination of physical and virtual laboratories should be considered in science classrooms. The following section will review this research on physical and virtual experimentation and evaluate gaps in the literature. Specifically, it will address where it is still unclear exactly *how* students learn with physical and virtual materials in science laboratory environments, and where it is still unclear *how* and *when* they should be combined.

Comparing Physical And Virtual Science Laboratories

When directly comparing physical and virtual experimentation, several studies have found no significant and consistent difference between simulations and physical laboratories (Triona, Klahr & Williams, 2005; Ma & Nickerson, 2006; Zacharia & Constantinou, 2008; Zacharia & Olympiou, 2011). However, there have also been instances where the use of virtual laboratories have better supported student learning than physical laboratories (Finkelstein et al., 2005; Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008). Though this may suggest that physical laboratories have little to offer learners when compared with purely virtual environments, when considering combinations of physical and virtual experiments in comparison to each by itself, several studies have found that combined physical/virtual experiments can be more beneficial for learning than either form alone (Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008; Jaakkola & Nurmi, 2008) though that is not always the case (Zacharia, 2010).

Some authors (e.g. Zacharia, Olympiou, & Papaevripidou, 2008; Olympio & Zacharia, 2012) argue that the reason that combinations of physical and virtual experiments often better support learning than either form alone is that physical and virtual materials offer different but overlapping affordances for learning (Olympio & Zacharia, 2012).[1] Physical laboratory environments and computer simulations, for example, can introduce students to the important conceptual and procedural knowledge of science and frame students' activities around important concepts in the domain (Hofstein & Lunetta, 2004); can provide perceptual grounding for concepts that might otherwise be

[1] The term affordances, first coined by psychologist James Gibson (1977) and later refined and popularized by cognitive scientist Donald Norman (1999, 2002) refers to the possibilities for action of an environment or object relative to an actor (Norman, 1999).

too abstract to be easily understood (Winn et al., 2006); and can provide exposure to scientific experimentation and its corresponding skills (Hofstein & Lunetta, 2004). However, only physical laboratory environments offer students experiences that involve the manipulation of the actual items of a lab experiment, helping them to develop perceptual-motor skills (Olympio & Zacharia, 2012). Additionally, conducting physical experiments naturally includes measurement errors, while computer simulations are often designed to avoid measurement error. Competency in the practices of science includes the knowledge of the types of measurement errors that exist in the domain and the ability to appropriately deal with them (Toth, Klahr & Chen, 2000).

Computer simulations, on the other hand, provide opportunities for exploration that would be impractical or impossible with physical materials (Zacharia & Anderson, 2003; Hofstein & Lunetta, 2004). Setting up simulations is often less time consuming than preparing physical investigations, thereby allowing students more time for reflection (Hofstein & Lunetta, 2004). They can also combine multiple representations – verbal, numerical, pictorial, conceptual and graphical – and allow students to perceive variables and conceptual relationships that are not directly observable in the physical environment (Snir, Smith, & Grosslight, 1993; Bell, 2004).

Combining Physical And Virtual Science Laboratories

Given the somewhat unique affordances of physical and virtual materials, several researchers have promoted using a combination of physical and virtual experiments in science laboratories and have offered different reasons for this (Nersessian, 1989; Snir, Smith & Grosslight, 1993; McKinney, 1997; Bell, 2004; Campbell, Bourne, Mosterman, & Brodersen, 2002; Jaakkola & Nurmi, 2008; Jaakkola et al., 2010; Toth et al., 2009;Winn et al., 2006; Yueh& Sheen, 2009; Zacharia & Constantinou, 2008; Zacharia & Olympiou, 2011; Zacharia, Olympiou, & Papaevripidou, 2008). Nersessian (1989) claims that both real and virtual experiments can be directed at facilitating students' conceptual change: simulations can assist students in the "conceptual framework of science" and physical labs can reinforce student conceptions by "demonstrating to what extent the representation matches real phenomenon." McKinney (1997) argues that the use of computer simulations provides a valuable conceptual tool, which "should be augmented with actual experiments in the classroom" (McKinney, 1997, p. 601).

Building from the idea that physical and virtual offer somewhat unique affordances for learning and should be combined in classrooms, some researchers have begun to explore how best to combine them. In choosing a sequential combination of physical and virtual experiments, some authors suggest that using computer simulations *first* can serve as a "cognitive framework" (Zacharia & Anderson, 2003), allowing students to first understand theoretical principles (Jaakkola & Nurmi, 2008) and later apply them to real-world inquiry. Meanwhile, other authors (e.g., Gire et al, 2010) suggest that conducting real-world experiments first provides important grounded, physical experience with the phenomena of interest, which can then be expanded upon and abstracted through a simulation environment. Still other researchers focus less on the sequence and suggest employing a thoughtfully interwoven combination of physical and virtual investigations. Olympiou & Zacharia (2012) found that such a "blended" combination of physical and virtual experiments on light and color – taking advantage of the unique affordances of physical and virtual experimentation in conjunction with the learning objectives of each experiment – was more effective than either purely physical or virtual experiments alone.

In sum, different science laboratory environments can have different affordances for learning, but in terms of building conceptual understanding, the results are not always consistent and there is no clear understanding of why and how these affordances exist. A focus on embodiment in science laboratory environments – how the specific perceptual-motor features of laboratory environments can serve to ground and otherwise influence conceptual understanding – can provide insights into *why* different science laboratory environments have unique affordances for building conceptual understanding of science phenomena.

In sum, different laboratory environments can have different affordances for learning. However, in terms od building conceptual understanding, the results are not always consistent and there is no clear understanding of how and why these affordances exist. A focus on embodiment in science laboratory environments – how the specific perceptual-motor features of a laboratory environment can serve to ground and otherwise influence conceptual understanding – can provide insights into *why* different laboratory environments have unique affordances for building conceptual understanding.

Embodiment and Learning in Science Laboratory Environments

As discussed earlier, there is growing evidence that sensorimotor experience can profoundly influence conceptual processes. Because of this, differences in students' perceptual-motor experiences when engaging in different kinds of science laboratory environments may influence their conceptual understanding. Specifically, the unique affordances of physical and virtual laboratory environments may be at least in part based on the perceptual-motor features of the environment (the actions the environment affords, the variables that are directly visible in the environment, etc.) Below, I will discuss the affordances of physical and virtual laboratories in terms of their perceptual-motor features. Then, I will review the research on emerging "mixed reality" technologies that directly couple digital representations with aspects of the physical world, and I will discuss how they may offer unique perceptual-motor features that further supports student learning beyond individual physical and virtual laboratories.

Virtual Laboratory Environments: Providing Dynamic, Flexible Visual Feedback

As mentioned earlier, there are several practical and theoretical advantages of using virtual experiments in science classrooms. In terms of their perceptual-motor features in relation to building conceptual understanding, computer simulations can "make the invisible visible", offering students multiple, dynamic, linked representations of the underlying science variables, including variables that cannot be measured directly in the physical world (Hofstein & Lunetta, 2004). The dynamic nature and flexibility of digital representations, as well as the ability to directly couple multiple representations (so that a change in one results in an immediate change another), offers unique affordances not available in purely physical environments. In short, virtual experiments can offer rich, flexible, real-time visual feedback to learners in ways that physical experiments cannot (Snir, Smith, & Grosslight, 1993; Bell, 2004). This is a powerful advantage for computer simulations in the classroom, and this may be a primary reason that, in many cases, virtual experiments have been superior to purely physical experiments in supporting student learning.

Physical Laboratory Environments: Providing Haptic Feedback From Physical Objects And Actions

In terms of their perceptual-motor features, physical laboratory environments are unique in that they can incorporate haptic feedback in addition to (relatively limited) visual feedback within the learning environment. Through interaction with physical materials, learners have access to tactile and kinesthetic information beyond what is available in purely virtual environments (Jones, 2000).

There is emerging research that both the perception of force and the perception of bodily movement can affect learning and reasoning. The perception of force has been studied directly in science learning environments, often through supplementing computer simulations with force feedback devices. Indeed, there is some empirical evidence that adding force feedback to dynamic visualizations can affect students' learning, reasoning and motivation (Minogue & Jones, 2006; Jones, Minogue, Tretter, Negishi, & Taylor, 2006; Bivall, Ainsworth & Tibell, 2011). Bivall, Ainsworth & Tibell (2011), for example, added a force feedback interface to a 3-D visual model of chemical structures to allow students to feel, as well as see, the interactions between molecules. Students who used the model augmented with force feedback learned more overall and incorporated more force-based explanations in their reasoning about molecules than did students with the visual-only model. The addition of force feedback, they contend, may have also prevented students from drawing erroneous conclusions that were observed with students who used the visual-only model. Though this work was done in the domain of chemistry, it may easily apply to other domains as well. For example, incorporating haptic feedback into physics learning environments may similarly influence students' reasoning and may be particularly beneficial for helping students to build accurate conceptions of force.

In addition to the perception of force, bodily movement and the resulting perception of one's own body movement may also influence learning and reasoning. There is growing evidence that action plays a central role in cognition and can have an effect on conceptual processing. Bodily movement can unconsciously influence problem solving and spatial reasoning (Thomas & Lleras, 2009; Thomas & Lleras, 2007). Additionally, actions on objects can affect children's categorization of those objects (Smith, 2005), and children's manipulation of objects during reading can enhance comprehension and memory of the material (Glenberg et al., 2004). Martin (2009) claims that for successfully learning how to solve mathematics problems with real objects, "actions coupled with interpretations serve as developmental precursors to general mathematical procedures, which can later be enacted mentally."

Though there is little research on how body movement may affect conceptual understanding within science laboratory environments specifically, emerging research on the influence of action on conceptual processes suggests that in some cases, physical action and perception of bodily movement may influence learners' conceptual processing somewhat similarly to the perception of force, particularly in grounding understanding of physics concepts that relate to distance and movement (e.g., velocity, acceleration & work).

Combined Physical and Virtual Laboratory Environments

As stated earlier, some research has made the case that by offering students access to both physical and virtual laboratory environments, they are provided the best of both worlds through combining their unique affordances (see Olympiou & Zacharia, 2012, for a review). Indeed, combinations of physical and virtual experiments are often more beneficial for students than either form alone (Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008; Jaakkola & Nurmi, 2008). Part of the reason for this may be perceptual in nature. When performing both physical and virtual investigations, learners are often exposed to both visual and haptic feedback about the phenomena of interest. However, in performing separate physical and virtual experiments, the haptic feedback provided in the physical experiments is largely divorced from the rich visual feedback provided by computer simulations.

There may also be additional benefits of *directly coupling* the haptic feedback offered by actions on physical materials with the rich, dynamic visual feedback provided in simulation environments. Our experience in the world is inherently multimodal – combining visual, auditory and haptic information – and mental representation itself may be multimodal as well (Barsalou, 1999). As such, the specific perceptual *combinations* of modalities utilized in interacting within a learning environment can also play an important role in conceptual understanding.

To understand how multimodal representations of scientific phenomena may influence learning, we can draw from Barsalou's theory of grounded cognition (Barsalou, 1999, 2003, 2009; Barsalou et al., 2003). According to Barsalou, concepts are built upon multimodal mental representations of events, which can be reenacted through mental simulation, and a fully functional conceptual system can be built upon these reenactment mechanisms. Indeed, current evidence from the neuroscience literature points to the existence of multimodal mental representations that may be flexibly accessed via either knowledge-driven or stimulus-driven processes (Lacey, Campbell & Sathian, 2007) and that haptic and visual information, in particular, share overlapping neural networks (Lederman & Klatzky, 2009).

If mental representation of concepts is indeed multimodal, offering directly coupled, visual-haptic science learning environments may provide important benefits beyond separate physical and virtual environments. For example, if in a physics learning environment, an abstract representation such as a force vector is repeatedly paired with the forces a learner applies to an object, this pairing may create a multimodal representation that contains both the visually perceived force vector and the learner's perception of force applied to the object. According to Barsalou's theory, later reenactments of either the force vector or the feeling of force on the object may trigger activation of the other modal representation. The ability to provide integrated, multimodal experiences may help build multimodal internal representations, which may lead to a more complete mental model of the intended phenomenon (Minogue and Jones, 2006). Directly coupling the rich, haptic information of physical objects and environments with the flexible, dynamic visual representations may help learners to actively interpret their multimodal experience of science phenomena and to build coherent, multimodal mental representations of science concepts.

Mixed Reality Technologies: New Opportunities for Embodied Science Learning

With emerging technologies, there are expanding possibilities for science learning environments, and designers of science laboratory environments can go beyond purely physical or purely virtual laboratories (or a sequence of one then the other). There are a growing number of technologies that combine digital information with elements of the physical world, for example through the overlaying of digital information onto the real world (augmented reality), the manipulation of physical objects with computational capabilities (tangible interfaces), and the addition of touch-based feedback to computer interfaces (haptic interfaces). These “Mixed Reality” technologies (Milgram, Takemura, Utsumi & Kishino, 1994) are becoming increasingly ubiquitous and less costly and may be of significant benefit to education (O’Malley & Fraser, 2004), but we are only beginning to understand how such technologies can affect learning (Marshall, 2007).

By incorporating physical actions and objects with digital representations, mixed reality learning environments can be designed to tightly integrate haptic and visual perceptual modalities in ways not possible with purely physical or virtual environments or with sequential combinations of the two. For example, actions on physical objects can be directly coupled with the formal representations of mathematics and science (e.g., graphs, vectors, equations) to allow learners to actively interpret one in terms of the other. Indeed, other researchers suggest that tightly coupling physical objects and actions with digital representations is one area where mixed reality technologies can be used to bridge the “abstraction gap” between everyday experience and the abstract, formal understanding of the domain of interest (Zufferey, Jermann, Do Lenh & Dillenbourg 2009). Beyond supporting abstraction, researchers also claim that mixed reality learning environments can support student exploration and reflection, through unique mappings between the physical and digital worlds and new ways of interacting (Rogers et al., 2002, Price et al., 2003), by combining the ease of manipulating physical objects with the flexibility of digital representations (Manches, O’Malley & Benford, 2009), and by creating a controlled context for physical interaction with content “from which foundational concepts can be explored and articulated" (Lindgren & Johnson-Glenberg, 2013).

In recent years, there have been some initial attempts to use mixed reality environments in science classrooms. For example, SMALLab (Tolentino et al., 2009; Birchfield, D. & Megowan-Romanowicz, 2009; Johnson-Glenberg, Birchfield, Savvides & Megowan-Romanowicz, 2010) is a platform for semi-immersive, mixed-reality learning where students can interact with dynamic visualizations projected onto the floor through the manipulation of physical objects and through gesture. It has been shown to benefit students significantly more than traditional classroom instruction (Johnson-Glenberg, Birchfield, Savvides & Megowan-Romanowicz, 2010). Another approach of mixing the physical and virtual – adding force feedback to digital simulations – has also been shown to support student learning (Bivall, Ainsworth & Tibell, 2012).

Though these approaches show some initial promise, as Lindgren & Johnson-Glenberg (2013) point out, research on the use of mixed reality technologies for learning "has been disparate, driven largely by specific technical innovations and constraints, and often lacking a clear focus on establishing their efficiency in educational contexts" (p. 445). For example, we know very little about how a mixed reality laboratory environment in a classroom would compare to traditional physical laboratories or purely virtual laboratories or to sequential combinations of the two.

Embodiment & Learning in Physics Classroom Contexts

A focus on embodiment in science laboratory environments – considering the influence of perception and action on conceptual processing – may be particularly beneficial in physics classroom contexts. Despite decades of research on physics education, learning physics remains difficult for students (Duit, Niedderer & Schecker, 2007). Many students see physics as overly abstract and complex and have difficulty connecting the formal physics of the classroom to their perceptual-motor experience in the world. Part of the problem for students is that physics knowledge exists on multiple epistemic planes at once (Schwartz & Black, 1999). That is, students come to the classroom with intuitive, body-based physics knowledge (Clement, 1980; diSessa, 1983; diSessa, 1993) while formal physics instruction deals largely with symbolic and verbal propositions including formal mathematical models (Schwartz & Black, 1999). Thus, "naïve physical intuition and formal instruction do not always make contact" (Schwartz & Black, 1999, p. 134). Though physics experts are able to fluidly connect the knowledge structures of formalized physics to intuitive body-based knowledge, many students have difficulties connecting intuitive and formal physics, and harbor misconceptions as a result (diSessa, 1983; diSessa, 1993; Clement, 1980).

Because of the prevalence of this problem of students connecting formal physics to their everyday sensori-motor experience of the world, considering embodiment in physics classrooms in particular may be extremely beneficial. In early work so far exploring embodiment in physics contexts, Johnson-Glenberg et al. (2013), compared students performing a highly embodied interaction (e.g., physically swinging a trackable object over their head) compared to a low-embodiment experience of the same phenomena (e.g., clicking the mouse to initiate a spinning simulation) on their knowledge of centripetal force. During the immediate posttest, all participants demonstrated equally significant learning gains; however, results on a 1-week follow-up revealed that only the high–embodied learning condition continued to show gains in physics knowledge.

Based on emerging work on embodiment in learning environments, a key feature of learning environments is the congruency between the actions taken in the environment and the intended concepts to be learned (Lindgren & Johnson-Glenberg, 2013). Physics offers a plethora of concepts that are directly congruent with actions that can be taken in the environment. For example, the formal concept of force within classical mechanics is directly congruent with the perception of force that occurs in lifting an object. It may be the case that physical laboratories that allow students to physically lift a real-world object may better support the concept of force than virtual laboratories that afford no such action. Meanwhile, virtual experiments may better support understanding of concepts that can't be directly perceived in the physical environment, such as the concept of work.

Mixed Reality Technologies in Physics Contexts

In addition to physics classroom contexts being especially good contexts for studying embodiment and learning, the use of mixed reality laboratory environments may also be especially useful in physics contexts, where digital representations can be used in real-time to shape how students interpret their actions in the physical world. By directly integrating the familiar physical world with the abstract formalisms of physics, mixed reality physics laboratory environments may help learners to connect their everyday experience of force and movement to the abstract ideas of the classroom better than with separate physical and virtual experiments.

Earlier, I have argued that coupling the haptic feedback of physical materials with the flexible, dynamic visual feedback of computer simulations may be beneficial for student learning in science laboratory environments, especially in physics. Though there is some research to suggest that this might be the case, it is still clearly an open question as to whether such mixed reality learning environments can provide unique affordances for learning above and beyond individual physical and virtual experiments.

Measuring Influences of Perception and Action on Learning in Science Laboratories

Studying embodiment and learning in science laboratory environments may offer additional methods for measuring conceptual understanding beyond traditional concept tests and verbal interviews. If the perceptual-motor features of laboratory environments shape learners' conceptions of science phenomena, how do we as researchers measure changes to learners' conceptions in a way that detects influences of perception as well? Typically, the existing research on physical and virtual science laboratory environments relies primarily on concept tests with occasional verbal interviews to detect changes in conceptual understanding. However, none of this research to date has focused on learners' gestures as a way to understand underlying mental representation of abstract science concepts.

Gesture is often considered as evidence of the embodiment of language and cognition, and much evidence suggests that gestures are "outward representations" of mental imagery and simulations (Hostetter & Alibali, 2008; McNeill, 1992, 2008). Such internal representations (including simulated action and perception) retain the spatial, physical and kinesthetic properties of the events they represent (Gibbs & Berg, 2002), and are contrasted with verbal representations (descriptions in natural language,) and propositional representations (systems of abstract, amodal symbols and predicates describing the relationships between symbols) (Hostetter & Alibali, 2008). Though traditional concept tests can reveal learners' verbal and propositional representations relatively easily, illustrating learners' underlying mental imagery can be more difficult.

Analyzing learners' gestures can be a powerful way to reveal underlying mental imagery that is not easily accessed through other methods, and provide insights into the particular perceptual-motor features of learning environments that learners internalized. If conceptual processing is built upon perceptually-based internal representations such as mental imagery and simulated action (Goldstone, Landy & Son, 2008; Barsalou, 2009), and gestures are outward manifestations of such internal representations (Hostetter & Alibali, 2008; McNeill, 1992, 2008), analyzing learners' gestures can be crucial in fully evaluating conceptual understanding. Indeed, some researchers suggest that examining how people gesture as they speak about artifacts they have just learned to manipulate helps us understand how physical interactions develop into simulated actions that impact future physical and cognitive performance (Goldin-Meadow & Beilock, 2010; Kirsh, 2013).

In the case of science laboratory environments, interactions with environments containing different perceptual-motor properties may lead to different internal simulated action and perception, which may be more accessible through gesture than through verbal descriptions of the science concepts. The perceptual-motor properties of laboratory environments may shape learner conceptions in ways that are sometimes not detected on written tests and through verbal descriptions during interviews. In addition to concept tests and verbal interviews, recording and analyzing learners' gestures while they explain abstract concepts may provide insights into mental representations not previously available in research on science laboratory environments.

Research Questions

The overarching aim of the research described in this dissertation was to investigate the influence of the perceptual-motor features of science laboratory environments on learners' conceptual understanding. As reviewed above, prior research on physical and virtual laboratories suggests that each form of experimentation offers different but overlapping affordances for learning. The overall goal of this study was to explore whether the affordances of different science laboratory environments are at least partly perceptually-based: how the unique perceptual-motor features of physical and virtual laboratory environments (and combinations thereof) may influence learners' conceptual understanding of science phenomena.

As described in the above review of the literature, there are four major possibilities for combinations of physical and virtual experiments in science classrooms, each with unique perceptual-motor aspects within the learning environment: completely physical laboratories, completely virtual laboratories, sequential combinations of physical and virtual laboratories, and mixed reality laboratories that directly couple physical and virtual elements. Given these four major possibilities for science laboratory environments, this study was designed to explore how the unique perceptual-motor features of physical, virtual and combined physical-virtual laboratory environments shape learners' conceptual understanding within physics contexts.

Specifically, the study aimed to address the following research questions:

RQ1). Do the unique perceptual-motor features of different physics laboratory environments lead to differences in learners' ***overall understanding*** *of physics concepts?*

RQ2). *Do the unique perceptual-motor features of different laboratory environments lead to differences in learners' understanding of* ***specific physics principles****?*

RQ3). *Do the unique perceptual-motor features of different physics laboratory environments lead to* ***specific misconceptions*** *about the nature of force and work?*

The findings from these research questions are addressed in Chapter 4 of this dissertation.

Beyond evaluating conceptual understanding based on concept tests and verbal responses during interviews, students may also reveal differences in their internal representations of concepts through their gestures. Because of this, Chapter 5 addresses the following research question:

RQ4*). Do the unique perceptual-motor features of physics laboratory environments lead to different* ***patterns of learners' gestures*** *as they explain physics concepts?*

The specific research questions, hypotheses and motivations for each will be discussed further in Chapters 4 and 5. Generally, this study was designed to contribute to the existing literature in the following ways:

1. Focusing on the unique perceptual-motor features of science laboratory environments may provide insights into *why* physical and virtual laboratory environments (and combinations thereof) have different affordances for learning; such affordances in part may be perceptually-based. Further, such affordances may be contingent on particular concepts (or groups of concepts) and the relationship between the concepts and learners' perception and action around those concepts in

within the laboratory environment. Thus, different perceptual-motor aspects of science laboratory environments may serve to ground abstract science concepts in different ways, leading to distinctions between laboratory environments in how they support learning of different science concepts.

2. Focusing on learners' gestures in addition to conceptual knowledge (as measured by concept tests) may offer additional insights into how the perceptual-motor features of laboratory environments influence students' conceptions. Perceptual-motor aspects of science laboratory environments may be internalized by learners in the form of simulated action, which can then be revealed through learners' gestures. The details of learners' gestures after interacting with different laboratory environments thus may provide further insights into *how* the perceptual-motor properties of laboratory environments influence conception beyond what can be understood by analyzing conceptual tests and verbal interviews.

The following chapter discusses the overall study design and research methods for addressing the above research questions. Chapter 4 then describes the analysis, results and conclusions in addressing the first three research questions investigating the influence of the perceptual-motor features of laboratory environments on conceptual understanding. Chapter 5 then describes the analysis, results and conclusions in addressing the fourth research question investigating the influence of the perceptual-motor features of laboratory environments on students' gesture and simulated action. Finally, Chapter 6 discusses the overarching conclusions and implications of this study.

Chapter 3: Study Design and Research Methods

Building upon prior research on embodiment and learning as well as physical and virtual science laboratory environments, the study described in this dissertation attempted to explore how the perceptual-motor features of physics laboratory environments – including physical, virtual, sequential combinations of physical and virtual, and mixed-reality laboratory environments – influence learners' conceptual understanding. The study was conducted in the context of an undergraduate physics laboratory, where 110 participants performed experiments with inclined planes in order to learn about the concepts of force, work, potential energy and mechanical advantage. This chapter describes the overall research methods for this study: the design of the individual learning environments, the experimental task and conditions employed as well as the setting and participants, all of which were common across all parts of the study. Later chapters address the specific data sources and analyses used to address more specific research questions.

Design of Learning Environments

This study incorporated four different inclined plane laboratory environments: a physical laboratory environment, a virtual laboratory environment, a sequential physical-virtual laboratory environment, and an integrated physical-virtual laboratory environment. There were several reasons for exploring the influence of the perceptual-motor features of laboratory environments on students' conception in the context of inclined planes. As discussed earlier, though physics generally and classical mechanics in particular can provide rich opportunities for connecting the abstract concepts of the domain to everyday sensori-motor experience, students continue to struggle in connecting these two epistemic planes. Second, simple machines are often taught in introductory mechanics courses in both primary and secondary school, and thus offer an early point in the curriculum to investigate how laboratory environments may serve to best build abstract conceptual understanding from everyday experience. The final reason was one of convenience: our research group has conducted several studies using the CoMPASS simple machines curriculum (e.g. Puntambekar, Stylianou & Goldstein, 2007; Gire et al., 2010; Chini et al., 2012), and three of the four laboratory environments (Physical, Virtual and Sequential) used in this study had been utilized in prior research.

The details of each laboratory environment, the design decisions made for each, and their specific perceptual-motor properties are discussed below.

Physical Laboratory Environment

The physical laboratory environment included three wooden ramps of different lengths (.6 meters, .9 meters, 1.2 meters), a wooden support (adjustable to height of .1 m, .25m, or .35m) for placing one end of the ramp, a brick (weighing roughly 8 Newtons) for students to pull up each ramp, and a spring scale that attached to the brick for measuring the amount of applied force necessary to pull the brick up the ramp (see *Figure 1*). The brick had a hook to attach to the spring scale and felt pads on the bottom to reduce the amount of friction between the brick and the ramp. The physical inclined plane laboratory environment was developed as part of the CoMPASS simple machines curriculum and had been used in several prior studies on inquiry physics curricula in both middle school and undergraduate settings (e.g. Puntambekar, Stylianou & Goldstein, 2007; Gire et al., 2010; Chini et al., 2012).

In terms of the specific perceptual-motor features of the environment, the physical laboratory provided multimodal feedback when moving the block up the ramp – including haptic feedback of the force required to move the block and of the arm movement required to lift the block up the ramp, as well as the visual feedback of the spring scale reading. However, in terms of visually displaying the underlying physics concepts, the visual feedback provided was fairly limited. Though the amount of force required was visible through the spring scale measurement, the values of work and potential energy were not perceptually present to the learners during their actions; they needed to be calculated at the end of each trial (see *Figure 1*).

Figure 1. Physical inclined plane laboratory environments for *Physical-only* condition.

Virtual Laboratory Environment

The virtual laboratory environment comprised of a computer simulation that was run on a laptop computer with a mouse attached (see *Figure 2*). The simulation consisted of a virtual inclined plane, where the height and length could be adjusted (the length from .1 to 2 meters, and the height from .1 to .5 meters), a virtual brick that could range in weight from .1 Newtons to 10 Newtons, a set of sliders and text boxes for adjusting those values, and dynamic bar graphs that display the resulting applied force, work, potential energy and mechanical advantage in real-time. The simulation allowed for students to "pull" the virtual brick up the inclined plane using the mouse. Once the student pulled with enough applied force to move the brick up the ramp (as determined by the distance they have dragged the mouse cursor) the brick would move up the ramp and the values of the bar graph would update as the brick moved up the ramp. The brick would then automatically stop at the top of the ramp.

The simulation was designed specifically for use with physical inclined plane environment (described above) for the CoMPASS simple machines curriculum, with the following pedagogical goals in mind:

1. The simulation allowed students to directly see the dynamically-changing variables that they could not see directly in the physical experiment. This included seeing that work and potential energy increased as the brick moved up the inclined plane. (These variables both needed to be calculated at the end of the experiment with the physical laboratory environment.)
2. The simulation also originally was designed to allow students to observe what would happen in a frictionless environment. As will later be described, this particular feature of the simulation was not utilized for this study.

Other aspects of the simulation were specifically designed to match the physical laboratory environment as closely as possible: with a 3D representation of a brick and a board, it presented a similar level of visual abstraction to the physical environment, students still had to "drag" the brick up the ramp using the mouse, and the range of values for the ramp length and height and the weight of the brick included those of the physical environment. Further, the version of the simulation used in this study inserted equivalent levels of measurement error and friction into the simulation so that students got similar results for their experiments whether they were utilizing the physical or virtual laboratory environment.

In terms of the perceptual-motor features of the environment, while work and potential energy needed to be calculated in the physical experiments, they were calculated and displayed in real-time by the simulation and were thus visible to the learners. However, compared to the physical environment, the haptic feedback provided was limited. There was some force feedback in terms of the resistance between the computer mouse and mouse pad when dragging the virtual block up the virtual ramp, but this resistance was constant and did not vary with the force needed to lift the virtual block. There was also limited feedback on the learner's motion when using the mouse to lift up the block. The arm movement required to lift the virtual block using the mouse did relate to the length of the ramp, but it was a much smaller scale and likely was not as noticeable to learners as the movement required in the physical experiment.

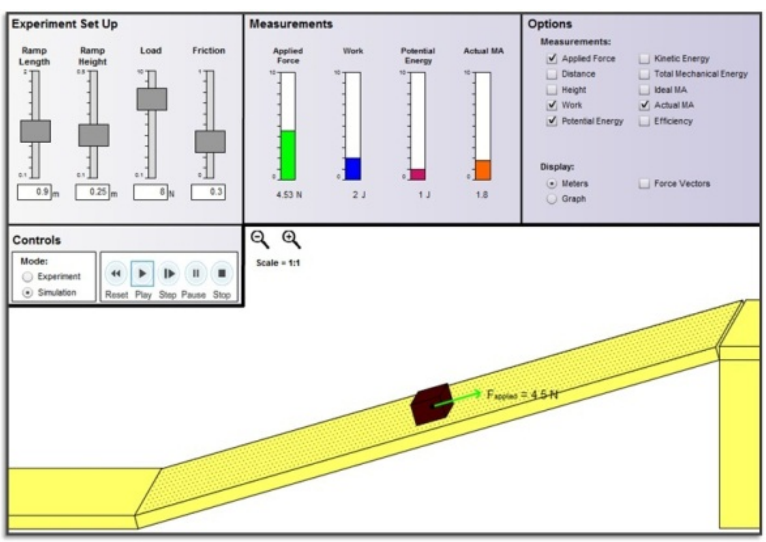

Figure 2. Inclined plane simulation used for Virtual-Only condition.

Sequential Physical-Virtual Laboratory Environments

For this study, a “Sequential Physical-Virtual” laboratory environment was also set up that was simply a sequential combination of the separate physical and virtual laboratories (see *Figure 3*). Students performed experiments in this laboratory environment either by performing a physical experiment followed by a virtual experiment, or vice versa.

In terms of the specific perceptual-motor features of the environment, this environment provided both the haptic feedback of the physical experiment and the visual feedback of the virtual experiment (as described above). However, the haptic feedback was not perceptually present *at the same time* as the visual feedback provided in the virtual environment.

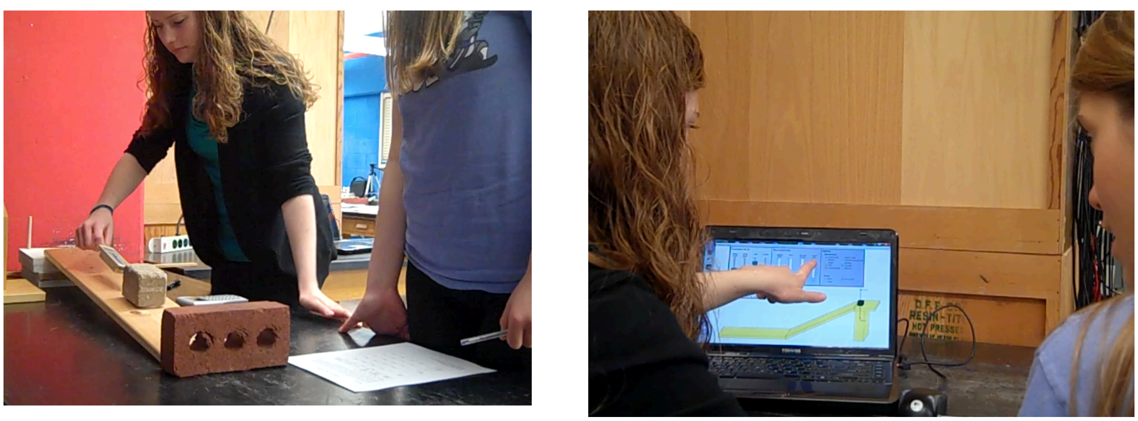

Figure 3. Physical (left) and virtual (right) inclined plane laboratory environments for *Sequential Physical-Virtual* condition.

Integrated Physical-Virtual Laboratory Environment

A fourth and final laboratory environment for this study directly integrated the physical laboratory environment and the virtual laboratory environments (as described above) through the use of mixed reality technologies (see *Figure 4*). Unlike the physical and virtual laboratory environments, the mixed reality inclined plane laboratory environment was designed specifically for this study. As such, it combined the same materials used in the physical laboratory with the same visual representations used in the computer simulation. In order to directly integrate the physical and virtual experiments, the location and orientation of the block as well as the force currently being applied to it must be known. In this environment, an electronic force sensor was used to track the amount of force applied while pulling the block up the inclined plane. A 2D fiducial marker on the block was tracked by a webcam, allowing for tracking of the position and orientation of the block. These inputs were fed to a laptop, and additional variables (e.g. work, distance and height) were calculated based on these input values. A projector displayed the resulting representations onto a screen behind the physical materials.[2]

Like the sequential physical-virtual environment, this laboratory environment provided the perceptual-motor features of both physical and virtual laboratory environments, including haptic and visual feedback of the actions being performed on the block and the associated formal physics variables. However, it offered the potential additional advantage that the haptic feedback was directly coupled with the visual feedback in the form of dynamic digital representations of the formal physics variables.

[2] Though it was not used in this study, the environment also allowed students to explore the same physics phenomenon in a simulation, enabling students to adjust additional variables (e.g. friction, load) that would be impossible or impractical in physical experiments. To adjust values of the simulation, an infrared pen was read by an infrared camera in a Nintendo Wii remote and also sent to the computer, allowing for students to manipulate the environment at the screen without a separate keyboard or mouse interface.

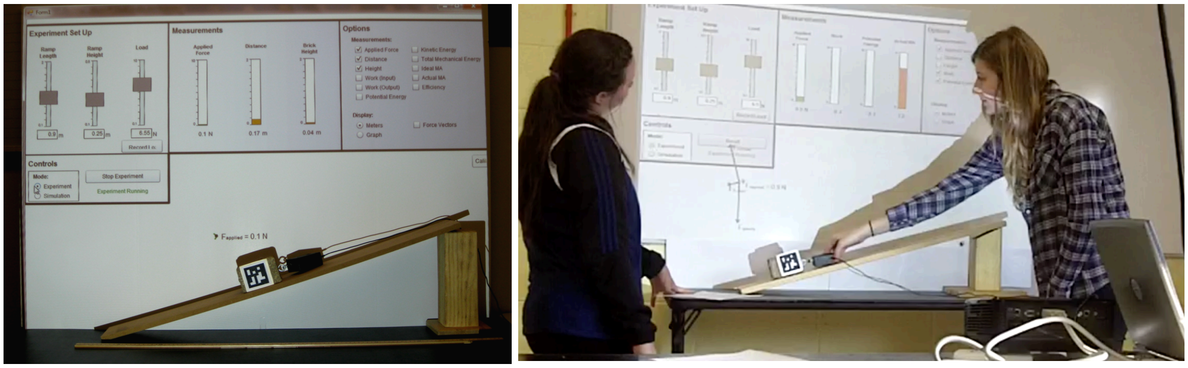

Figure 4. Mixed reality inclined plane laboratory environment for *Integrated Physical-Virtual* condition.

Experimental Task

Participants in this study were asked to complete two inclined plane experiments, which were developed as part of the CoMPASS simple machines curriculum (Puntambekar, Stylianou & Goldstein, 2007). Participants, working in dyads, were given a worksheet with instructions on performing the experiments, as well as a data table to fill out for each experiment (see Appendix A). The first experiment was the *length* experiment, in which participants investigated the effect of three different inclined plane lengths on the amount of force required to lift a block to the top of the ramp, the amount of work done when lifting the block, and the change in potential energy. Following the length experiment, participants completed a second experiment, the *height* experiment, investigating the effects of three different heights of inclined planes on force, work, and potential energy. During each experiment, participants were asked to fill out a data table where the three pre-determined values for the manipulated variable (length or height) as well the variables to be recorded (force, work, potential energy and mechanical advantage) were pre-populated. After each experiment, participants were given a set of observation and analysis questions and asked to discuss their answers to the questions (see below). Trials of each experiment were conducted twice. In the first trial, one participant performed the experiment and the other recorded the results. In the second trial, the roles were reversed so that all participants had approximately the same amount of time performing the experiments. The total task took approximately 45 minutes, with an additional 15 minutes for the pre and post tests and surveys (see *Figure 5*).

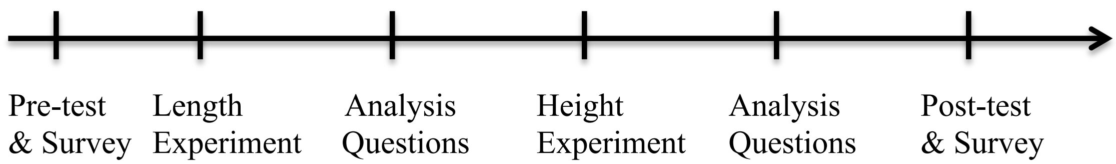

Figure 5. Sequence of activities for participants in Study 1.

Experimental Conditions

The participants (in dyads) were randomly assigned to one of four conditions prior to the experimental task: *Physical-only*, *Virtual-only*, *Sequential Physical-Virtual* and *Integrated Physical-Virtual*. Each condition corresponded to a different inclined plane laboratory environment, as follows:

Physical-only Condition

In the *Physical-only* condition, students performed the inclined plane experiments within the physical laboratory environment (as described above). Students pulled a block up an inclined plane, using a spring scale to measure the amount of force it took to move the block up the ramp. They then calculated the work needed to move the block up the ramp and the potential energy at the top of the ramp using the provided equations. Three different ramp lengths, and different height supports were provided for running the length and height experiments.

In performing the length and height experiments in the *Physical-only* condition, students could see the amount of force needed to pull the block up the ramp through the reading on the spring scale. Additionally, they could physically feel the amount of force required when pulling the block up the ramp. For work, potential energy and mechanical advantage, they calculated the value after each trial using a calculator and given formulas.

Virtual-only Condition

Participants in the *Virtual-only* condition used the computer simulation to complete the inclined plane experiments. Students pulled a virtual block up an inclined plane using a mouse. The simulation provided values for the force required to move the block up the inclined plane, as well as the work done and potential energy of the block in real-time. Participants used the same inclined plane lengths and heights as in the physical experiment.

Unlike those in the *Physical-only* condition, students in the *Virtual-only* condition did not receive haptic feedback on the amount of force required to pull the brick up the ramp. The only feedback on force was visual in nature, (in the form of a force vector and a dynamic bar graph in the simulation). Additionally, students in this condition did not perform the physical, real-world action of pulling a block up a ramp. Instead, they "dragged" the virtual block up the ramp by moving the computer mouse. Students in the *Virtual-only* condition, however, did receive additional visual feedback on work, potential energy and mechanical advantage than those in the *Physical-only* condition. Rather than needing to calculate final values of these variables after each trial, the simulations provided dynamic bar graphs and numerical values representing the values of each of these variables in real time. So, students in this condition could visually see that both work and potential energy increased as the block moves up the ramp, while mechanical advantage remained constant.

Since many researchers (e.g., Triona, Klahr & Williams, 2005) argue that virtual experiments can support student learning as well as physical experiments, the existence of the *Virtual-only* condition allowed for determining whether combinations of physical and virtual experiments are preferable to entirely virtual experiments at all.

Sequential Physical-Virtual Condition

In the *Sequential Physical-Virtual* condition, participants still performed the length experiment followed by the height experiment, but one of the experiments was physical and the other virtual. For half of the participants in this condition (N=14, randomly assigned), they first performed the length experiment within the physical laboratory environment (as in the *Physical-only* condition*)* and then performed the height experiment with the computer simulation (as in the *Virtual-only* condition) (see *Figure 3*). For the other half of the participants in this condition (N=14, randomly assigned), they performed a virtual length experiment followed by a physical height experiment. Balancing the sequence of physical and virtual experiments allowed for evaluation of whether the particular sequence of physical and virtual experiments was important in this context.

Overall, this condition allowed for analyzing whether a simple, sequential combination of physical and virtual experiments will support student learning better than either form alone, as has been shown in some cases (e.g., Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008; Jaakkola & Nurmi, 2008). Students in this condition had the perceptual-motor experiences of the *Physical-only* condition during one experiment and the perceptual-motor experiences of the *Virtual-only* condition during the other experiment. This condition allowed for investigating whether simply providing some haptic feedback on force as well as some visual feedback on work and potential energy provided the advantages of both the physical and virtual laboratories for these concepts.

Integrated Physical-Virtual Condition

In the *Integrated Physical-Virtual* condition, participants completed the length and height experiments within a mixed-reality learning environment that combined the real-world materials from the inclined plane physical experiment and projected digital representations (e.g. graphs, numeric values, vectors) of formal variables (e.g. force, work, potential energy) onto the surface behind the experiment. In this condition, students performed both the length and height experiment with physical materials while the relevant physics variables (force, work, potential energy, mechanical advantage) were projected onto the environment.

As in the *Sequential Physical-Virtual* condition, students in this condition received both the haptic feedback of the force needed to pull the brick up the ramp. They also performed the real-world action of pulling the brick on the ramp. Additionally, they saw dynamic representations of work and potential energy as they pulled the brick up the ramp. Unlike those students in the *Sequential Physical-Virtual* condition, however, they received this haptic and visual feedback *at the same time* and during both the length and height experiments. This condition allowed for investigating whether providing directly-coupled haptic and visual feedback at the same time (not just the mere presence of each) may offer students further opportunities to reflect on the relationships between them and, in turn, develop a deeper understanding of the underlying formal physics.

Across all experimental conditions, the inclined plane environment (physical, virtual or mixed) had the same (small) amount of friction and measurement error to control for those variables across the different conditions. Though virtual environments can display an idealized world without friction and measurement error, in order to keep the conditions comparable, the virtual environments in this experiment contained an equivalent amount of friction and variability in measurement as the physical environment. This may also be beneficial for learning, as Chen (2010) has asserted that virtual science learning environments often display a too idealized world, leading to a limited view on experimentation.

Based on the specific designs of the four learning environments and the four corresponding experimental conditions, this study could offer certain insights in comparing these laboratory environments, but it was also limited in some ways by the design decisions made. First, the laboratory environments and conditions were designed to compare some key perceptual-motor features that are typical of physical and virtual laboratory environments, namely that physical laboratories can offer physical actions and haptic feedback that virtual environments typically do not, while virtual laboratory environments typically allow students to directly see the changing values of variables that physical laboratory environments typically do not. To compare laboratory environments primarily on the existence of these two perceptual-motor features, the physical and virtual environments were otherwise designed to match each other as closely as possible. This included restricting the virtual environment to simulate levels of friction equivalent to that in the physical experiment and to add measurement error to the simulation that matched that of the simulation. This limited an affordance of virtual experiments: to display what would happen in an idealized environment. Because of this, any results from this study comparing physical and virtual experiments should focus on the particular perceptual-motor features that were distinct between the two environments and not be generalized to all physical and virtual experiments.

Similarly, the Sequential Physical-Virtual laboratory environment was simply a sequential combination of the physical laboratory and virtual laboratory. Again, this decision was made to determine whether simply providing both the haptic feedback of the physical environment and the visual feedback of the virtual environment (though not at the same time) would better support learning than either perceptual-motor feature alone. There are other ways to design a sequential combination of physical and virtual experiments that better take advantage of the affordances of each (see Olympiou & Zacharia, 2012 for an example), but the environment was constrained to investigate the effects of simply combining the physical and virtual sequentially. The Integrated Physical-Virtual environment was similarly constrained to be able to make a fair comparison to the other environments. For the purposes of this study, the Integrated Physical-Virtual condition was designed to investigate whether simply combing the haptic feedback of the physical environment with the visual feedback of the virtual environment in real-time would impact student learning. A mixed reality laboratory environment that more fully took advantage of combining physical and virtual elements in real-time may compare differently to physical, virtual, and sequential physical-virtual laboratories than in this study. In effect, the approach of this study could be considered a "minimum differences" comparison, investigating the effects of small, but typical differences in perceptual-motor features between laboratory environments. All four laboratory environments, though somewhat constrained for the purposes of comparison, are fairly typical of physics classrooms. A separate study comparing these four types of environments, but designing them to fully take advantage of the affordances would also offer insights into the efficacy of physical and virtual laboratories and combinations thereof, but would not provide much detail on *why* any differences between environments occurred. This study was designed as a starting point, investigating whether relatively small differences in the perceptual-motor features of laboratory environments would lead to differences in students' conceptual understanding of physics phenomena.

Setting and Participants

A total of 110 participants were randomly assigned to one of the above four conditions (for a total of 28 total participants in each of 3 conditions, 26 participants in the fourth condition). Participants across all conditions consisted of undergraduate elementary education majors at Kansas State University and were recruited from an undergraduate physics class designed for elementary education majors.

The participants consisted of 98 females and 12 males with a median age of 20 years (*SD* = 3.0). Nineteen participants were freshmen, 46 sophomores, 27 juniors and 17 seniors. For the vast majority of students (106), this was their first college-level physics course, though roughly half (57) had covered simple machines previously in their educational career (mostly between 3^{rd} and 8^{th} grade).

Within the course, students were given credit for one of their regular laboratories for participating in this experiment.[3] The study was conducted in the laboratory space that was generally used for this course. Sessions of the experiment lasted approximately one hour. The sessions spanned one week in total, and the experimental conditions were balanced for time of day and for day of the week. Four students participated in the study during each session, and were randomly divided into groups of two. There was one staff member (a teaching assistant, the lecturer, or the researcher) present with each dyad to give instructions on how to complete the experiments. The staff member followed a script in giving instructions on completing the experiments (see Appendix A). The staff members were assigned to the experimental conditions such that each staff member facilitated the study roughly the same number of times for each condition.

Data Sources and Analyses

The two overarching goals of the study were:

1) To investigate the influence of the perceptual-motor features of physics laboratory environments on students' conceptual understanding, as measured by concept tests and interviews.
2) To investigate the influence of the perceptual-motor features of physics laboratory environments on student's gestures, and in turn their internal representations of physics phenomena.

The parts of the study corresponding to each of these overall goals are described in the next two chapters. For each portion of the study, separate data sources and analyses were

[3] Though the laboratory experiments performed were not directly related to previous lectures in the course, the course did previously cover the basic concepts of force, work and potential energy (though not in the context of simple machines).

utilized in answering the specific research questions addressing each goal. For the next two chapters, corresponding to these two overall goals, the specific research questions are outlined, the data sources and analyses employed in addressing the research questions are described, and the results of the analyses are reported and discussed.

Chapter 4: Investigating the Influence of Laboratory Environment on Conceptual Understanding

The overall aim of this study was to investigate the influence of perceptual-motor features of science laboratory environments on learners' conceptual understanding. To address this overarching aim of the research, the first goal was to investigate whether different combinations of physical and virtual physics laboratory environments, with unique but overlapping perceptual-motor features, led to differences in conceptual understanding of physics principles, as measured with concept tests and interviews.

Research Questions and Hypotheses

This chapter aims to answer the following research questions:

RQ1). Do the unique perceptual-motor features of different physics laboratory environments lead to differences in learners' ***overall understanding*** *of physics concepts?*

This research question was addressed by comparing how students performed on a physics concept test after conducting inclined plane experiments in one of four laboratory environments (Physical-only, Virtual-only, Sequential Physical-Virtual and Integrated Physical-Virtual). Based on prior research on physical and virtual laboratory environments in science classrooms, as well as emerging research on embodied cognition, the study tested the following hypotheses:

H1: Students in the *Virtual-only* condition will outperform those in the *Physical-only* condition on the overall concept test.

Prior research comparing physical and virtual experiments has shown virtual experiments to be equally or more beneficial for student learning than physical ones in many contexts (Triona, Klahr & Williams, 2005; Finkelstein et al., 2005; Zacharia, 2007;

Zacharia & Constantinou, 2008; Zacharia & Olympiou, 2011). In this study, the virtual inclined plane environment allowed students to see variables directly (work, potential energy and mechanical advantage) that they had to calculate at the end of the experiments in the physical laboratory environment. This may provide some advantage over the physical laboratory environment. The Virtual-only condition outperforming the Physical-only one would be in keeping with prior results. However, in this study, the simulation did not provide idealized values for the variables without friction or measurement error. This potential advantage of virtual environments was not utilized in this study, so the findings from this study may also align more with prior studies that found no differences between physical and virtual laboratories on students' conceptual understanding.

H2: Students in the *Sequential Physical-Virtual* and *Integrated Physical-Virtual* conditions will outperform those in the *Physical*-only and *Virtual-only* conditions on the overall concept test.

Prior research has found that a sequential combination of physical and virtual experiments has either been as beneficial (e.g., Zacharia & Olympiou, 2011), or more beneficial (e.g., Jaakkola & Nurmi, 2008; Olympiou & Zacharia, 2012) for student learning than either form alone. If physical and virtual experiments do indeed have unique affordances for learning that are at least in part based on their perceptual-motor properties, offering learners opportunities to interact with both physical and virtual experiments may better support student learning than restricting learner interaction to one form or the other.

H3: Students in the *Integrated Physical-Virtual* condition will outperform those in the *Sequential Physical-Virtual* condition on the overall concept test.

Beyond sequential combinations of physical and virtual laboratories that have been previously researched, are there distinct advantages to science laboratories that directly couple visual and haptic feedback? Some research suggests that mixed reality learning environments can aid students' learning and reasoning (e.g., Johnson-Glenberg, Birchfield, Savvides & Megowan-Romanowicz, 2010), but such environments as of yet are typically only compared to traditional lecture-based instruction. By comparing a tightly integrated physical-virtual laboratory to a sequential combination of separate physical and virtual laboratories on students' conceptual understanding, it was hypothesized that there would be unique advantages to offering mixed reality laboratory environments over sequential combinations of separate physical and virtual environments that would appear on an overall concept test.

RQ2). *Do the unique perceptual-motor features of different laboratory environments lead to differences in learners' understanding of* ***specific physics principles****?*

Though prior research comparing physical and virtual experiments has often measured student learning as a whole across many science concepts, there is reason to believe that physical or virtual experiments offer different advantages and disadvantages for learning different science concepts in different situations. Based on emerging work on embodiment and learning, a key feature of learning environments is the congruency between the actions taken in the environment and the intended concepts to be learned (Lindgren & Johnson-Glenberg, 2013). It may be the case, for example, that physical laboratories better support learning of certain concepts while virtual laboratories better support learning of other concepts. Based on the relationships between specific perceptual-motor features of each of the four laboratory environments in this study and the intended concepts to be learned during students' experiments, the following hypotheses were tested concerning this second research question:

H4: Students in the *Physical-only and Integrated Physical-Virtual* conditions will outperform those in the *Virtual-only* condition on the concepts of force and mechanical advantage.

The formal concept of force within classical mechanics is directly congruent with the perception of force that occurs in lifting an object. In this study, the *Physical-only and Integrated Physical-Virtual* conditions both provided learners with direct perception of the force needed to lift the block up the ramp. This direct haptic feedback may positively influence their understanding of force in a way that leads them to more accurately answer questions about force during the concept test and interview. The *Virtual-only* condition, meanwhile, provided no such haptic feedback on the force needed to lift the block on the inclined plane, which may lead students to less accurately understand the concept of force. Since mechanical advantage is directly related to force, there may be some similar patterns with the concept of mechanical advantage, though the effect is likely to be less pronounced. Since the *Sequential Physical-Virtual* condition provides the haptic feedback of physically pulling the block up the ramp in only one of the two experiments, it is further hypothesized that students in this condition will be somewhere in between the *Physical-only* and *Virtual-only* conditions in their understanding of force and mechanical advantage.

These results would correspond with research on science learning environments that has shown that supplementing computer simulations with haptic feedback can support learners' conceptual understanding beyond purely virtual environments (Minogue & Jones, 2006; Jones, Minogue, Tretter, Negishi, & Taylor, 2006; Bivall, Ainsworth & Tibell, 2011). Though most studies comparing completely physical and virtual experiments have not found a distinct advantage for physical experiments in supporting conceptual understanding (cf. Gire et al, 2010), based on our emerging understanding of how perceptual processes influence conceptual processes, there may in fact be unique advantages of physical laboratories in certain domains for certain concepts, based on the haptic feedback physical laboratories can provide.

H5: Students in the *Virtual-only and Integrated Physical-Virtual* conditions will outperform those in the *Physical-only* condition on the concepts of work and potential energy.

As physical laboratories may better support learning concepts such as force, virtual experiments may better support understanding of concepts that cannot be directly perceived in the physical environment, such as the concepts of work and potential energy. In this study, the *Virtual-only and Integrated Physical-Virtual* conditions both provide learners with direct visual feedback on the amount of work being done to lift the block up the inclined plane as well as the current potential energy (as compared to the block at the bottom of the ramp). This direct visual feedback on work and potential energy may positively influence their understanding of these concepts in a way that leads them to more accurately answer questions about work and potential energy during the concept test and interview. For the *Physical-only* condition, meanwhile, students must calculate the work and potential energy at the end of the experiment, which may lead students to less accurately understand these concepts. Since the *Sequential Physical-Virtual* condition provides the same visual feedback on work and potential energy, but only for one of the two experiments, it is further hypothesized that students in this condition will be somewhere in between the *Virtual-only* and *Physical-only* conditions in their understanding of work and potential energy.

RQ3). *Do the unique perceptual-motor features of different physics laboratory environments lead to* ***specific misconceptions*** *about the nature of force and work?*

Beyond a scored understanding of specific physics concepts, the unique perceptual-motor aspects of laboratory environments may lead to different misconceptions about certain concepts. For example, does performing virtual experiments without force feedback lead to increased misconceptions about force? Similarly, does a lack of visual feedback about change in work over time while lifting an object lead to misconceptions about work? There were no specific hypotheses for this research question. Rather, as described in the research methods section, this study investigated this question qualitatively through interviews with participants on their understandings of force and work after completing the experiments.

The research methods employed in answering the above three research questions, the results of the analyses, and conclusions are discussed below.

Research Methods

Data Sources

To investigate the first overall aim of this study – whether the perceptual-motor properties of physics laboratory environments shape learners' understanding of physics concepts – a pre-post physics concept test, in-depth concept interviews, and a brief survey were employed. The concept test measured participants' understanding of key physics concepts within the domain of inclined planes. The interview delved deeper into student's particular conceptions for the key concepts of force and work. The survey allowed for determining whether changes in test scores from pre to post were correlated with participant demographics as well as for better understanding learners' experiences across the four different laboratory environments.

Concept test. To measure participants' learning of physics concepts, all participants (N=110) were given a concept test before beginning the inclined plane experiments and after completing all of the experiments. Multiple-choice test items covered the concepts of force, work, potential energy and mechanical advantage and how they change when manipulating the length and height of an inclined plane. Transfer items were also included that addresses the concepts of force, work and potential energy outside of the context of inclined planes. For select multiple choice items across the test, participants were asked to explain their reasoning for their associated multiple choice answer. The test was based on inclined plane tests from previous years of the CoMPASS simple machines curriculum, which, in past implementations of the curriculum, have been shown to be reliable (See appendix C for test items).

In order to analyze the pre and post-test results, open-ended test items (where participants were asked to explain their reasoning for a multiple choice question) were first scored on a scale from 0 to 2, where a score of 0 indicated that the participant either did not explain their reasoning or gave an incorrect explanation, a score of 1 was given for responses that were partially correct but incomplete, and a score of 2 was given to responses that completely, correctly explained the phenomenon (see Appendix F for scoring rubric). Inter-rater reliability with another researcher was established on 10% of the data, with a Cohen's kappa of .826 (Cohen, 1968).

Pre and post interviews. To better understand participants' conceptions of the key concepts of force and work, 8 participants from each condition were randomly selected for semi-structured pre and post-interviews on their understanding of force and work (N=32). Three questions were asked concerning participants' understanding of force in an inclined plane (see Appendix E for interview protocol):

1. Describe in your own words, the relationship between force and distance in an inclined plane.
2. How much force would you need to raise something using a ramp versus lifting it straight up by hand? Would you need more, less, or the same amount of force? Why?
3. If you are using a ramp, as you are lifting an object up the ramp, do you think the force you need to apply increases, decreases or stays the same during that time? Why?

Similarly, three questions were asked about participants' understanding of work in an inclined plane:

1. Describe in your own words, the relationship between work and distance in an inclined plane.
2. How much work would it take to raise something using a ramp versus lifting it straight up by hand? Would it take more, less, or the same amount of work? Why?
3. If you are using a ramp, as you are lifting an object up the ramp, do you think the work you are doing increases, decreases or stays the same during that time? Why?

The interviews were all conducted by the same researcher and followed the script specified in Appendix E. Participants responses to the questions were all video recorded, and their verbal answers were transcribed.

Surveys. A pre-laboratory survey was given to all participants (N=110) after they completed the concept pre-test, and included questions on the participants' age, gender, year in school, major, background in physics, background with computers, and familiarity with their partner for the experiment (see Appendix D for questions). These questions allowed for checking that these characteristics of participants were balanced across the four experimental conditions as well as to investigate whether any of these characteristics were significantly correlated with participants' improvement from pre-test to post-test.

Analyses and Results

To answer the research questions above comparing completely physical, completely virtual, sequential physical-virtual, and integrated physical-virtual laboratories, first comparisons were made on overall conceptual understanding across the four laboratory environments. Next, the four conditions were compared in more detail, on groups of test items separated by concept and experiment. Finally, secondary analyses were completed to shed further light on the answers to the primary research questions.

For Research Question 1, comparing student conceptual understanding across different laboratory environments on overall conceptual understanding, the four laboratory environments (*Physical-only*, *Virtual-only*, *Sequential Physical-Virtual* and *Integrated Physical-Virtual*) were compared on participants' overall gains in conceptual understanding, as measured by post-test score (with pre-test as a covariate).

For Research Question 2, the four laboratory environments were first compared on participants' gains in conceptual understanding of specific physics principles, as measured by scores on post-test items, grouped by physics principle (with pre-test score on the same items as a covariate). For each of these omnibus tests that were found to be significant, specific comparisons were made to directly address the above hypotheses (i.e.

comparing *Physical-only* vs. *Virtual-only*, *Sequential P-V* vs. *Physical-only* and *Virtual-only*, and *Integrated P-V* vs. *Sequential P-V*).

To further address Research Question 2, data from the pre and post interviews were used to compare students' understanding of force and work across the four conditions. Data from the pre and post interviews were also used to address Research Question 3. Further details of these analyses as well as the results are provided in the next section.

Comparing Overall Conceptual Understanding across Laboratory Environments

Overall results from the pre and post concept test were first used to determine how participants' conceptions of the physics of inclined planes changed after completing the experiments. To analyze the concept test results, a paired t-test was performed to evaluate whether participants' scores as a whole increased significantly from pre-test to post-test (across all conditions). A one-way analysis of covariance (ANCOVA) was then performed to test for overall differences between the four conditions from pre to post on the concept test (with condition as the fixed factor and pre-test score as the covariate). Six planned contrasts were then conducted as needed (based on a significant omnibus ANCOVA) to directly compare the four different conditions with each other. The planned contrasts used a Bonferroni adjusted critical value of .0083 (.05 divided by six contrasts). These comparisons allowed for directly addressing the three hypotheses related to the first research question:

H1: Students in the *Virtual-only* condition will outperform those in the *Physical-only* condition on the overall concept test.

H2: Students in the *Sequential Physical-Virtual* and *Integrated Physical-Virtual* conditions will outperform those in the *Physical*-only and *Virtual-only* conditions on the overall concept test.

H3: Students in the *Integrated Physical-Virtual* condition will outperform those in the *Sequential Physical-Virtual* condition on the overall concept test.

Prior to comparing the different laboratory environments on the overall concept test, a paired-sample t-test was conducted to determine whether students significantly improved overall from pre-test to post-test (across all experimental conditions). Overall, students significantly improved from the pre-test ($M = 15.42$, $SD = 3.59$) to the post-test ($M = 16.81$, $SD = 3.59$), $t(109) = 3.80$, $p < .001$. This indicated that overall, participants made small, but significant, improvements to their understanding of the physics of inclined planes over the course of the hour-long laboratory.

Next, in order to establish whether there were significant differences on prior knowledge across conditions, a one-way analysis of variance (ANOVA) was conducted to check for a significant difference between the four conditions on the pre-test. There was no significant difference overall between the four conditions on the pre-test, $F(3,106) = .096$, $p = .962$. This indicated, as with the pre-experiment survey results, that the experimental conditions were sufficiently randomized on participants' prior knowledge.

Next, to address the three research questions comparing laboratory environments on overall conceptual understanding, a one-way Analysis of Covariance (ANCOVA) was conducted comparing the four conditions on pre-post test gain, with the post-test score as the dependent variable and the pre-test score as the covariate. For the ANCOVA test, preliminary analyses evaluating the homogeneity-of-slopes assumption indicated that the relationship between the covariate and the dependent variable did not differ significantly as a function of the independent variable. The ANCOVA indicated that there was no significant main effect of condition on the post-test score on these items, $F(3, 105) = 1.80$, $p = .151$ (see Table 1, *Figure 6*), though there was a main effect of the covariate, $F(1, 105) = 40.27$, $p < .001$, partial $\eta^2 = .277$. Since there was no significant effect of condition on the omnibus ANCOVA test, no pairwise comparisons were conducted.

This result indicates that overall, there were no significant differences across experimental conditions (*Physical-only*, *Virtual-only*, *Sequential P-V* and *Integrated P-V*) on overall conceptual understanding as measure by the concept test. When taking into account all four concepts (force, work, potential energy and mechanical advantage) and both the length and height experiments, participants learned an equivalent amount from each condition.

Table 1

ANCOVA results and descriptive statistics for post-test score by condition and pre-test score.

Condition	Post-test Score			
	Observed Mean	Adjusted Mean	SD	n
Physical-Only	17.46	17.41	4.03	28
Virtual-Only	17.69	17.78	4.25	26
Sequential P-V	16.32	16.16	3.81	28
Integrated P-V	15.82	15.94	4.43	28

Source	SS	df	MS	F
Pre-test score	502.49	1	502.49	40.27***
Condition	67.44	3	22.482	1.80
Error	1310.23	105	12.48	

Note. $R^2 = .303$, Adj. $R^2 = .276$, adjustments based on pre-test score mean = 15.42.
*** $p < .001$

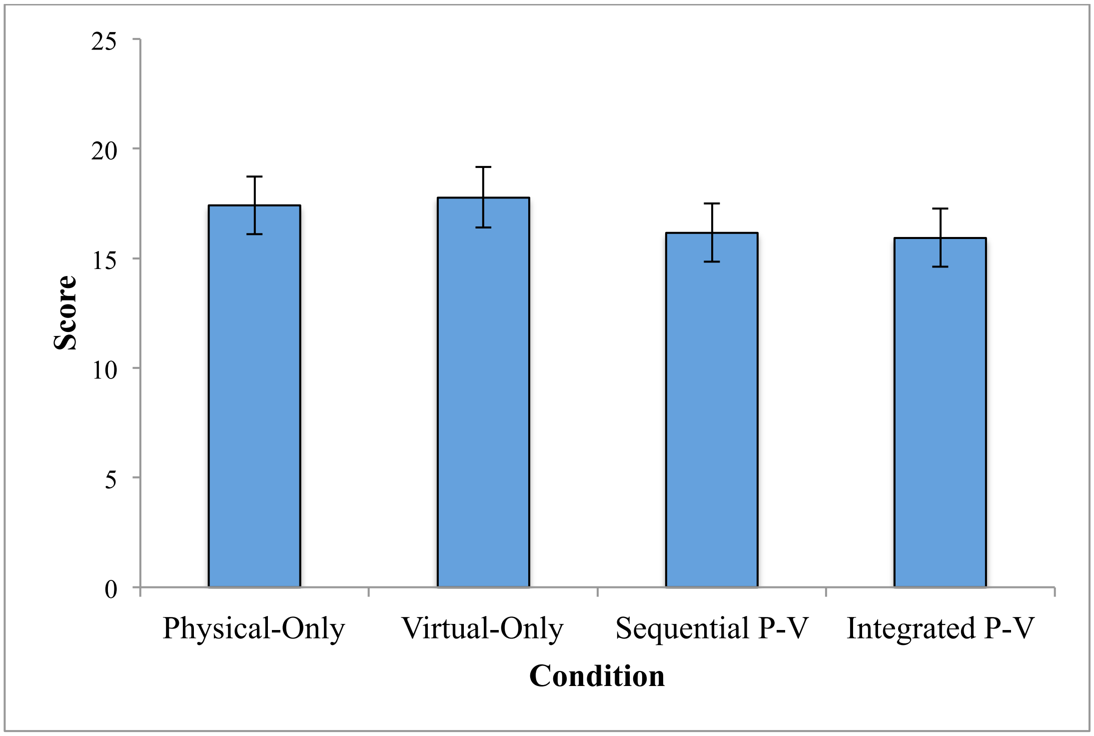

Figure 6. Overall Post-test Score by Condition, with bars representing 95% confidence intervals.

Comparing Conceptual Understanding across Laboratory Environments, Grouped by Physics Principle

Beyond overall test scores, this study also investigated participants' conceptual understanding in more detail. To do this, the concept test was subdivided by specific physics principles that corresponded to different concepts and situations when using inclined planes.[4]

One major physics principle of the length experiment used in this study was that the applied force needed to lift an object up an inclined plane decreases with the length of the inclined plane (when lifting to the same height) and the mechanical advantage thus increases with the length of an inclined plane (since it is inversely proportional the force

[4] The physics principles that were intended to be learned from each experiment were based on the CoMPASS simple machines curriculum that is used in middle school classrooms (Puntambekar, Stylianou & Goldstein, 2007).

needed). The second major physics principle of the length experiment was that the change in potential energy and work done in lifting an object up an inclined plane does not depend on the length of the inclined plane (when lifting to the same height). Potential energy only depends on the height of the inclined plane (and the weight of the object) and work remains roughly the same (exactly the same in a frictionless environment) when lifting to the same height as the force and the distance balance out.

Similarly, the height experiment had two major physics principles that were intended to be learned, also corresponding to two concept groups. One major principle of the height experiment was that the applied force needed to lift an object up an inclined plane increases with the height of the inclined plane and the mechanical advantage thus decreases with the height of an inclined plane (since it is inversely proportional the force needed). The second major principle of the height experiment was both the change in potential energy and the work done in lifting an object up an inclined plane increases with the height of the inclined plane.

Corresponding to these four physics principles, the concept test was subdivided into four groups of items, one group of items contained questions involving what would happen with force and mechanical advantage when varying the length of an inclined plane (items 1, 2 and 11), one group of items on work and potential energy when varying length (items 5, 7, 8, 15, 17, 18 and 19), one group of items on force and mechanical advantage when varying height (items 3, 12 and 21), and one group of items on work and potential energy when varying height (items 6, 9, 10, 16 and 23; see Appendix C for test items). These resulting four groups of items then corresponded to the overall behavior of the physics variables that the participants observed during the two different experiments.

This combination of concept and situation allowed for analyzing whether the experimental conditions differentially affected students' conceptions during the length and height experiments.

There were three primary reasons for evaluating learning by these particular physics principles and corresponding grouping of test items:

1. Prior research has suggested that the affordances of physical and virtual laboratories, as well as combinations thereof, at least partly depend on the specific learning goals that the laboratories are meant to address (Olympiou & Zacharia, 2012).
2. Researchers exploring embodiment and mixed reality environments have suggested that congruencies between learners' actions in the environment and particular concepts may be particularly important in understanding and designing for embodiment in mixed reality environments (Lindgren & Johnson-Glenberg, 2013).
3. In prior research on physical and virtual experiments within the CoMPASS simple machines curriculum, a factor analysis indicated that learners' concept test scores grouped together not by individual concepts alone, but by groups of related concepts (e.g. force and mechanical advantage) in different situations (e.g. different pulley configurations).

To investigate whether the laboratory environment encountered had differential effects on learning particular physics concepts in particular situations, ANCOVAs were performed on the concept test broken down by each physics principle. For each of the four omnibus ANCOVA tests that were found to be significant, six planned contrasts were conducted to directly compare the four different conditions with each other, using a Bonferroni adjusted critical value of .0083 (.05 divided by six contrasts).

As described earlier, comparisons were conducted across the four laboratory environments on understanding of four physics principles: force and mechanical advantage when varying the length of an inclined plane, work and potential energy when varying length, force and mechanical advantage when varying height, and work and potential energy when varying height. (These four principles correspond to the next set of subheadings in this chapter). This combination of concept and situation allowed for investigating whether the experimental conditions differentially affected students' understanding of different concepts as well as whether they affected students' conceptions differently during the length and height experiments. The results of ANCOVA tests to determine differences between conditions on each of these four test item groupings are specified below.

Force and mechanical advantage when varying length. One major physics principle of the length experiment used in this study was that the applied force needed to lift an object up an inclined plane decreases with the length of the inclined plane (when lifting to the same height) and the mechanical advantage thus increases with the length of an inclined plane (since it is inversely proportional the force needed). Overall, participants did not improve much on this physics principle from pre to post, scoring a mean of 2.18 (SD = .911) on the pre-test and 2.21 (SD = .858) on the post-test. With a maximum score of 3 on the three items (items 1, 2 and 11; see Appendix C), participants generally already understood this physics principle to some extent on the pre-test.

To compare the four conditions on test items covering this first physics principle of the length experiment, a one-way Analysis of Covariance (ANCOVA) was conducted, with the post-test score on test items on force and mechanical advantage when using different length inclined planes to lift an object (items 1, 2 and 11; see Appendix C) as the dependent variable and the pre-test score on the same items as the covariate. The ANCOVA indicated that there was no significant main effect of condition on the post-test score on these items, $F(3, 105) = .831$, $p = .480$ (see Table 2, *Figure 7*), though there was a main effect of the covariate, $F(1, 105) = 6.57$, $p = .012$, partial $\eta^2 = .059$. This indicates that understanding the underlying big idea of the length experiment – that the amount of force required to lift an object up a ramp decreases with the length of the ramp (while mechanical advantage consequently increases) – did not significantly differ across conditions.

Table 2

ANCOVA Results and Descriptive Statistics for Post-test Score (on Force and Mechanical Advantage Items corresponding to the Length Experiment) by Condition

Condition	Post-Test Score: Force & MA,Varying Length			
	Observed Mean	Adjusted Mean	SD	n
Physical-Only	2.21	2.17	.876	28
Virtual-Only	2.27	2.28	.780	26
Sequential P-V	2.00	2.03	.981	28
Integrated P-V	2.35	2.36	.780	28

Source	SS	df	MS	F
Pre-test score	4.61	1	4.61	6.57*
Condition	1.75	3	.583	.831
Error	73.65	105	.701	

Note. $R^2 = .082$, Adj. $R^2 = .047$, adjustments based on pre-test score mean = 2.18.
* $p < .05$

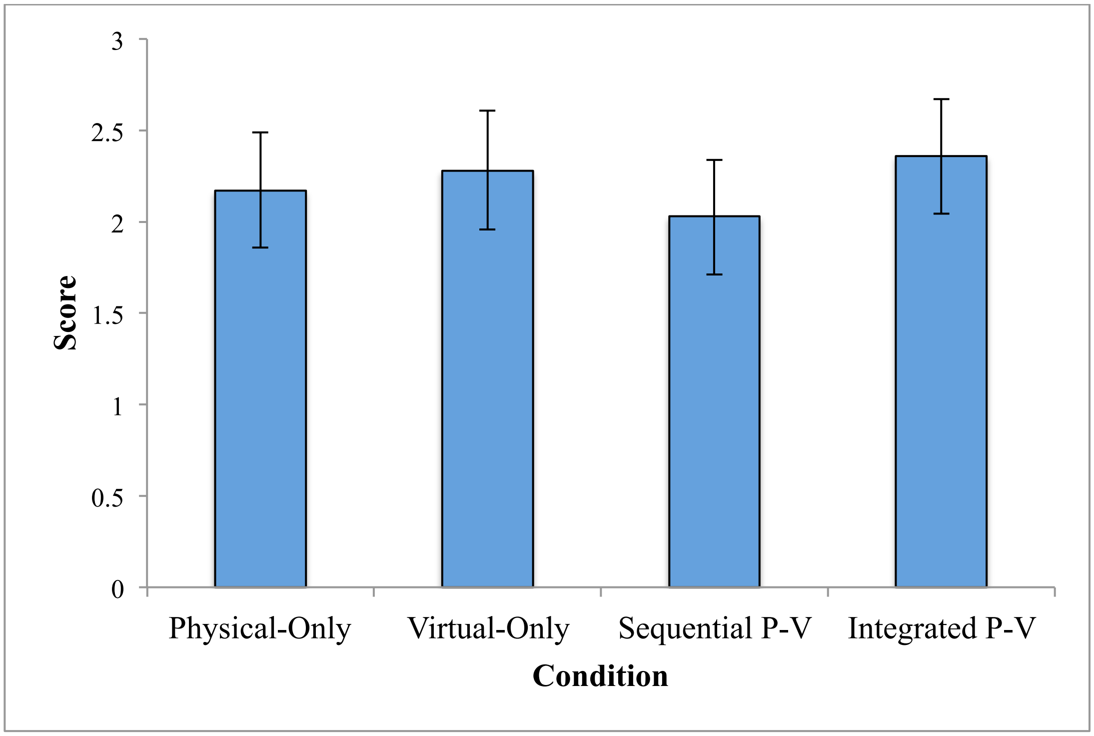

Figure 7. Post-test Score (on Force and Mechanical Advantage Items corresponding to the Length Experiment) by Condition, with bars representing 95% confidence intervals.

Work and potential energy in length experiment. The second major physics principle of the length experiment was that the change in potential energy and work done in lifting an object up an inclined plane does not depend on the length of the inclined plane (when lifting to the same height). Potential energy only depends on the height of the inclined plane (and the weight of the object) and work remains roughly the same (exactly the same in a frictionless environment) when lifting to the same height as the force and the distance balance out. Overall, participants actually performed slightly worse on the post-test items for this physics principle (items 5, 7, 8, 15, 17, 18 and 19; see Appendix C), scoring a mean of 4.01 (SD = .2.06) on the pre-test 3.95 (SD = 1.71) on the post-test. Unlike for the first physics principle, however, the mean score was relatively low compared to the maximum score of 11 on both pre and post tests.

To compare the four conditions on work and potential energy when varying the length of an inclined plane, a one-way Analysis of Covariance (ANCOVA) was conducted, with the post-test score on test items on work and potential energy when using different length inclined planes to lift an object (items 5, 7, 8, 15, 17, 18 and 19; see Appendix C) as the dependent variable and the pre-test score on the same items as the covariate. The ANCOVA indicated that there was a significant main effect of condition on the post-test score on these items, $F(3, 105) = 3.28$, $p = .024$, partial $\eta^2 = .086$ (see Table 3, *Figure 8*) as well as a significant main effect of the covariate, $F(1, 105) = 18.93$, $p < .001$, partial $\eta^2 = .153$. Six planned comparisons were conducted, using a Bonferroni adjusted critical value of .0083 (.05/6). These comparisons indicated that the *Virtual-Only* condition scored significantly higher on these post-test items than the *Integrated Physical-Virtual* condition (Mean Difference = 1.25, p = .004). There were no significant differences for any of the remaining pairwise comparisons (see Table 4). These results indicate that, for this second physics principle of the length experiment – that the amount of work done and the change in potential energy while lifting an object up a ramp largely remains the same when the length of the ramp increases[5] – scores did differ significantly across the conditions. This pattern was different from the results for force and mechanical advantage: in this case, the *Virtual-only* condition significantly outperformed the *Integrated Physical-Virtual* condition.

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[5] Without friction, both work and potential energy would remain exactly the same. In their experiments with some friction, participants observed that potential energy remained the same but work increased slightly with the length of inclined plane.

Table 3

ANCOVA Results and Descriptive Statistics for Post-test Score (on Work and Potential Energy Items corresponding to the Length Experiment) by Condition

Condition	Post-Test Score: Work & PE, Varying Length			
	Observed Mean	Adjusted Mean	SD	n
Physical-Only	3.75	3.75	1.51	28
Virtual-Only	4.73	4.62	2.13	26
Sequential P-V	4.11	4.14	1.29	28
Integrated P-V	3.29	3.37	1.61	28

Source	SS	df	MS	F
Pre-test score	44.10	1	44.10	18.93***
Condition	22.94	3	7.65	3.28*
Error	244.66	105	2.33	

Note. $R^2 = .082$, Adj. $R^2 = .047$, adjustments based on pre-test score mean = 2.18.
* $p < .05$, *** $p < .001$

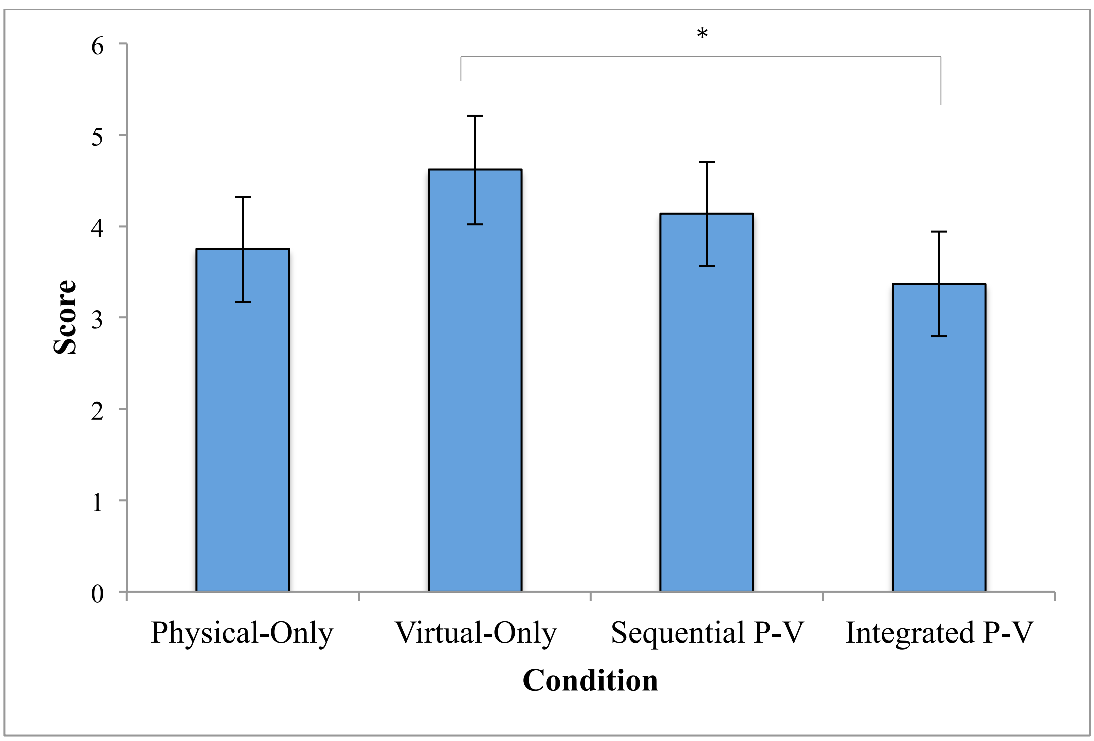

Figure 8. Post-test Score (on Work and Potential Energy Items corresponding to the Length Experiment) by Condition, with bars representing 95% confidence intervals.
*$p < .05$

Table 4

Mean Differences and p-values for Pairwise Comparisons across conditions for Work and Potential Energy in Length Experiment.

	Virtual-Only	Sequential P-V	Integrated P-V
Physical-Only	-.873 (p = .039)	-.578 (p = .105)	.376 (p = .360)
Virtual-Only		.482 (p = .250)	1.25 (p = .004)*
Sequential P-V			.766 (p = .063)

Force and mechanical advantage in height experiment. One major physics principle of the height experiment was that the applied force needed to lift an object up an inclined plane increases with the height of the inclined plane and the mechanical advantage thus decreases with the height of an inclined plane (since it is inversely proportional the force needed). Like with force and mechanical advantage in the length experiment, participants did not much improve on understanding of this physics principle from pre to post (items 3, 12 and 21; see Appendix C), scoring a mean of 1.54 (SD = .553) on the pre-test and 1.56 (SD = .516) on the post-test.

To compare the four conditions on test items covering this physics principle, a one-way Analysis of Covariance (ANCOVA) was conducted, with the post-test score on test items on force and mechanical advantage when lifting an object to different heights using an inclined plane (items 3, 12 and 21; see Appendix C) as the dependent variable and the pre-test score on the same items as the covariate. The ANCOVA indicated that there was a significant main effect of condition on the post-test score on these items, $F(3, 105) = 5.06$, $p = .003$, $\eta^2 = .126$ (see Table 5, Figure 9), though there no main effect of the covariate, $F(1, 105) = .909$, $p = .343$. Six planned comparisons were conducted, using a Bonferroni adjusted critical value of .0083 (.05/6). These comparisons indicated that the

Integrated Physical-Virtual condition scored significantly higher on these post-test items than the *Virtual-only* condition (Mean Difference = .463, p = .001). There were no significant differences for any of the remaining pairwise comparisons (see Table 6). These results indicate that, for this physics principle of the height experiment – that the amount of force required to lifting an object up a the same-length ramp increases with the height of the ramp (while mechanical advantage decreases) – did differ significantly across the conditions, unlike for force and mechanical advantage in the length experiment. In this case the *Integrated Physical-Virtual* condition significantly outperformed the *Virtual-only* condition. Interestingly, this was the opposite pattern from items corresponding to work and potential energy in the length experiment.

Table 5

ANCOVA Results and Descriptive Statistics for Post-test Score (on Force and Mechanical Advantage Items corresponding to the Height Experiment) by Condition

Condition	Post-Test Score: Force & MA, Varying Height			
	Observed Mean	Adjusted Mean	SD	n
Physical-Only	1.68	1.69	.476	28
Virtual-Only	1.35	1.32	.485	26
Sequential P-V	1.43	1.44	.573	28
Integrated P-V	1.79	1.78	.418	28

Source	SS	df	MS	F
Pre-test score	.219	1	.219	.909
Condition	3.664	3	1.22	5.06**
Error	25.34	105	.241	

Note. R^2 = .128, Adj. R^2 = .094, adjustments based on pre-test score mean = 1.54.
* p < .05, ** p < .01

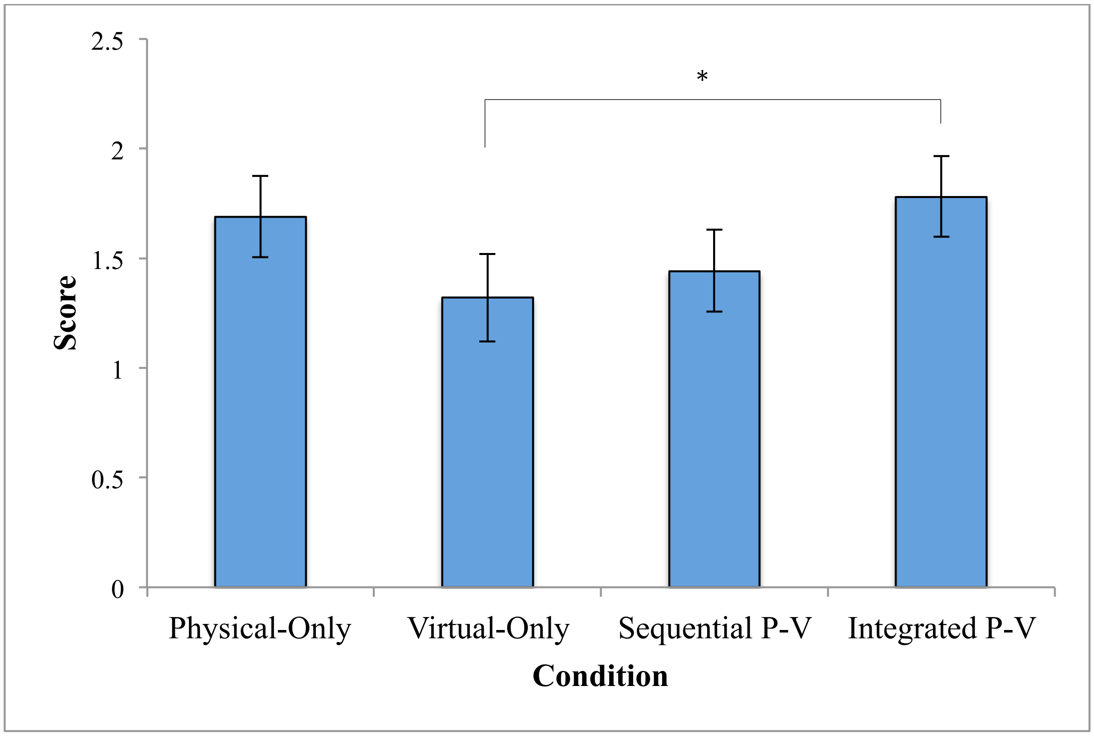

Figure 9. Post-test Score (on Force and Mechanical Advantage Items corresponding to the Height Experiment) by Condition, with bars representing 95% confidence intervals. *p < .05

Table 6

Mean Differences and p-values for Pairwise Comparisons across conditions for Work and Potential Energy in Length Experiment.

	Virtual-Only	Sequential P-V	Integrated P-V
Physical-Only	.371 (p = .009)	.293 (p = .012)	-.092 (p = .490)
Virtual-Only		-.124 (p = .380)	-.463 (p = .001)*
Sequential P-V			-.339 (p = .012)

Work and potential energy in height experiment. The second major physics principle of the height experiment was that both the change in potential energy and the work done in lifting an object up an inclined plane increases with the height of the inclined plane. For this physics principle, participants did improve substantially from pre to post on these test items (items 6, 9, 10, 16 and 23; see Appendix C), scoring a mean of 4.09 (SD = 1.24) on the pre-test and 4.86 (SD = 1.72) on the post-test.

To compare the four conditions on test items covering to work and potential energy when varying the height of an inclined plane, a one-way Analysis of Covariance (ANCOVA) was conducted, with the post-test score on test items on work and potential energy when lifting an object to different heights using an inclined plane (items 6, 9, 10, 16 and 23; see Appendix C) as the dependent variable and the pre-test score on the same items as the covariate. The ANCOVA indicated that there was no significant main effect of condition on the post-test score on these items, $F(3, 105) = .778$, $p = .509$ (see Table 7, Figure 12), nor was there a main effect of the covariate, $F(1, 105) = 1.80$, $p = .343$. This indicates that, as with force and mechanical advantage in the length experiment, understanding this principle of the height experiment – that the amount of work done and the change in potential energy when lifting an object up a ramp increases with the height of the ramp – did not significantly differ across conditions.

Table 7

ANCOVA Results and Descriptive Statistics for Post-test Score (on Work and Potential Energy Items corresponding to the Height Experiment) by Condition.

Condition	Post-Test Score: Work & PE, Varying Height			
	Observed Mean	Adjusted Mean	SD	n
Physical-Only	5.21	5.23	2.01	28
Virtual-Only	4.81	4.82	1.63	26
Sequential P-V	4.68	4.65	1.63	28
Integrated P-V	4.75	4.70	1.60	28

Source	SS	df	MS	F
Pre-test score	5.33	1	5.33	1.80
Condition	6.91	3	.778	.778
Error	310.78	105	2.96	

Note. $R^2 = .032$, Adj. $R^2 = -.005$, adjustments based on pre-test score mean = 4.09.
* $p < .05$

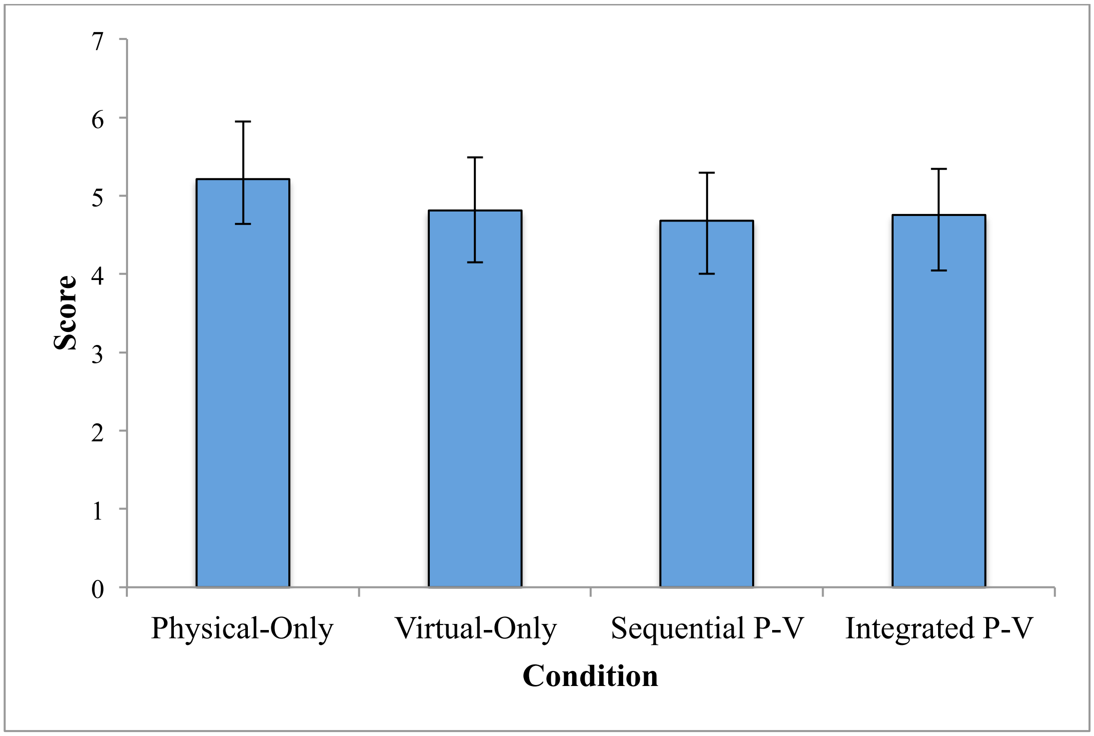

Figure 10. Post-test Score (on Work and Potential Energy Items corresponding to the Height Experiment) by Condition, with bars representing 95% confidence intervals.

Conceptions of Force and Work

To understand participants' conceptions of force and work before and after completing the experiments, responses to pre and post interview questions were analyzed. First, a rubric was developed for scoring student conceptions for each of the six questions (3 on force, 3 on work). In general, the rubric was setup such that a score 0 indicated an incorrect answer, a score of 1 indicated a technically correct answer, but with only a partial answer as to why (for example, claiming that work increases with distance, but failing to mention force as a factor as well), and a score of 2 indicated a correct answer with complete reasoning as to why (see Appendix F for the complete rubrics). Participants' responses during pre and post interviews were then scored according to these rubrics, and inter-rater reliability was established with another researcher on 10% of the data, with a Cohen's kappa of .809 (Cohen, 1968). For each of the concepts of force and work, a Kruskal-Wallis test was conducted to evaluate differences between the four experimental conditions (*Physical-only*, *Virtual-only Sequential Physical-Virtual* and *Integrated Physical-Virtual*) on median pre to post gain during the interviews. The non-parametric Kruskal-Wallis test was chosen due to the relatively small sample size of 8 participants per condition. For each of these omnibus Kruskal-Wallis tests that were found to be significant, six planned contrasts were conducted to directly compare the four different conditions with each other, utilizing the Mann-Whitney U test for the planned comparisons and a Bonferroni approach for controlling for Type I error.

The pre and post interviews with participants allowed for observing whether participants' explanations of the concepts of force and work corresponded to the patterns found in the pre and post test results, as well as to get a deeper understanding of their understanding of these physics concepts.

First, to understand participants' overall changes in their conceptions of force and work before and after completing the experiments, their answers to the three interview questions pertaining to force were summed to create a total interview score for force. Similarly, the scores for the three questions on work were summed to create a total score for work. Overall, in the interviews, participants improved their scores from the pre-interview to the post-interview on both their conceptions of force and work. On the concept of force, participants significantly improved overall, with a mean gain from pre to post of .494, $SD = 1.50$, $t(31) = 2.24$, $p = .032$. On the concept of work, participants also significantly improved from pre to post with a mean gain of 1.53, $SD = 1.12$, $t(31) = 7.83$, $p < .001$. As with the pre and post test results, participants made significant but small improvements in their understanding of the physics concepts by completing the experiments. With the interviews, these gains were more pronounced for the concept of work than for force.

Conceptions of force. Though participants improved overall on conceptions of force, there were wide differences on mean pre to post gain between the four conditions. Participants in the *Physical-only* condition gained the most from pre to post (M = 2.00), followed by those in the *Integrated P-V* condition (M = 0.63). Meanwhile, participants in the *Virtual-only* condition on average made no gains in conception of force (M = 0.00) and those in the *Sequential P-V* condition actually decreased in score after completing the experiments (see Table 8).

A Kruskal-Wallis test was conducted to evaluate differences between the four experimental conditions (*Physical-only*, *Virtual-only Sequential Physical-Virtual* and *Integrated Physical-Virtual*) on pre to post gain on conceptions of force during the interviews. The test, which was corrected for tied ranks, was significant χ^2 (3, N=32) = 11.09, p = .011. Follow-up tests were conducted to evaluate pairwise differences among the four groups, controlling for Type I error across tests by using the Bonferroni approach. The results of these tests indicated a significant difference between the *Physical-only* condition and the *Virtual-only* condition (Mann-Whitney U = 4.50, p = .003) as well as between the *Physical-only* condition and the *Sequential Physical-Virtual* condition (Mann-Whitney U = 6.50, p = .005). Participants in the *Physical-only* condition gained significantly more on conceptions of force from pre to post than participants in the *Virtual-only* and *Sequential Physical-Virtual* groups.

Table 8

Descriptive Statistics for Pre and Post-Interview Scores on Force by Condition.

	Pre-interview mean (SD)	Post-interview mean (SD)	Gain	n
Physical-Only	1.75 (1.04)	3.75 (1.67)	2.00 (.926)	8
Virtual-Only	2.63 (1.30)	2.63 (1.50)	0.00 (1.20)	8
Sequential P-V	2.88 (1.13)	2.50 (1.31)	-.380 (1.19)	8
Integrated P-V	2.13 (1.55)	2.75 (1.67)	0.63 (1.77)	8

Conceptions of work. Unlike on conceptions of force, participants across all conditions performed quite similarly on conceptions of work. The mean gain from pre to post on overall conceptions of work ranged from 1.25 for the *Integrated P-V* condition to 1.63 for the other three conditions (see Table 9). A Kruskal-Wallis test was conducted to evaluate differences between the four experimental conditions (*Physical-only*, *Virtual-only Sequential Physical-Virtual* and *Integrated Physical-Virtual*) on median pre to post gain on conceptions of work during the interviews. The test, which was corrected for tied ranks, was not significant χ^2 (3, N = 32) = .279, p = .964. There were no significant differences between the conditions. Unlike for force, the particular laboratory environment did not matter for developing participants' overall understanding of work.

Table 9

Descriptive Statistics for Pre and Post-Interview Scores on Work by Condition.

	Pre-interview mean (SD)	Post-interview Mean (SD)	Gain	n
Physical-Only	.25 (.707)	1.88 (.835)	1.63 (1.06)	8
Virtual-Only	.50	2.13	1.63	8

	(.756)	(.991)	(1.06)	
Sequential P-V	.50 (.756)	2.13 (1.13)	1.63 (1.32)	8
Integrated P-V	.50 (.926)	1.75 (.886)	1.25 (1.17)	8

Specific Misconceptions

Beyond overall conceptions of force and work, participants' misconceptions were also investigated in order to answer the following research question:

RQ3). *Do the unique perceptual-motor features of different physics laboratory environments lead to* ***specific misconceptions*** *about the nature of force and work?*

To answer this question, participants' reasoning was categorized by their explanation of why each result occurred (e.g., that force decreases with a longer ramp due to the slope or angle). The categories were developed inductively based on participants' responses. Further, these categories of explanations were analyzed for the most common misconceptions that occurred during the post-interviews. The two most common misconceptions involved conflating the concepts of force and work and misunderstanding how force and work change while lifting an object up an inclined plane.

Conflating force and work. In addition to comparing overall understanding of force and work in the post-interviews across conditions, the interviews allowed a more detailed analysis of participants' conceptions of force and work. In both the pre and post interviews, the most common misconceptions that occurred involved some form of conflating the two concepts of force and work. Some participants, when asked about the concept of force, answered in a way that would have been a correct answer (or at least a better answer) for work. For example, one participant in the *Virtual-only* condition claimed that, “You'd need more force for a longer ramp, because you need to push it further.” Others even mentioned the concept of work when specifically asked about force. For example, one participant in the *Integrated Physical-Virtual* condition explained, “It would take more force to use the ramp. It's just more work and more distance to push up a ramp, I feel like.” Similar misconceptions occurred when participants were asked about work. For example, one participant in the *Virtual-only* condition explained the following when asked about the relationship between work and distance: “The steeper a ramp is, the more work you will have to put into it, because it's harder to push something steeper than something flatter.” This student, though attempting to explain work, was giving a much more accurate description of force than of work. Still other students were explicit that they knew that force and work were technically different concepts, but claimed they behaved the same way. For example, one student in the *Integrated Physical-Virtual condition* claimed that, “I think that it would be more work to lift straight up rather than up a ramp, cause it's work and applied force, I feel like they go hand in hand. So, if you're going to use more force, you're going to do more work.”

Overall, these misconceptions were extremely common. Of the 32 participants interviewed, only five never indicated any of these misconceptions in their post-interview answers (see Table 10). Claiming that work increased with force (without accounting for distance) was a more common misconception than claiming that a longer ramp required more force, indicating that work was likely a more difficult concept to grasp. Generally, even when students understood that using a long ramp would take more work than a short ramp (when there was friction), many did not transfer this finding to a comparison of moving an object up a ramp compared to lifting it straight up.

Interestingly, there were differences in how these misconceptions appeared across the different conditions. Participants in the *Physical-only* condition responded in ways that indicated these misconceptions the least of any condition, while participants in the *Virtual-only* and *Integrated Physical-Virtual* conditions had these misconceptions the most of any condition (see Table 10). A Fisher's exact probability test was conducted on the frequency of participants making either of these errors (versus making neither error) and indicated a significant difference between conditions ($p < .001$).

Table 10

Number of participants who conflated force and work at least once in the post-interview (N = 32).

Conflating Force and Work	Physical-Only	Virtual-Only	Sequential P-V	Integrated P-V	TOTAL
When asked about force	1	3	3	2	9
When asked about work	1	5	2	6	18
TOTAL	2	8	5	8	27

Understanding changes of force and work in inclined plane experiments. Beyond conflating force and work, the next most common misconceptions involved students' understanding of changes in force and work as an object is being moved up an inclined plane. When asked during the post-interview what happens to the applied force needed to lift an object up a ramp as you are dragging the object up a ramp, 8 participants incorrectly stated that the amount of force needed increases as you drag the object further up the ramp. For example, one participant in the Virtual-only condition claimed that, "I think the force increases. Because as you're going up … as you go up, the force of gravity is going to grow stronger, forcing the box down toward the ramp more." In contrast, 19 participants correctly claimed that the amount of force would remain the same. These participants pointed to the fact that the ramp was at the same angle the whole time: “The force stays the same. Nothing has changed about the object. It still has the same weight and you're still going at the same angle.”

Interestingly, of the 8 participants who held the misconception that force increases as an object is lifted up a ramp, 5 of those participants were in the *Virtual-only* condition (where the computer simulation provided no force feedback). Meanwhile, the *Physical-only* condition had no participants who held this misconception, the *Integrated Physical-Virtual* condition had only one such participant, and the *Sequential Physical-Virtual* condition had 2. A Fisher’s exact test of independence was conducted on the frequency of participants correctly indicating that the force stays the same (versus incorrectly stating that it increases) and indicated a significant difference between conditions ($p =.016$).

Overall, more of the interviewed students had misconceptions about changes to *work* done during the course of lifting an object up a ramp than they did about force. When asked during the post-interview what happens to the work being done as you are dragging the object up a ramp, only half of the participants (16) correctly stated that the work increases as you continue to pull the object up a ramp, while 10 students incorrectly stated that the amount of work done stays the same. For example, one student in the *Physical-only* condition claimed that, “It stays the same, because work is force applied times distance and force doesn't change and the distance doesn't change”, incorrectly claiming that the distance does not change as you are moving an object up a ramp. In contrast, other participants understood that work increases as the object is moved up the ramp because distance increases: "The work does increase. The work increases because it's figured at each point by the distance so as you've gone further distance, it increases."

Unlike the same question about force, participants in the *Physical-only* condition held this misconception about work most often (5 participants) while those in the *Virtual-only* and *Integrated Physical-Virtual* condition had this particular misconception the least (1 participant each). Three participants in the *Sequential Physical-Only* condition held this misconception. A Fisher's exact test of independence was conducted on the frequency of participants correctly indicating that the work increases (versus incorrectly stating that it remains the same) and indicated difference between conditions that was approaching significance (p =.090).

Overall, in analyzing participants' specific misconceptions of force and work, these results indicated that different laboratory environments often led to different misconceptions: participants in the *Virtual-only* and *Integrated Physical-Virtual* conditions most often conflated force and work, participants in the *Virtual-only* condition most often misunderstood that the force required to lift an object up an inclined plane remains constant, and participants in the *Physical-only* condition most often misunderstood that the work being done increases as an object is lifted up a ramp. The implications of these differences between conditions will be examined in the discussion section of this chapter.

Secondary Analyses

In addition to addressing the primary research questions, some secondary analyses were performed to explore issues related to the primary research questions. These analyses investigated the relationships between participants' background and the concept test results and the effect of the sequence of separate physical and virtual laboratories. Though these analyses did not directly address the three primary research questions of this part of the study, they did provide some additional depth in understanding the potential effects of the different laboratory environments.

Relationships between survey and concept test results. To determine whether there were any relationships between participants' physics conceptions and their pre-survey results (including participant demographics, participants' physics and computer backgrounds, and how well they knew their partner), correlations were conducted between post-test results and pre-survey responses. This allowed for determining whether there were additional factors driving differences in post-test score in addition to the four experimental conditions. Further, to ensure that the experimental conditions were balanced with respect to participant demographics and backgrounds, correlations were also conducted between experimental condition and pre-survey results.

Demographic data from the pre-experiment survey was analyzed to see if there were any correlations between demographic data and post-test scores. The only survey item that was significantly correlated with post-test score was whether participants had previously covered simple machines in their educational career, which was positively correlated with post-test score ($r = .221$, $n = 109$, $p = .021$). None of the other pre-experiment survey results (i.e. gender, age, year in school, number of physics classes, how well they knew their partner, computer usage) were significantly correlated with post-test scores. Further, there were no significant differences on the pre-experiment survey results by the experimental condition, indicating that the conditions were sufficiently randomized on participant demographics and background.

Comparing physical-virtual and virtual-physical sequence. Additionally, within the *Sequential Physical-Virtual* condition, a set of separate one-way ANCOVAs was performed to compare the physical-virtual sequence to the virtual-physical sequence (both on overall the overall concept test as well as broken down by concept/situation). This allowed for the testing for any effect of sequence for separate physical and virtual experiments, which in some cases has been found to be a factor (e.g., Gire et al, 2010).

To determine if the sequence of physical and virtual experiments was important for participants in the Sequential Physical-Virtual condition, a separate ANCOVA was conducted with the post-test score as the dependent variable, the sequence (Physical-Virtual or Virtual-Physical) as the independent variable and the pre-test score as the covariate. The mean post-test score for the P-V sequence was 16.50 (*SD* = 4.57) while the mean score post-test score for the V-P sequence was 16.14 (*SD* = 3.03). The ANCOVA indicated that there was no significant main effect of sequence on the post-test score on these items, $F(1,25) = .396$, $p = .535$, though there was a main effect of the covariate, $F(1, 25) = 6.50$, $p = .017$, partial $\eta^2 = .206$. These results indicate that the sequence of Physical and Virtual experiments had no impact on the post-test results for the *Sequential Physical-Virtual* condition. Similarly, there were no significant differences across conditions on the concept test when separated by concept and experiment.

Discussion

This portion of the study first attempted to address the following research questions:

*RQ1). Do the unique perceptual-motor features of different physics laboratory environments lead to differences in learners' **overall understanding** of physics concepts?*

RQ2). *Do the unique perceptual-motor features of different laboratory environments lead to differences in learners' understanding of* ***specific physics principles****?*

Thus, different laboratory environments, with different perceptual-motor features, were evaluated both on overall conceptual understanding, as well as on particular physics principles based on the different concepts and experiments of the study. The following section discusses the results of the study in relation to these two research questions.

Comparing Overall Conceptual Understanding Across Laboratory Environments

The results from the pre and post concept tests indicated that participants overall increased their knowledge of the concepts of force, work, potential energy and mechanical advantage in inclined planes. When comparing the experimental conditions (*Physical-only, Virtual-only, Sequential Physical-Virtual* and *Integrated Physical-Virtual*) on the concept test as a whole, there were no significant differences between the conditions. In terms of the first three hypotheses, this result indicated that:

H1: Students in the Virtual-only condition will outperform those in the Physical-only condition on the overall concept test.

On overall conceptual understanding, completely physical and completely virtual laboratories were equally effective at supporting student learning (in contradiction to this hypothesis). This result concurs with those of Triona, Klahr & Williams (2005) and Zacharia & Olympiou (2011), who found virtual and physical learning environments equally effective at supporting learning in physics contexts.

H2: Students in the Sequential Physical-Virtual and Integrated Physical-Virtual conditions will outperform those in the Physical-only and Virtual-only conditions on the overall concept test.

Providing a sequential combination of physical and virtual experiments to learners was equally effective to either a completely physical or completely virtual laboratory in supporting overall conceptual understanding (in contradiction to this hypothesis). This result concurs with Zacharia & Olympiou (2011) who found no benefit to combining physical and virtual experiments, but differs from other studies (e.g., Jaakkola & Nurmi, 2008; Olympiou & Zacharia, 2012), who found that combinations of physical and virtual can better support conceptual understanding over either form alone. It may be that without more time on task to fully explore each of the physical and virtual environments, the advantages of providing both physical and virtual laboratories were not fully realized. This possibility will be discussed further later in the paper.

H3: Students in the Integrated Physical-Virtual condition will outperform those in the Sequential Physical-Virtual condition on the overall concept test.

On overall conceptual understanding, a mixed reality laboratory environment that tightly integrated physical and virtual laboratories was equally effective in supporting overall conceptual understanding as a sequential combination of physical and virtual experiments (as well as with either physical or virtual laboratories alone), again in contradiction with this hypothesis. As this kind of laboratory environment has not previously been directly compared with sequential physical and virtual laboratories, this result establishes a baseline for future research on methods for combining physical and virtual experimentation in physics classrooms.

Though these results comparing laboratory environments showed no significant differences on overall conceptual understanding, the results align with some similar studies comparing physical and virtual laboratories. However, when comparing laboratories by particular physics principles based on concept and situation, this study found significant differences across laboratory environments, as described below.

Comparing Conceptual Understanding across Laboratory Environments, Grouped by Physics Principle

Unlike on the overall concept test, when separating the test by concept groups (force and mechanical advantage, work and potential energy) and experiments (length and height), there were significantly different patterns across the conditions. This indicated that there were some laboratory environments that were more effective for learning some physics principles, while other environments were more effective for learning other physics principles, all of which roughly balanced out when evaluating the test results as a whole.

The overall main effects were that, for work and potential energy in the length experiment, participants in the *Virtual-only* condition outperformed those in the *Integrated Physical-Virtual* condition, while for force and mechanical advantage in the height experiment, participants in the *Integrated Physical-Virtual* condition significantly outperformed those in the *Virtual-only* condition (see Table 11). In both cases, participants in the *Physical-only* condition and the *Sequential Physical-Virtual* conditions were in between, with the *Physical-only* condition scores closer to that of the *Integrated P-V* condition, and the *Sequential P-V* condition closer to that of the *Virtual-only* condition. What this means for the two hypotheses of this part of the study is described below.

Table 11

Summary of Concept Test Results Grouped by Concept and Experiment

	Force & MA	Work & PE
Length Experiment	(No significant differences)	*Virtual only* > *Integrated P-V*
Height Experiment	*Integrated P-V* > *Virtual-only*	(No significant differences)

H4: Students in the Physical-only and Integrated Physical-Virtual conditions will outperform those in the Virtual-only condition on the concepts of force and mechanical advantage.

Students in the *Integrated Physical-Virtual* condition did significantly outperform those in the *Virtual-only* condition, where the only distinction between these two laboratory environments was the addition of the physical materials to the dynamic visualizations of the virtual laboratory. Additionally, the *Physical-only* condition closely tracked with the *Integrated P-V* condition throughout the results. In fact, for force and mechanical advantage in the length experiment, the difference between the *Physical-only* and *Virtual-only* conditions was nearing significance with a p value of .009, just over the Bonferroni-adjusted critical value of .0083.

However, this effect only occurred during the height experiment, but not during the length experiment, where there were no significant differences between conditions. This was likely due to somewhat of a ceiling effect: with a maximum score of 3 on the three items and a score of 2.18 on the pre-test, participants generally already understood force and mechanical advantage when varying length to some extent before performing the experiment.

These results taken together indicate that the physical experience of pulling the block up the ramp had a positive effect on participants' conception of force, though not in all situations. This provides evidence that this kind of direct physical experience within laboratory environments is important for understanding the concept of force, at least for some students. This contradicts some studies on physical and virtual laboratory environments (eg., Triona & Klahr, 2003; Klahr, Triona & Willams, 2007) where researchers posit that virtual laboratories are as effective or more effective than physical ones. At least to some extent, the equivalence of virtual and physical laboratories likely depends largely on the domain and the concepts to be learned, but this data indicates that educators and designers of learning environments should carefully consider the potential tradeoffs before replacing a physical laboratory environment in a science classroom with a computer simulation.

The in-depth interview questions on the concept of force provide further evidence that the physical experience of pulling the block up the inclined plane may have led to better understandings of the concept of force. As measured by responses during the interviews, participants in the *Physical-only* condition gained significantly more on conceptions of force from pre to post than participants in the *Virtual-only* and *Sequential Physical-Virtual* groups. These overall patterns for conception of force generally aligned with participants' conceptions of force and mechanical advantage on the physics concept test, though there were some differences. One difference was that participants in the *Integrated Physical-Virtual* condition performed better on the concept test than in the interview (relative to other conditions), while participants in the *Physical-only* condition performed better in the interviews. It is currently unclear whether differences in patterns between the concept test and the interview had more to do with the questions asked or the particular students sampled for the interviews. In any case, when considering both the concept test results and interview results together, the overriding finding on learners' understanding of force is that the *Physical-only* and *Integrated Physical-Virtual* conditions exhibited the deepest understanding of force, while the *Virtual-only* and *Sequential Physical-Virtual* conditions exhibited the least. Taken together, this provides strong evidence that the existence of the physical manipulatives positively impacted learners' conceptions of force. Interestingly, based on the interview data, providing physical experience for only one of the two experiments (as in the *Sequential Physical-Virtual* condition) was not enough to improve participants' conception of force. Only when the haptic feedback in pulling the object up the ramp was provided for both experiments was such physical manipulation helpful in providing better understanding of force.

H5: Students in the Virtual-only and Integrated Physical-Virtual conditions will outperform those in the Physical-only condition on the concepts of work and potential energy.

Interestingly, the only significant difference on the post-test concerning work and potential energy was that the students in the *Virtual-only* condition outperformed those in the *Integrated Physical-Virtual* condition. There was no significant difference between the *Virtual-only* condition and the *Physical-only* condition, as was expected, nor between the *Integrated Physical-Virtual* condition and the *Physical-only* condition.

Why might the simulation environment in the *Virtual-only* condition have been more effective at building understanding of potential energy than the mixed reality environment of the *Integrated P-V* condition? One aspect that might have contributed was that, since the mixed reality environment did not calculate potential energy accurately enough to give the exact same result when lifting to the same height (due to minor differences where students began and ended lifting the blocks), it was decided that, unlike for the other variables, students would calculate the potential energy as participants in the *Physical-only* condition did. So, one difference between the *Virtual-only* condition and the *Integrated Physical-Virtual* condition was that participants needed to calculate potential energy after each trial with the mixed reality environment, where in the virtual environment they observed it directly.

Though not significantly different from either the *Virtual-only* condition or the *Integrated P-V* condition, those in the *Physical-only* condition performed second-worst of the four conditions on potential energy (behind the *Integrated P-V* condition). This may indicate that directly observing the potential energy does indeed have some benefits over calculating it. (While having both observed potential energy directly and calculated it, as the *Sequential P-V* condition did over the course of the two experiments, offered no improvement to only observing it directly.)

Though participants overall significantly improved their basic understanding from the pre-interview to post-interview on the conception of work, there were no differences between the conditions, unlike for force. This result provided some further depth on the results of the concept tests. From the concept test results, there were differences between the conditions on conceptions of work and potential energy when varying the length of an inclined plane, namely that the *Virtual-only* condition outperformed the *Integrated Physical-Virtual* condition. This overall result on learners' understandings of work in the interviews suggests that the differences between conditions on work and potential energy on the concept tests were likely more related to potential energy than work. There were some results of the interviews, however, that suggest that the differences between the laboratory environments did lead to some more subtle differences in how learners' understood the concept of work. These results will be discussed in the next section.

In this study, participants in the *Sequential Physical-Virtual* condition generally fell somewhere in the middle of all conditions for all concept test results. Providing separate physical and virtual laboratories avoided the worst of each form alone, but also was never the most effective environment for learning specific physics principles. This finding is contrary to some other research on combining physical and virtual experiments (e.g. Jaakkola & Nurmi, 2008; Olympiou & Zacharia, 2012), which has shown that providing both physical and virtual laboratories can support student learning better than either form alone, though it does concur with other studies that have found them to be equivalent (e.g. Zacharia & Olympiou, 2011). One reason this study may have led to no advantage for combined physical and virtual laboratories is the short amount of time that students spent on the experiments. Though only having one hour to complete experiments is typical of laboratories in the classroom, this amount of time is fairly short for trying to learn from experiments in two different environments. There may have been additional confusion for participants in this condition to try to synthesize everything they learned across two different environments when answering questions on physics concepts. As one participant in this condition explained, speaking about the experiments she conducted, "they helped some, but I would have needed more time and study for it to really sink in." No participants in any other condition mentioned the amount of time as being a factor in how much they learned. It may be the case that if learners were given more time, the *Sequential Physical-Virtual* condition would begin to outperform the *Physical-only* and *Virtual-only* conditions, as they have in some other studies.

Influences of Perceptual-Motor Features of Laboratory Environments on Specific Learner Misconceptions

Finally, this portion of the study attempted to address the following research question:

> RQ3). *Do the unique perceptual-motor features of different physics laboratory environments lead to* ***specific misconceptions*** *about the nature of force and work?*

Across all participants, the two most common misconceptions that occurred involved learners conflating the concepts of force and work and misunderstanding the dynamic nature of these variables.

Conflating force and work: Overall, participants often conflated the concepts of force and work, either by answering a question on one concept in a way that would be correct for the other, or more explicitly conflating them by specifically misnaming one concept as the other. Interestingly, there were differences across the conditions in how often participants conflated force and work during the post interviews, with the participants in the *Physical-only* condition performing the best by far (2 instances of the misconception) and those in the *Virtual-only* and *Integrated Physical-Virtual* conditions performing the worst (8 instances of the misconception). Those conditions that displayed the real-time value of work directly in the environment (i.e. *Virtual-only* and *Integrated Physical-Virtual*) versus having students calculate work (as in the *Physical-only* condition), led to participants more often conflating force and work. Though in many cases the mixed reality environment seemed to shape learning similarly to the physical environment, here was one case where it did not. This may be due to the fact that in the *Physical-only* environment, students calculated work as a separate step after reading the value of force from the spring scale. Meanwhile, with the mixed reality environment (as with the simulation environment), participants observed both force and work directly from the graphs. Displaying both variables in front of learners at the same time required them to differentiate and remember which variable was which. The fact that participants in these conditions often conflated force and work suggests that some students (particularly in the *Virtual-only and Integrated P-V* conditions) had difficulty remembering which concept was which when they were both simply displayed on the screen as dynamic bar graphs.

This has implications for the design of mixed reality (as well as purely virtual) learning environments. Part of the justification for mixed reality environments (or even multi-representational virtual environments) is that providing additional representations may be better for various reasons, such as allowing one representation to supplement or constrain interpretations of another (Ainsworth 1999, 2006). However, this data illustrates that separating force and work may have had unintended benefits with the physical environment: participants rarely confused the two. A potential solution to this problem with virtual and mixed reality environments would be something akin to model progression (Swaak, van Joolingen & de Jong, 1998), where the simulation model is gradually increased in complexity. Learners could have time to understand each variable individually before understanding the relations between multiple variables. Further, providing additional cues within the representations themselves as to what concept they correspond to may also help avoid this problem. In these particular mixed reality and simulation environments, force and work were simply dynamic bar graphs of different colors that were labeled "force" and "work". Instead of simple bar graphs with no additional cues as to their meaning, the value for force could be displayed adjacent to the force vector, and work could be displayed as a dynamic equation that illustrates that work increases while distance increases (while force remains constant). In short, further perceptual cues could be added to the displays of both force and work that provide more information about their meaning and could thus be internalized within learners' mental imagery of the phenomena. Without such additional perceptual cues, there were drawbacks to simply graphing two concepts next to each other, which is often done in virtual laboratory environments.

Understanding change of force and work in inclined plane experiments: The second most common misconceptions in the interviews involved mistakes in understanding changes in force and work as an object is being moved up an inclined plane. Here, there were significant differences across the conditions in the frequencies of misconceptions of both force and work.

On the interview question on what happens to *force* as an object is being lifted up an inclined plane, participants in the *Physical-only* and *Integrated Physical-Virtual* conditions responded correctly most often, while those in the *Virtual-only* condition most often incorrectly responded that the amount of force increases as an object is being pulled up a ramp. This suggests that the force feedback of the physical and mixed reality environments was important for building conceptions of force that included an understanding of how it remained constant when pulling up a constant angle.

From the interview question on what happens to work as an object is being moved up a ramp, the opposite pattern emerged: participants in the *Virtual-only* and *Integrated Physical-Virtual* conditions most correctly understood this dynamic aspect of the concept of work. This suggests that without directly seeing work increase as they moved the block up the ramp, those in the *Physical-only* condition were less likely to understand that work increased the entire time. They knew from the equation that work is equal to force multiplied by distance, but few of them realized that meant that distance would be increasing the entire time.

These findings on understanding the dynamic nature of force and work give examples of places where the specific perceptual-motor features of the different laboratory environments tended to lead toward specific patterns of conceptions about the physics concepts: offering force feedback in the environment made it more likely that learners' would correctly understand that the amount of force needed remains constant when pulling an object up an inclined plane, while visually displaying the value of work in real-time led to learners more often understanding that work increases gradually as the distance the object is being pulled increases.

Overall, the concept test results reveal that, though modest in size, there are some advantages and disadvantages to each form of laboratory environment, and that relatively small changes to the combination of physical and virtual experiments can affect learning of physics concepts. Since the only significant differences for the concept test results involve differences between the *Virtual-only* condition and the *Integrated Physical-Virtual* condition, these results revealed that adding physical materials and associated haptic feedback to virtual environments can affect learning, both positively and negatively. In this case, adding haptic feedback to the virtual environment helped improve conception of force, but somewhat hindered conception of potential energy. The *Physical-only* condition, though not statistically significantly different than the other conditions, did tend to exhibit results closer to the *Integrated P-V* condition than the *Virtual-only* condition. This may indicate that adding the physical materials and processes to the simulation environment made the mixed reality environment act more closely to a purely physical environment than to a purely virtual environment.

One of the stronger results of this study was that there were advantages to the haptic feedback provided in the physical and mixed reality laboratories, especially in helping shape understanding of the concepts of force and mechanical advantage. This finding suggests that educators should carefully consider when to replace physical experiments with virtual ones, especially to aid in the understanding of concepts such as force that are directly related to our physical experience in the world. [6]

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[6] One caveat to the advantage of the physical experiments that should be mentioned is that in this study, one potential advantage of the virtual and mixed reality environments was removed: the ability to simulate idealized situations. For example, both of these environments would be capable of modeling what would happen in a frictionless environment, and in the case of the length experiment a frictionless environment would show that the amount of work done is independent of the length of the ramp. In order to keep participants' data the same across all conditions, the simulation environment added friction. In short, there are additional advantages of virtual experiments that weren't utilized in this study, particularly in exploring phenomena that depend in part on an idealized environment.

From the interview results, it is also clear that providing haptic feedback positively supported students' conceptions of force, the case for what to do about work is less clear. Allowing participants to calculate work for themselves (rather than displaying it directly) led to fewer instances of conflating force and work, but it also led to increased misconceptions about the dynamic nature of work. Displaying work directly in the environment had the opposite problem: participants understood that work increased with distance, but also were more likely to conflate work with force. Displaying work dynamically while offering perceptual cues as to how it relates to, but is different than, force may be a helpful solution to this problem.

Chapter 5: Influence of Laboratory Environments on Gesture and Simulated Action

Chapter 4 addressed the first major goal of this study concerning the influence of the perceptual-motor features of laboratory environments on conceptual understanding, as measured by concept tests and verbal responses during interviews. It established that there were differences in students' understanding of physics concepts by the laboratory environment that students encountered. The second major goal of this study was to dig deeper into how such conceptions were embodied: were specific perceptual-motor features of the laboratory environment internalized in a way that lead to such differences in conceptual understanding?

This portion of the study addressed the following primary research question:

RQ4). Do the unique perceptual-motor features of physics laboratory environments lead to different patterns of learners' gestures as they explain physics concepts? Interactions with physics laboratory environments that contain different perceptual-motor features may lead to differences in internal representations of physics phenomena, including differences in simulated action and perception. These internal representations may be more accessible through gesture than through verbal descriptions of the science concepts. Gesture is often considered as evidence of the embodiment of language and cognition, and much evidence suggests that gestures are "outward representations" of mental imagery and simulated action (Hostetter & Alibali, 2008; McNeill, 1992, 2008). Though concept tests can fairly easily reveal learners' verbal and propositional representations, illustrating learners' underlying mental imagery can be more difficult. Analyzing learners' gestures can be a powerful way to reveal underlying mental imagery and simulated action that is not easily accessed through other methods, and provide insights into the particular perceptual-motor features of learning environments that learners internalized.

In the case of science laboratory environments, interactions with environments containing different perceptual-motor properties may lead to different perceptually-based internal representations, which may be more accessible through gesture than through verbal descriptions of the science concepts. The perceptual-motor properties of laboratory environments may shape learner conceptions in ways that are sometimes not detected on written tests and through verbal descriptions during interviews.

In this study, it was hypothesized that different patterns of gesture would emerge across different laboratory environments, matching the actions that students performed in the laboratory environment, specifically:

H1: Students in the *Physical-only* condition and the *Integrated Physical-Virtual* condition will perform more action gestures than those in the *Virtual-only* condition.

In pulling a real-world block up an inclined plane, students in the *Physical-only* condition and the *Integrated Physical-Virtual* performed this "pulling" action repeatedly during their experiments. Meanwhile, in pulling a virtual block up a virtual inclined plane, students in the *Virtual-only* condition only performed the action of moving a mouse slightly to "pull" the virtual block up the ramp. It was hypothesized that the real-world action of pulling the physical block up the ramp would be more likely to be internalized as simulated action and revealed later through gesture than was the act of moving the mouse to pull up the virtual block. This would result in more action gestures overall for the *Physical-only* condition and the *Integrated Physical-Virtual*, specifically the act of “pulling” an imagined block up an inclined plane.

The following sections describe the methods utilized in addressing this research question as well as the analyses performed and the results and conclusions of this portion of the study.

Research Methods

Data Sources

To address the above research question on the influence of laboratory environment on students’ gestures, this portion of the study analyzed participants’ gestures, both during pre and post interviews as well as during their laboratory experiments.

Pre and post interviews. As described in Chapter 4, to better understand participants’ conceptions of the key concepts of force and work, 8 participants from each condition were randomly selected for semi-structured pre and post-interviews on their understanding of force and work (N = 32). Three questions were asked concerning participants’ understanding of force in an inclined plane and three questions were asked concerning work in an inclined plane. Additionally, participants were asked what they were thinking about or imagining as they were answering those questions on force and work (see Appendix E for interview protocol). The interviews were all conducted by the same researcher and followed the script specified in Appendix E. Participants responses to the questions were all video recorded, and their verbal answers were transcribed.

Participants’ explanations of their experiment data. To gain a deeper understanding of participants’ evolving conceptual understanding *during* their laboratory experiments, short, structured interviews were conducted with participants after they complete each of the experiments (one immediately after the length experiment and one immediately after the height experiment). In the interview, participants (in dyads) were asked to explain their data corresponding to each physics concept (force, work, potential energy, and mechanical advantage). They were asked what they noticed about their results for each concept, why they thought those results occurred, and how they knew that their explanation was correct. The full questions were as follows for the length experiment:

1. Using the data from this experiment, what do you notice about the relationship between *distance* and *applied force* in an inclined plane? Why do you think that occurs? Explain your reasoning.

2. Using the data from this experiment, what do you notice about the relationship between *distance* and *work* in an inclined plane? Why do you think that occurs? Explain your reasoning.

3. Using the data from this experiment, what do you notice about the relationship between *distance* and *potential energy* in an inclined plane? Why do you think that occurs? Explain your reasoning.

4. Using the data from this experiment, what do you notice about the relationship between *distance* and *mechanical advantage* in an inclined plane? Why do you think that occurs? Explain your reasoning.

The questions for the height experiment were identical to these except for asking about the relationship to height rather than distance (see Appendix B).

Participants' responses were video recorded for each of the length and height experiments. Being that participants answered the observation and analysis questions in dyads, dyads were treated as the unit of analysis. All dyads' responses to the observation and analysis questions were videotaped during these interviews. Of the videos, 13 from each condition were transcribed (N = 52) and used for analysis of the dyads' explanations of their data. (All 13 available videos for *Virtual-only* condition were utilized, while 13 of the 14 available videos for each of the other three conditions were randomly selected for analysis.)

Analyses

Though this portion of the study used in part the same interview data as in Chapter 4, instead of analyzing participants' verbal explanation of physics concepts, participants' gestures while explaining the physics concepts were analyzed. This analysis was performed both on participant interviews before and after the laboratory experiments, and on participants' explanations of their data during the height and length experiments.

Gesturing Before and After Laboratory Experiments

First, this portion of the study investigated how participants' gestured while explaining the physics concepts of force and work during pre and post interviews. Categories of gestures were developed both deductively, based on the research literature on gesture and thought (McNeil, 1992, 2008; Goldin-Meadow & Beilock, 2010), and inductively, based on participants' responses while explaining the concepts of force and work during the interviews. First, instances of iconic gestures were noted from the video corpus. Iconic gestures are those gestures that imagistically represent object attributes, actions, and spatial relationships (McNeil, 1992). Iconic gestures were chosen for coding and analysis since they were the most likely to reveal specific properties of participants' simulated action and mental imagery when explaining their understanding of force and work[7]. Next, after noting instances of iconic gestures, codes for these gestures were developed inductively by what properties of actions or objects they represented

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[7] In focusing on iconic gestures, the other dimensions of McNeil's model of gesture (metaphoric, deictic and beat gestures) were ignored.

imagistically. Finally, the codes developed were further grouped into two larger categories, based on the research literature on gesture and thought. Gestures that corresponded to real-world actions, in that they incorporated components of actions into their form, were categorized as "action gestures" (Goldin-Meadow & Beilock, 2010). These gestures included "pulling" gestures, "pushing" gestures, "tracing" gestures, and "lifting up" gestures that involved the action of moving an imaginary object (see Table 12 for a description and example of each gesture). Gestures that included the attributes of an imaginary object without including any components of actions were categorized as "attribute" gestures. These gestures included "angle" gestures, "height" gestures and "length" gestures (see Table 13 for a description and example of each gesture).

Instances of each category of gesture were then counted from the video data for each participant within the pre and post interviews and inter-rater reliability with another researcher was established on 10% of the data, with a Cohen's Kappa of .830 (Cohen, 1968). To test for differences between experimental conditions on the frequency of action versus attribute gestures, two Chi-square tests of independence were conducted: one for the pre interview and one for the post-interview. Evaluating differences in the patterns of action and attribute gestures across conditions allowed for investigating whether conducting experiments in some laboratory environments elicited more simulated action (as evidenced by action gestures) than others.

Meanwhile, evaluating differences in the more fine-grained patterns of gesture suggested which components of the actions and objects of the laboratory environment remained most salient for learners. Gesture, and the underlying simulated action that evokes it, are representations rather than literal recreations of actions (Goldin-Meadow & Beilock, 2010). The pulling gesture, in grasping an imaginary object and pulling it up an imaginary inclined plane, included both a movement component (at an angle) and a force component. The pushing gesture also included both movement and force components, but indicated that participants were simulating an action other than what they performed during the inclined plane experiments, since participants pulled the block up the inclined plane rather than pushed. The tracing gesture, in moving a finger or hand up an imaginary ramp without pushing or grasping, still contained a movement component, but lacked a force component. The angle gesture, meanwhile, lacked the movement component of the tracing gesture as well as any force component, and thus contained no information about the action performed in the inclined plane experiment, but exhibited the angle or slope of the inclined plane (which is also included in the pulling, tracing and pushing gestures) as part of the underlying mental imagery.

Table 12

Action gestures coded for during pre and post-interviews.

Gesture	Description	Example
Pulling	Moving hand up an invisible ramp, with partially, closed hand indicating pulling an invisible object.	

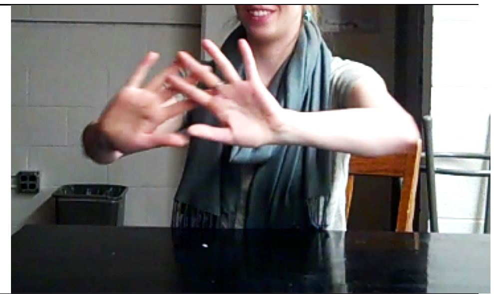
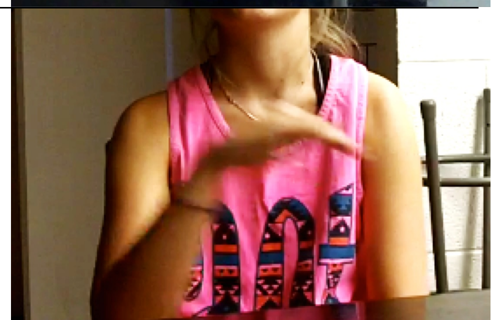
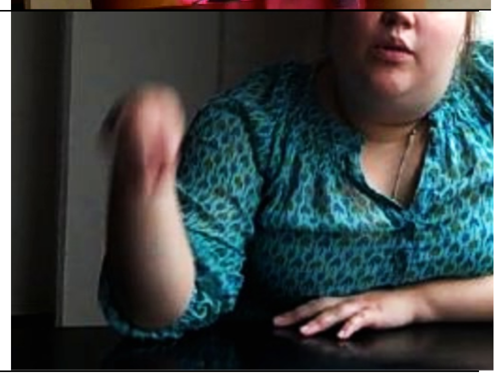
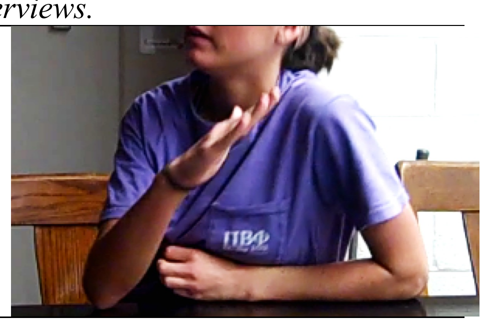
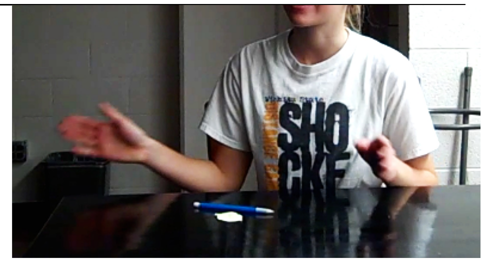
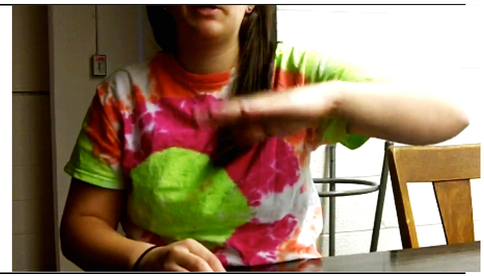
Pushing	A two-handed or one-handed push with open palms.	
Tracing	Moving hand up an invisible ramp, with either flat hand or index finger tracing the shape of the ramp.	
Lifting up	Moving hand directly up, lifting an imaginary object straight up.	

Table 13

Attribute gestures coded for during pre and post-interviews.

Angle	Placing hand at an angle (without moving up or down an invisible ramp) while discussing slope or angle of a ramp.	

Length	Either a two-handed gesture with open palms facing each other displaying a horizontal distance, or tracing an invisible horizontal distance with one hand or finger. (Different from tracing gesture in that there is no vertical movement to the gesture.)	
Height	Either displaying one hand palm-down above a surface, or tracing an invisible vertical distance with one hand or finger. (Different from tracing gesture in that there is no horizontal movement to the gesture.)	

Gesturing During Laboratory Experiments

In addition to investigating how students gestured during pre and post-interviews, participant gestures while they explained the data from their length and height experiments were also analyzed. This analysis allowed for comparison with the gestural results during pre and post interviews. Specifically, the results of this new analysis indicated how learners across the four conditions may have created initial mental imagery and simulated actions associated with the concepts that later matched those revealed during the post-interview. To analyze participants' gestures while explaining their data, the same categories of gestures were used as in the interviews: iconic action gestures of "pulling", "pushing", "tracing" and "lifting up" and iconic attribute gestures of "angle", "length" and "height" (see

Table 12 and Table 13). Instances of these gestures were then counted from the video data for each dyad while they explained the results of their length and height experiments. Instances of each category of gesture were then counted from the video data and inter-rater reliability with another researcher was established on 10% of the data, with a Cohen's Kappa of .830 (Cohen, 1968). To test for differences between experimental conditions (*Physical-only*, *Virtual-only*, *Sequential-Physical-Virtual*, and *Integrated Physical-Virtual*) on the frequency of action versus attribute gestures, a Chi-square tests of independence was conducted.

Participant Reports of Mental Imagery

In addition to gesture, another way to understand what perceptual-motor components (if any) of the laboratory environments students were utilizing when explaining the physics concepts was to ask them more directly. In addition to using gesture as evidence for simulated action and mental imagery, participants were also directly asked during the pre and post interviews what they were thinking about or imagining when explaining their understanding of force and work. This data offered further indications beyond gestures about which parts of the experiment remained most salient when explaining the physics concepts, and could be triangulated with the gesture data to understand learners' underlying mental imagery after performing the experiments. The categories were developed inductively based on participants' responses, each participant's response was coded, and inter-rater reliability with another researcher was established on 10% of the data, with a Cohen's Kappa of .937 (Cohen, 1968). A Fisher's exact test of independence was conducted to analyze the frequency of drawing from an everyday situation versus something encountered during the experiment (the experiment itself, equations or the data table) across the four conditions.

Results

Gesturing Before and After Laboratory Experiments

As described above, instances of gesture were coded and analyzed for both the pre-interviews and post-interviews. During the pre interviews, when explaining their understanding about force and work, participants exhibited action gestures 92 times in total, while exhibiting attribute gestures only 24 times. Of the action gestures, the tracing gesture was the most common overall (56 instances), followed by the lifting up and pushing gestures (29 and 25 instances, respectively). Participants only exhibited the pulling gesture on two occasions.

To compare the patterns of gestures across conditions during the pre-interview, a chi-square test was performed on overall frequency of action and attribute gestures between the four conditions (*Physical-only, Virtual-only, Sequential P-V* and *Integrated P-V)*. The chi-square test revealed no significant differences in the frequencies of action and attribute gestures between the four conditions, χ^2 (3) = 1.99, p = .575.

After performing the experiments, however, there was a different overall pattern to participants' gestures. During the post-interview, participants performed 100 action gestures to 58 attribute gestures. Of the action gestures, the gesture of tracing up an invisible ramp was still the most common (47 instances), however the pulling gesture was now the second-most common (25 instances, see Table 14). In effect, the pushing up and lifting gestures that were common during the pre-interview were somewhat replaced by the pulling gesture during the post-interview.

Further, unlike during the pre-interview, there were differences in patterns of gestures between conditions. To compare the patterns of gestures across conditions, a chi-square test was performed on overall frequency of action and attribute gestures between the four conditions (*Physical-only, Virtual-only, Sequential P-V* and *Integrated P-V)*. The chi-square test revealed a significant difference in the frequencies of action and attribute gestures between the four conditions, χ^2 (3) = 10.71, p = .013. From the standardized residuals of the chi-square test (see Table 15), participants in the *Physical-only* condition and the *Integrated P-V* condition performed action gestures (+1.0, +.95) more often than attribute gestures (-1.3, -1.24), while participants in the *Virtual-only* condition and the *Sequential P-V* condition performed attribute gestures (+.85, +1.67) more often than action gestures (-.65, -1.28 , see Table 15).

Table 14

Participant gesture by condition during the post-interview.

Gesture	Physical-Only	Virtual-Only	Sequential P-V	Integrated P-V	TOTAL
Action gestures:					
Pulling	11	1	7	6	25
Pushing	1	5	2	5	13
Tracing	12	15	4	16	47
Lifting up	2	5	3	5	15
Attribute gestures:					
Angle	1	7	3	1	12
Length	4	7	15	8	34
Height	3	7	1	1	12
TOTAL	34	47	35	43	159

Table 15

Standardized residuals from chi-square test on action and attribute gestures.

Gesture Type	Physical-Only	Virtual-Only	Sequential P-V	Integrated P-V
Action Gestures	+1.0	-.65	-1.28	+.95
Attribute Gestures	-1.3	+.85	+1.67	-1.24

Much of the difference between conditions on patterns of action versus attribute gestures was driven by differences in patterns of the pulling gesture and the angle gesture that the participants exhibited. The pulling gesture was performed far more often by participants in the *Physical-only*, *Sequential Physical-Virtual*, and *Integrated Physical-Virtual* conditions (11, 7 and 6 instances, respectively) than the *Virtual-only* condition (1 instance), while the angle gesture was performed far more by participants in the *Virtual-only* condition (7 instances) than those in the *Physical-only* and *Integrated Physical-Virtual* condition (1 instance each).

These results indicated that, in addition to differences in their verbal explanations of the concepts, participants across the different conditions gestured differently when explaining the concepts. In particular, participants who had experienced pulling a physical brick during their experiments displayed a pulling gesture that matched their experience with the physical environment. (No participants did this in the pre-interview, and only one did in the Virtual-only condition.) This may indicate that the perceptual-motor features of their interaction with the environment may have been internalized and now persisted as part of their understanding of the physics concepts. These results also provide some additional clues as to what participants in the different conditions found to be the most salient features of the learning environment. For example, according to their gestures, participants in the *Virtual-only* condition focused far more on the angle of the ramp as being an important feature than those in any other condition.

Gesturing During Laboratory Experiments

When analyzing how participants gestured while explaining their data (across both the length and height experiments), the patterns of gesture were similar to those during the post-interview. Overall, participants performed 72 action gestures and 79 attribute gestures. Of the action gestures, tracing and pulling were each the most common (with 33 instances each). Of the attribute gestures, the angle gesture was the most common, with 39 instances.

Also as during the post-interview, the *Physical-only* and *Integrated Physical-Virtual* conditions tended to produce more action gestures (26 and 21 instances, respectively) than attribute gestures (16 and 13 instances). Meanwhile, participants in the *Virtual-only and Sequential Physical-Virtual* conditions produced more attribute gestures (29 and 21 instances, respectively) than action gestures (12 and 13 instances).

Table 16

Total instances of participant gestures while explaining their data by condition.

Gesture	Physical-Only	Virtual-Only	Sequential P-V	Integrated P-V	TOTAL
Action gestures:					
Pulling	11	0	8	14	33
Pushing	0	6	0	0	6
Tracing	15	6	5	7	33
Attribute gestures:					
Angle	5	17	13	4	39
Length	7	2	4	6	19
Height	4	10	4	3	21
TOTAL	49	38	44	36	167

To compare these patterns of gestures across conditions, first a chi-square test was performed on overall frequency of action and attribute gestures between the four conditions (*Physical-only, Virtual-only, Sequential P-V* and *Integrated P-V)*. The chi-square test revealed a significant difference in the frequencies of action and attribute gestures between the four conditions, χ^2 (3) = 10.96, p = .012. From the standardized residuals of the chi-square test (see Table 17), participants in the *Physical-only* condition and the *Integrated P-V* condition performed action gestures (+1.26, +1.08) more often than attribute gestures (-1.17, -1.00), while participants in the *Virtual-only* condition and the *Sequential P-V* condition performed attribute gestures (+1.47, +.73) more often than action gestures (-1.59, -.78).

Table 17

Standardized residuals from chi-square test on iconic action and attribute gestures during data explanations.

Gesture Type	Physical-Only	Virtual-Only	Sequential P-V	Integrated P-V
Action Gestures	+1.26	-1.59	-.78	+1.08
Attribute Gestures	-1.17	+1.47	+.73	-1.00

Much of the difference between conditions on patterns of action versus attribute gestures was driven by differences in patterns of the pulling gesture and the angle gesture that the participants exhibited. The pulling gesture was performed far more often by participants in the *Physical-only* condition (11 instances) than the *Virtual-only* condition (0 instances), while the angle gesture was performed far more by participants in the *Virtual-only* condition (17 instances) than those in the *Physical-only* condition (5 instances). This pattern of gesture was similar to later during the post-interview, where the pulling gesture was again performed the most by participants in the *Physical-only* condition and the least by those in the *Virtual-only* condition, and the angle gesture was performed far more by participants in the *Virtual-only* condition than those in the *Physical-only* condition.

These results indicate the following: 1) For those participants who pulled a physical block up an inclined plane (all conditions except for the *Virtual-only* condition), components of the movements taken during the experiments by were incorporated later into their gestures during the post-interviews. 2) Participants in the *Virtual-only* condition tended to focus more on the angle of the inclined plane as the salient perceptual feature. 3) Further, when participants in the *Virtual-only* condition did include a component of movement in their gestures (with performing the tracing gesture), it did not include a force component (as the pulling gesture more often used by participants in other conditions did).

Participant Reports of Mental Imagery

In addition to using gestural data as a window into students' internal imagistic representations of physics phenomena, this study also used participants' own reports of their mental imagery to triangulate with the gestural data. During the pre and post interviews, participants were asked what they were thinking about or imagining when answering the interview questions on force and work. In their responses to this question during the pre-interview, participants universally explained that they drew from some kind of everyday experience to answer questions on the relationship between force/work and distance, for example imagining running up a large hill or lifting a hay bale into a truck. During the post interview, however, what participants drew from in their explanations was much more varied: participants either imagined some everyday experience, as in the pre-interview (9 instances), or their experience in performing the actual experiments with the physical or simulation environment (10 instances), or thought about the data table (5 instances) or the equations (for 4 instances) from the experiment (see *Figure 11*).

A Fisher's exact test of independence was conducted to analyze the frequency of drawing from an everyday situation versus something encountered during the experiment (the experiment itself, equations or the data table) across the four conditions. The Fisher's exact test was significant, $p = .025$, indicating significant differences in the frequency of drawing from some part of the experiment across conditions. In particular, with only 2 instances, the *Virtual-only* condition was significantly less likely to draw from any part of the experiment than the other conditions, and many even used the same everyday example as they did during the pre-interview. For example, one student claimed that they were imagining, "still the same scenario of me pushing a box up a ramp." In contrast, with 6 instances of imagining some part of the experiment, participants in the *Physical-only* condition explained that, "I was thinking about what the inclined planes looked like when we actually did them" and "The experiments that we just did. The actual boards and stuff." Further, some participants were explicit in mentioning they were no longer envisioning the same everyday situation they were in the pre-interview. One participant in the *Integrated P-V* condition explained:

> "I was thinking about the experiment we just did. I was imagining the paper that we wrote it on. I was imagining the incline, and I was imagining pulling it up and watching it all on the screen. I was actually imagining an experiment instead of mountains."

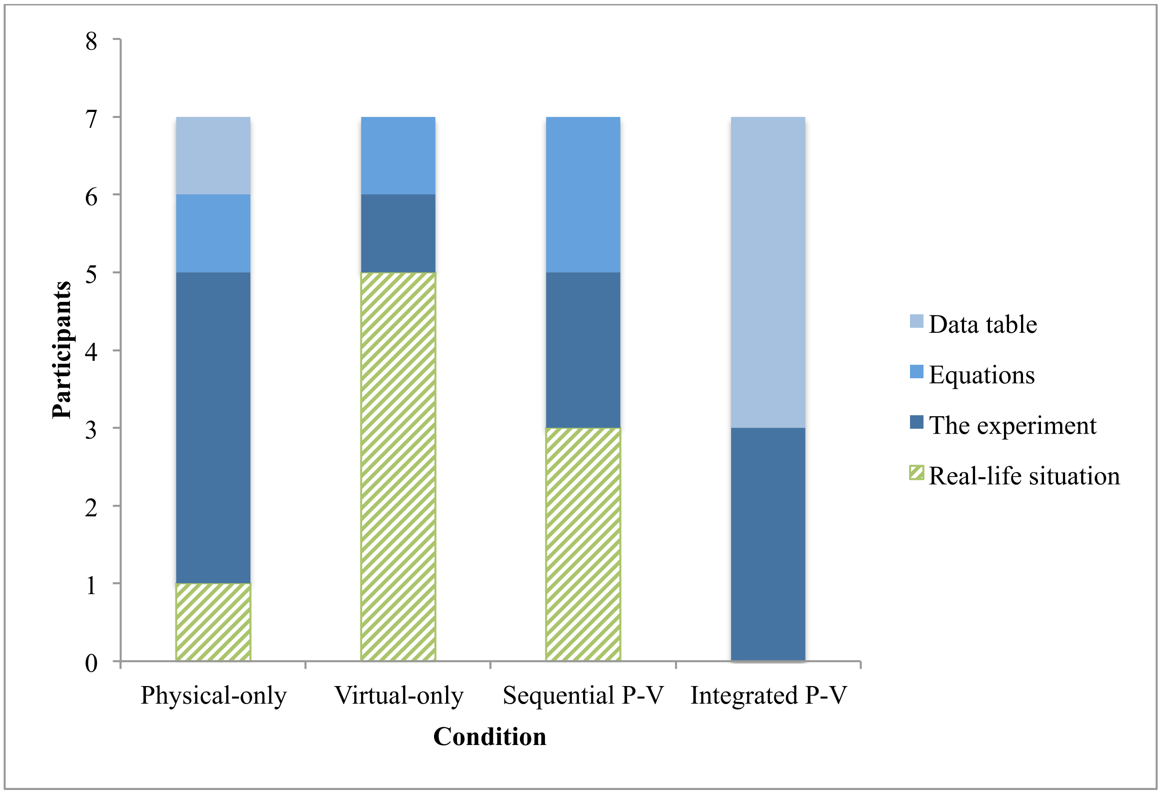


Figure 11. What participants claimed to be thinking about when attempting to explain the concepts of force and work in an inclined plane.

When asked what they were thinking about when explaining their understanding of force and work, only two participants in the *Virtual-only* condition imagined the experiment they had just done, while most of them drew from the same real-life situation they had imagined in the pre-interview. One potential explanation for this is that the physical experience of pulling the brick up the ramp provided a grounding for the concepts of force and work that was not available in the simulation; those who only used the simulation were more likely to continue to use their everyday experience as grounding for the formal physics concepts.

Discussion

This portion of the study addressed the following primary research question:

RQ4). Do the unique perceptual-motor features of physics laboratory environments lead to different patterns of learners' gestures as they explain physics concepts? This question was addressed through analyses of participants' gestures and self-reports of their mental imagery.

The gesture data from the interviews indicated that, in addition to differences in their verbal explanations of the concepts, participants across the different conditions also gestured differently when explaining the concepts. In particular, participants who had experienced pulling a physical block during their experiments displayed a "pulling" gesture that matched their experience with the physical environment. (None of the participants did this in the pre-interview.) Based on research that suggests that gestures can be taken as evidence that thinking is embodied or tied to perceptual and motor states (Hostetter & Alibali, 2008), it is likely that the learners had internalized the perceptual-motor features of the laboratory environments in the form of visual and/or motor representations, and that these representations now persisted as part of their understanding of the physics concepts.

As gestures and the underlying simulated actions that evoke them are representations rather than literal recreations of actions (Goldin-Meadow & Beilock, 2010), the details of participants' gestures also provided some clues as to which perceptual-motor aspects of the laboratory environments learners found to be the most salient features of the environment. For example, based on their gestures, participants in the *Virtual-only* condition focused far more on the angle of the ramp as being an important feature than those in any other condition, suggesting that their mental imagery of inclined planes included the angle of the inclined plane as an important feature. The pulling gesture that was prevalent in other conditions, however, included not only an angle component, but also a motion component, as well as a force component (as evidenced by grasping with one hand as they did to pull the block during the experiment). The participants who displayed a pulling gesture during their explanations likely were simulating the action of the experiments, and therefore their mental imagery included not only the angle of the ramp, but the motion up the ramp and the feeling of the force in pulling the object up the ramp. (The tracing gesture may have indicated both the angle and motion up the ramp, but not the motoric representation of force.)

When examining participants' gestures while explaining their data, there were also significant differences between the conditions. Action gestures were performed more often by participants in the *Physical-only* and *Integrated Physical-Virtual* conditions – those conditions where they had performed the actions of pulling the physical block up the inclined plane for both the length and height experiment. Similarly, participants in those two conditions also more frequently exhibited the "pulling" gesture in particular. This gesture both included a force component and closely matched the movement that they had performed during the inclined plane experiments. Meanwhile, those participants in the *Virtual-only* and *Sequential Physical-Virtual* conditions more often performed attribute gestures, specifically focusing on the angle of the inclined plane through their gestures.

This overall pattern of gesture was consistent with the patterns of gesture during the post-interview (see *Figure 12*, *Figure 13*). For example, the "pulling" gesture that later appears in the post interview (for conditions with a physical component) first appeared when trying to explain their data. Similarly, participants in the *Virtual-only* condition displayed the "angle" gesture most often both during their initial data explanations and later during the post-interviews. This may indicate that, different perceptual-motor components of the different environments were more or less salient while performing the experiments, which revealed themselves in participants' gestures during their data explanations and again during the post-interview. To some extent, the gestures "stuck", particularly the "pulling" gesture for the *Physical-only* condition and the "angle" gesture for the *Virtual-only* condition, revealing some difference in what they took away from the experiments.

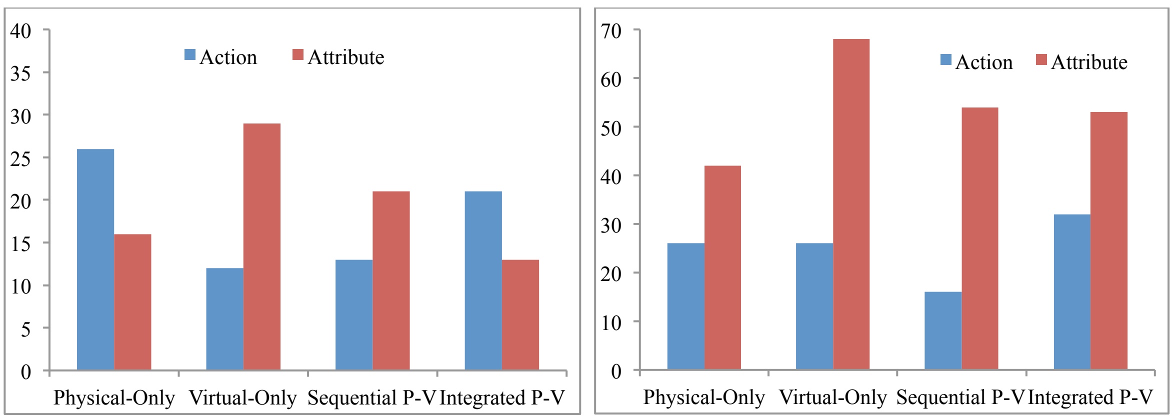


Figure 12. Frequency of action and attribute gestures across conditions during the experiments (left) and later during the post-interview (right).

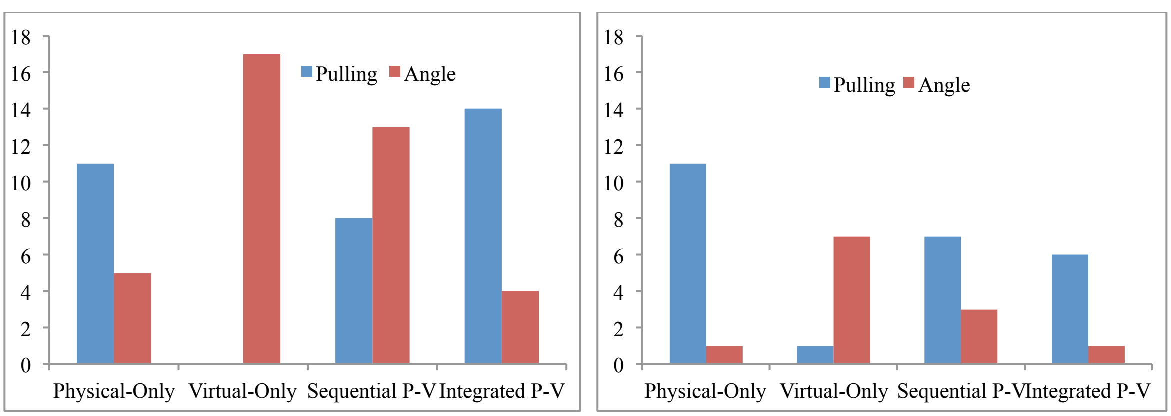


Figure 13. Frequency of "pulling" and "angle" gestures across conditions during the experiments (left) and later during the post-interview (right).

This suggests that the internal representations of participants' interactions were built during interactions with the laboratory environment, encapsulated different perceptual-motor features of the laboratory environment, and not only persisted until the post-interviews, but shaped participants' later verbal explanations of the physics concepts. This result – that there were differences in gestures between conditions both initially, while explaining their data, and later during the post interview - suggests that, instead of building verbal or rule-based representations of the concepts during each experiment (which likely would have led to differences in their immediate verbal explanations of their data), the representations they built were primarily visual and motor in nature. Further, differences across conditions in participants' mental imagery in turn influenced both conceptions on the post-test and verbal explanations during the post-interview. The motor and visual representations that were built during their interactions with the laboratory environments carried perceptual-motor components of the environments with them, and in turn shaped later explanation of the concepts.

Taken together, these results on learners' initial understanding of the physics concepts, as expressed verbally and through gestures, suggest a process by which learners built internal simulations of their interactions with the learning environment – mental representations that maintained key perceptual-motor aspects of the environment (e.g., force feedback, dynamic visual display of work, etc.). These different visual and motor representations were later evoked in verbally explaining the physics concepts, which by the time of the post-interview led to significant differences across conditions in verbal explanations of the physics concepts.

From the gesture data during the post-interviews, there was evidence that learners had built mental imagery that closely matched the laboratory environment they encountered. When asked what they were thinking about when attempting to describe the concepts of force and work, some learners displayed more direct evidence of this by explicitly stating that they were imagining their actions in performing the experiments. Additionally, there were differences across laboratory environments in how much mental images of the laboratory environments were utilized during explanations of concepts and differences in which parts of the environments were utilized. Participants in the *Physical-only and Integrated Physical-Virtual* condition, who used the physical block and ramps for both experiments, were more likely to claim that they were imagining the experiment itself than those who ran purely virtual experiments. Those in the *Virtual-only* condition, on the other hand, more often imagined a real-life situation in trying to explain the concepts than something from the experiment. This shows that, though participants often created internal visual and motoric representations of the laboratory environments, there were differences in how often they drew upon these mental images in explaining the concepts.

In a way, the physical experiment “stuck” more: it replaced everyday imagined scenarios with learners’ interactions in the laboratory environment as a resource to draw from more often than did the virtual experiment. This is a powerful reason why the physical experience of laboratory environments may be important, especially in physics classrooms. Many students have difficulty connecting formal physics to their perceptual-motor experience in the world (Schwartz & Black, 1999). This study shows that when explaining physics concepts after learning from a simulation environment, many students skip the experiment entirely as a resource to draw from, and continue to explain concepts based on their initial intuitive understanding. Providing a fuller perceptual-motor experience that includes haptic feedback can allow students to build visual and motor representations that include aspects of both everyday experience and formal physics, and can serve as a resource to draw from instead of only relying on their everyday intuitions.

Further, participants' reports of mental imagery showed that the experiments themselves were not the only piece of the laboratory environment that participants utilized when explaining the concepts: they also claimed to be "imagining" the equations and the data tables that they used during the experiment. This suggests that, in addition to paying attention to the design of the primary components of science laboratory environments (physical materials, simulations, etc.), the perceptual properties of other artifacts in the environment may be important as well. For example, participants who tried to imagine their data tables from the experiment often struggled to recall the direction of the relationships between variables. Either building in more perceptual cues within the data tables themselves, or integrating data tables into virtual and mixed reality environments to provide perceptual cues as to how the data relates to the concepts, may positively impact the visual representations of the data that are developed and thus affect conceptual understanding.

In sum, the unique perceptual-motor features of each physics laboratory environment did lead to different patterns of learners' gestures as they explained physics concepts. Specifically, participants who had experienced pulling a physical block during their experiments displayed a "pulling" gesture that matched their experience with the physical environment. Meanwhile, participants who did not experience pulling the physical block up the inclined plane were more likely to perform attribute gestures rather than action gestures, often performing an “angle” gesture demonstrating the slope of an inclined plane. The prevalence of both action and attribute gestures that matched the perceptual-motor features of the laboratory environment suggests that learners had internalized the perceptual-motor features of the laboratory environments in the form of visual and/or motor representations, and that these representations persisted as part of their understanding of the physics concepts. Analyzing students’ gestures after performing experiments in different physics laboratory environments revealed details about learners’ perceptually-based internal representations that were not available through concept tests and verbal interviews.

Chapter 6: Conclusions

The goal of this study was to explore how the unique perceptual-motor features of physical, virtual and combined physical-virtual laboratory environments shape learners' understanding of physics concepts. To answer this question, the first goal of the study (described in Chapter 4) was to investigate whether different combinations of physical and virtual laboratories led to differences in learners' understanding of physics concepts. The second goal (described in Chapter 5) was to dig deeper into how such conceptions were embodied: whether specific perceptual-motor features of the laboratory environment were internalized in a way that led to differences in participant gestures and underlying simulated action. In the section below, the basic research questions for each of these goals are reviewed as well as the findings from each section of the study. Then, the overall conclusions and implications of this study are discussed.

Summary of the Results

The overall aim of this study was to investigate the influence of perceptual-motor features of science laboratory environments on learners' conceptual understanding. To address this overarching aim of the research, the first goal was to investigate whether different combinations of physical and virtual laboratories lead to differences in learners' understanding of physics concepts. Based on prior research on comparing and combining physical and virtual laboratories in science classrooms, in Chapter 4, the study first aimed to address the following research questions comparing student learning across different laboratory environments:

RQ1). Do the unique perceptual-motor features of different physics laboratory environments lead to differences in learners' ***overall understanding*** *of physics concepts?*

RQ2). *Do the unique perceptual-motor features of different laboratory environments lead to differences in learners' understanding of* ***specific physics principles****?*

RQ3). *Do the unique perceptual-motor features of different physics laboratory environments lead to* ***specific misconceptions*** *about the nature of force and work?*

These comparisons of different laboratory environments based on their perceptual-motor features were evaluated both on overall conceptual understanding as well as on particular principles based on the different physics concepts and experiments the learners encountered. It established that there were differences in participants' conceptions by the laboratory environment that they engaged with. On overall conceptual understanding, all laboratories were equally effective at supporting student learning. However, the laboratory environments differentially supported learners' understanding of different physics principles in inclined planes. In particular, participants in the *Virtual-only* condition better understood work and potential energy when varying the length of an inclined plane than those in the *Integrated Physical-Virtual* condition. Meanwhile, participants in the *Integrated Physical-Virtual* condition better understood force and mechanical advantage when varying the height of an inclined plane than those in the *Integrated Physical-Virtual* condition. Additionally, through the pre and post interviews, this portion of the study found that the different laboratory environments led to differences in learners' overall understanding of force, but not of work. Specifically, participants in the *Physical-only* condition gained significantly more on conceptions of force from pre to post than participants in the *Virtual-only* and *Sequential Physical-Virtual* groups.

Overall, the concept test results revealed that, though modest in size, there were some advantages and disadvantages to each form of laboratory environment, and that relatively small changes to the combination of physical and virtual experiments could affect learning of physics concepts.

The results also revealed different patterns of misconceptions across the four laboratory environments. Participants in the *Physical-only* condition (where work was calculated separately) were the least likely to conflate the concepts of force and work. Laboratories that provided force feedback (as in the *Physical-only* and *Integrated Physical-Virtual* conditions) were the least likely to mistakenly think the amount of force required to lift an object changes as it is pulled up an incline plane. Finally, participants in the *Virtual-only* and *Integrated Physical-Virtual* conditions, where a dynamic real-time graph of work was provided, most correctly understood that the amount of work done gradually increases with distance. In total, these results provide further evidence of the unique perceptual-motor features of the laboratory environments shaping learners' conceptions of physics phenomena.

Beyond participants' understanding of force and work based on their verbal explanations of the concepts, Chapter 5 also explored participants' gestures as they explained the concepts of force and work. Specifically, the study aimed to address the following question:

RQ4*). Do the unique perceptual-motor features of physics laboratory environments lead to different* ***patterns of learners' gestures*** *as they explain physics concepts?*

The gesture data from the interviews indicated that, in addition to differences in their verbal explanations of the concepts, participants across the different conditions also gestured differently when explaining the concepts. In particular, participants who had experienced pulling a physical block during their experiments displayed a "pulling" gesture that matched their experience with the physical environment. Participants who did not engage with laboratory environment that included force feedback, however, more often performed "angle" gestures in the post-interviews. Based on research that suggests that gestures can be taken as evidence that thinking is embodied or tied to perceptual and motor states (Hostetter & Alibali, 2008), it is likely that the learners had internalized the perceptual-motor features of the laboratory environments in the form of visual and/or motor representations, and that these representations then persisted as part of their understanding of the physics concepts. Participants' self-reports of mental imagery further supported this interpretation. While explaining their conceptions of force and work in the post-interview, learners who engaged with physical materials in the laboratory environment were more likely to claim that they were imagining the experiment itself than those who ran purely virtual experiments. Those in the *Virtual-only* condition more often continued to imagine a real-life situation in trying to explain the concepts than something from the experiment.

In total, this section of the study provided further evidence of the ways in which the perceptual-motor features of laboratory environments shaped learners' conceptions, and suggested that learners' mental imagery and simulated action of the laboratory environments may have played a role in shaping their conceptions.

From the results of this study, there are two overarching conclusions: 1) The perceptual-motor features of science laboratory environments do shape learners' understanding of the underlying science concepts, and 2) Because of this, there are unique advantages and disadvantages to different forms of laboratory environments, based on their perceptual-motor features. These two overarching conclusions are discussed in the next two sections.

Embodiment and Learning within Science Laboratories

The physics concept test and interview results demonstrated that the unique perceptual-motor features of different laboratory environments shaped learners' conceptions differently. In particular, the haptic feedback of physically pulling an object up an inclined plane better supported conceptions of force than did a completely virtual lab environment that lacked such haptic feedback. On the other hand, the availability of dynamic representations in the virtual environment better supported learners' conceptions of work, in particular the fact that work changes in conjunction with the distance that a force is applied. The virtual environment also better supported conceptions of potential energy, possibly due to a difference in the learners' visual perspective of the inclined plane. In all, this study illustrated that there were significant differences across the experimental conditions in learners' understandings of different physics concepts. These differences were likely driven, at least in part, by differences in the perceptual-motor features of the laboratory environments.

Further, how participants gestured while initially explaining their data, and later during post-interviews, suggests a particular learning process that eventually led to different understandings of the physics concepts across conditions. During their interactions with the laboratory environments, learners likely created visual and motor representations of their interactions with the environment, which included the unique perceptual-motor properties of those environments (such as force feedback for the physical labs). These mental representations then persisted after the experiments, and learners drew from them when answering concept test questions and explaining the physics concepts during post-interviews.

Advantages and Disadvantages of Physical, Virtual, Sequential and Mixed Reality Laboratories

Because the perceptual-motor features of science laboratory environments influenced conceptual understanding, each of the four major categories of physical-virtual laboratory environments – completely physical labs, completely virtual, sequential physical-virtual labs, and mixed reality labs – had unique advantages and disadvantages for helping to build learners' understanding of science concepts.

Physical Laboratories

One of the main findings of this study was that having the physical experience of pulling a block up a ramp (as was provided through both the physical and mixed reality laboratories) supported learners' conceptions of force better than lifting a virtual object up a virtual ramp. The physical laboratory environment provided haptic feedback of force and movement that was likely internalized into simulated action and perception that was later drawn upon when explaining the concept of force. This likely indicates an "action-concept congruency” (Lindgren & Johnson-Glenberg, 2013) between pulling the block up the inclined plane and the concept of force. It may also explain why, though conception of force was better supported in the physical experiment, the concepts of work and potential energy were not. Work and potential energy were not directly visible in physical experiments, as they are calculated based on other primary variables. Indeed, participants understood key aspects of work and potential energy worse when learning from the completely physical laboratory, for example that the amount of work done is increasing as an object is being lifted up an inclined plane because the distance is increasing. These findings on physical laboratories illustrate some of the limitations that other research has shown (e.g., Snir, Smith & Grosslight, 1993; Zacharia & Anderson, 2003; Hofstein & Lunetta, 2004), but also provides direct evidence that physical experience can be important in laboratory environments, especially for understanding concepts such as force that are congruent with action in the real world.

Virtual Laboratories

Another finding of this study was that virtual laboratories can influence conception through providing dynamic representations of variables that are usually not directly observable. This affordance of computer simulations for “making the invisible visible” has been discussed in the literature previously (e.g. Hofstein & Lunetta, 2004), and this study provided an example of where it occurs. However, this study also illustrated a potential disadvantage of purely virtual environments that has not been discussed in the literature. The fact that learners were significantly less likely to draw from their experience with the simulation in explaining the concepts during the post-interview suggests that the simulation may not have grounded the abstract concepts in physical experience as much as the other lab environments. Before interacting with any of the learning environments, all participants utilized their everyday experience to try to understand and explain the formal concepts of force and work, but after performing the experiments, those who used the computer simulation often continued to do so, rather than utilizing their experience with the simulation. One of the primary goals of providing laboratory environments in classrooms is to enhance students' understanding of science concepts (Hofstein & Mamlok-Naaman, 2007). However, if learners are not utilizing the laboratory environment in elucidating concepts immediately after experiments, such an environment might not meet a basic criterion of an effective laboratory environment.

Sequential Physical-Virtual Laboratories

Prior studies on combining physical and virtual laboratories have been mixed in terms of whether a combination of physical and virtual experiments is more beneficial than either form alone. Some studies (e.g. Jaakkola & Nurmi, 2008; Olympiou & Zacharia, 2012) have found that a combination of physical and virtual experiments better supported student conceptions than either form alone, but others (e.g., Zacharia & Olympiou, 2011) have found no significant differences.

The current study showed no overall differences between a sequential combination of physical and virtual experiments and either completely physical or completely virtual experiments, but it did provide some insights into why other studies may have had mixed results. First, the study illustrated that, though both physical and virtual laboratories had different affordances for supporting learning based on their unique perceptual-motor features, these affordances related to particular physics concepts and situations. The physical laboratory better supported conceptions of force and mechanical advantage in some situations and the virtual experiment better supported conceptions of work and potential energy in other situations. Since physical and virtual laboratories each provide unique advantages and disadvantages, offering both environments to learners does not necessarily provide only the advantages of both. This study showed that, for example, though the haptic feedback of the physical experiment aided learners' conceptions of force, providing this haptic feedback only part of the time (as in the *Sequential Physical-Virtual* condition) was not significantly different than not providing it at all (as in the *Virtual-only* condition). This supports the findings of Olympiou & Zacharia (2012), who found that a "blended" combination of physical and virtual experiments, which took advantage of the unique affordances of physical and virtual laboratories in conjunction with the learning objectives of each experiment, was more effective than either purely physical or virtual experiments alone.

Matching the advantages of a particular experiment to a particular physics principle, which can include building understanding of a particular concept in a particular situation, can help a combination of physical and virtual laboratories enrich learning better than either individual physical or virtual laboratories. Without matching the affordances of experiments to particular learning goals, we may see results similar to this study, where providing both physical and virtual laboratories offered both the advantages *and* disadvantages of each, which overall led to no significant benefit over separate physical or virtual laboratories.

Further, though these results provided some reasons why combining physical and virtual experiments may sometimes be beneficial (when purposefully taking advantage of the affordances of each while limiting the disadvantages), it also illustrates another reason to be wary of combining them in certain situations. In situations similar to this study, where participants only had about an hour to complete the two experiments, providing both separate physical and virtual laboratories may cause confusion. When trying to explain the physics concepts during post-interviews, some participants who had performed both physical and virtual experiments paused for long periods of time trying to recall what they had done in each experiment. It may be that without time to investigate more deeply within each laboratory environment, the advantages of providing both physical and virtual experiments do not outweigh the disadvantages. With more time on task, other studies may find that providing both physical and virtual experiments begins to better support student learning than either form alone. However, with limited time (as is often the case in classrooms), providing separate physical and virtual labs may not be worth the additional overhead in implementing both laboratories in the classroom.

Mixed Reality Laboratories

In reviewing the literature in Chapter 2, I speculated that by directly integrating the familiar physical world with the abstract formalisms of physics, mixed reality physics laboratory environments may help learners to connect their everyday experience of force and movement to the abstract ideas of the classroom better than with separate physical and virtual experiments. There was no direct evidence of that in this study, but there was evidence to suggest that the individual components that were provided in the mixed reality laboratory were important. Specifically, the mixed reality environment provided both the haptic feedback that was later shown to improve learners' conceptions of force, as well as the dynamic bar graph of work, which led to a better understanding of the dynamics of work during the post-interviews. So, the mixed reality environment did display some of the advantages of both the physical and virtual experiments. It did, however, have its own disadvantages (especially in learning the concept of potential energy) and also took more time for the learners to understand how to perform the experiments than the other environments. With more time to perform the experiments, and further design to take advantage of the unique affordances of mixed reality, such environments may be shown to better support student learning in future studies.

Implications

The findings in this study have direct implications for research, for the design of science laboratory environments, and for using such laboratory environments in teaching.

Implications for Research

This study continues the long conversation on physical and virtual laboratories in science classrooms. Most importantly, it shows that the haptic feedback provided in physical laboratory environments can be quite important in shaping students' conceptions, especially about concepts such as force that are congruent with everyday actions in the world. This contradicts previous studies that have shown that virtual labs are as effective (e.g., Triona, Klahr & Williams, 2005; Ma & Nickerson, 2006; Zacharia & Constantinou, 2008; Zacharia & Olympiou, 2011) or more effective (e.g., Finkelstein et al., 2005; Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008) than physical laboratories. For particular concepts and situations, like building understanding of force, replacing physical laboratory environments with virtual ones may be a mistake. More generally, the study adds to this line of research by illustrating that the specific perceptual-motor features of laboratory environments do matter in building learners' conceptual understanding.

This study also contributes to research on embodied learning and cognition. It establishes that science laboratory environments can be a rich test bed for investigating the influences of perception on conceptual processes. Further, it provides an application for the idea that gestures are outward instantiations of underlying mental imagery and simulations. Analyzing learners' gestures can be a powerful way to analyze conception in science contexts beyond written tests, and can reveal underlying mental imagery that is not easily accessed through other methods. Indeed, Lindgren and Johnson-Glenberg (2013) point to assessment as one of the grand challenges of measuring the impact of embodied learning environments. Using gesture to investigate underlying mental representations can provide insights that would be unavailable with more traditional methods.

Finally, this study contributes to research on mixed reality learning environments, which are beginning to draw interest with the spread of emerging mixed reality technologies. This study showed that simply combining physical and virtual laboratories through mixed reality technologies is not a panacea, but that the specific design decisions and logistics of the learning environments can influence outcomes. Future studies comparing mixed reality labs to more traditional physical and virtual experiments can more deeply explore the particular advantages that mixed reality may offer beyond a simple and direct integration of existing physical and virtual labs.

Implications for The Design of Science Laboratory Environments

Based on the basic finding of this study that the perceptual-motor features of science laboratory environments can influence conceptual understanding, this study showed that science laboratories are not simply mechanisms for producing data on science phenomena, about which students are expected to build an understanding through abstract reasoning about the data. Instead, laboratory environments can be rich opportunities for shaping conceptual understanding through perceptual-motor processes, opportunities for learners to “actively interpret perceptually present situations” in order to train their perceptual systems (Goldstone, Landy & Son, 2010). Based on the results of this study, I offer some preliminary design guidelines on utilizing the perceptual features of laboratory environments to shape student conception:

Start with physical experience: In this study, learners who performed the physical actions of pulling an object up in inclined plane in both experiments built better conceptions of force than those who had not. In domains where there are strong congruencies between actions and concepts such as classical mechanics, beginning the design of learning environments around physical actions may be the most appropriate approach. Interestingly, with the learning environments of this study, increasing the weight of the block to be lifted could have made the force required to lift the object even more salient, as roughly a quarter of participants in the physical-only claimed that they did not feel a difference in the amount of force needed to pull the block up different ramps.

A*dd digital elements that shape interpretation of the physical*: Importantly, this study illustrated that perceptual-motor features of learning environments can be internalized in the form of visual and motor imagery and later drawn upon when explaining concepts. Therefore, the specific perceptual-motor features of representations of the learning environment can shape conception. With the environments in this study, force and work were both displayed simply as bar graphs that were next to each other, but there were no perceptual features of either graph (except for a label above them) that perceptually tied them to the underlying concepts of force and work. Because of this, some students had difficulty recalling which graph was which when trying to answer questions about the concepts. In these laboratory environments, the perceptual features of the graphs can be adjusted to more closely tie them to the concepts of force and work, which may especially aid in later recall when learners are mentally simulating the actions they engaged in with the laboratory environments.

Build in opportunities for reflection: Laboratory environments, especially when combining physical and digital elements, can provide opportunities for rich interactions between physical world and abstract formalisms of science. In this study, learners' physical interactions with the environment were important, but their social interactions about the concepts during the experiments were somewhat disappointing. Participants largely read off a value of a concept for their partner to write down, and then moved onto the next concept. One place where participants did more deeply engage with the concepts, however, was when they were surprised to see that potential energy ended up at the same value when lifted by different ramps to the same height; most students immediately began to try to figure out why that would occur. Building in such surprises and opportunities for reflection in the laboratory process could further support learning of the intended concepts through richer social interactions in lab groups.

The mixed reality environment could have also been used to offer opportunities for reflection that would not be possible in other environments. Since the mixed reality environment took participants' actions and the locations of objects as inputs (i.e. the amount of force being applied to the block, the location of the block and the ramp), it could have been used to allow students to further review and reflect on their physical data. One limitation of the mixed reality environment in this study was that participants often focused intently on pulling the block slowly so they could collect reliable data from the system, often without attending to the other digital representations that were available to them. If learners were then able to review a digital simulation of their physical data, without having to pay attention to the logistics of running the experiment, they may have been able to further their understanding of the physics phenomena by interpreting the additional representations present in the environment. The environment could also provide additional opportunities for reflecting on the physical data, by allowing learners to directly compare data across trials, for example.

Though this study did not show direct evidence of the efficacy of mixed reality environments over other laboratory environments, there are some hints at what design features effective mixed reality laboratory environments may entail. Future work on mixed reality laboratories may further explore the potential advantages of these environments, namely how they may provide a single learning environment for building coherent, stable, multimodal mental representations of phenomena, may shape conceptions through perceptual features of physical-digital links, and may provide opportunities for reflection that are not possible in purely physical or virtual systems.

Implications for Teaching

Many science teachers are faced with choices on what kinds of laboratories students will engage in and how students are to interact with the laboratory environment. What specific laboratory environment a teacher choses is influenced heavily by his or her learning goals and the availability of resources. This study offers ideas for additional considerations that should be made. In explicating some of the *disadvantages* of specific laboratory environments, this study suggests that teachers may need to supplement each kind of laboratory environment with additional instruction to make sure learners fully understand the concepts and phenomena of interest:

- If students are performing entirely virtual experiments in the classroom, teachers may want to provide classroom demonstrations of the physical phenomena in real life, where each learner gets to perform the physical manipulation to help ground concepts in physical experience and have a common example for discussion.
- If students are performing physical experiments only, teachers may want to discuss in more detail situations or variables that students could not observe directly in their experiments. To accomplish this, teachers could pose questions on what they could not see directly, have students create graphs of the underlying variables over time, or provide supplemental animations, among other strategies.
- If students are provided both physical and virtual experiments, teachers should be sure there is plenty of time for exploration of each laboratory environment individually, and focus on helping learners build connections between the two environments through discussion.
- If students are performing experiments within a mixed reality laboratory environment, teachers can help to build connections between physical and virtual elements, pointing out the relationships and shaping learners' investigations to build from the physical interactions to more formal reasoning about the concepts.

Limitations and Future Directions

This study has several limitations that should be followed up in future studies. First, the amount of time participants spent performing the experiments was fairly short, with about one hour total for the experiments and the pre- and post-tests and surveys. Providing more time with the laboratory environments may have led to somewhat different results. Students in the *Sequential Physical-Virtual* and *Integrated Physical-Virtual* conditions, in particular, may have benefitted from more time with the relatively more complex environments. However, often in the reality of classrooms there is limited time for laboratories and similar activities, so this study provides a picture of what to expect across different laboratory environments with such time constraints.

Second, though this study found significant differences across conditions in immediate learning gains, it did not measure any longer-term learning gains. Differences in learners' internal representations may have led to further differences when measured weeks or months after the experiment. Indeed, other researchers currently studying embodiment and mixed reality suggest using delayed assessments because mixed reality environments have been shown to influence long-term retention (Lindgren & Johnson-Glenberg, 2013).

Third, in order to make fair comparisons between the experimental conditions and to control for as many extraneous variables as possible, both the virtual and mixed reality environments were constrained to match the physical experiments where possible. For example, the virtual environment was able to simulate the physics phenomena in a frictionless environment, but in order to match the physical environment the simulation included friction. In doing so, one potential advantage of performing virtual laboratories was removed from this experiment. Future studies should take full advantage of the additional affordances of virtual and mixed reality environments that were not present in this study. If they establish that these environments better support learning, they should then later break down the environments by their components to determine the most important features of these environments.

Finally, future studies should investigate in more depth the relationships between mental imagery, simulated action (as evidenced in this study by gesture), and conceptual understanding (as evidenced in this study by concept tests and verbal explanations) within science laboratory environments. Though this study found significant results that hint at a relationship between simulated action and conceptual understanding, this study was not designed to investigate this link directly. The relationships between gesture, simulated action and conceptual understanding are likely not so simple that those who gesture more (or in certain ways) better understand physics concepts, but from the results of this study suggest that the connections between gesture, simulated action and conceptual understanding are important ones to understand. Thus, the particular links between mental imagery and conceptual understanding should be studied in more detail within the context of laboratory environments.

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Appendix A: Script for Running the Study

Introduction:

Hi, my name is __________. Thank you for agreeing to participate in this study. Today you'll be completing two inclined plane experiments in groups of 2. You'll first complete a short test and interview, the complete two inclined plane experiments, followed by a post-test and interview to see what you have learned. The whole process should take about an hour. Do you have any questions at this point? Before we start, I would like you to read over this consent form and sign it if you agree to participate in this study.

Pre-Test & Survey:

(One person per group does test first, the other does interview first.)

Now, to take the pre-test and survey, pick one of these computers and click on the link on the desktop that says "Pre-test and survey". Answer the questions to the best of your ability. Please let me know when you are finished.

Interview:

Now I'd like to ask you a few questions about physics concepts in inclined planes. If it's ok with you, I'm going to video tape your responses for research purposes. (Start video. Show participant code to video camera.) Please answer these questions to the best of your ability and try to explain your reasoning for each question.

Length Experiment:

(Get partners together for experiments.)

Now, you'll both complete an experiment on varying the length of an inclined plane. Use this data sheet to set up your experiment and record your results. I'll ask that you each perform the experiment once, the first person filling out trial 1 on the sheet and the second filling out trial 2.

For Virtual-Only Condition:

For this experiment, you'll use a simulation of an inclined plane. Use the sliders on the left and the text boxes below them to input the variables, and drag the block up the ramp with your mouse to run the experiment. You want to drag the block up with the minimum amount of force to get it moving (the arrow will turn green). Clicking the reset button will allow you to start the experiment over.

For Physical-Only Condition:

For this experiment, you'll use three different lengths of boards to lift a brick to a height of 25cm. Use this spring scale to record the amount of force it takes to lift the brick up the ramp, and calculate the other variables on the data sheet using the formulas at the bottom.

For Sequential Physical/Virtual Condition:

For this experiment, you'll use three different lengths of boards to lift a brick to a height of 25cm. Use this spring scale to record the amount of force it takes to lift the brick up the ramp, and calculate the other variables on the data sheet using the formulas at the bottom.

For Integrated Physical/Virtual Condition:

For this experiment, you'll be using three different lengths of boards to lift a brick to a height of 25cm. You'll drag the brick up with this digital spring scale and the amount of force being applied to lift the brick will be displayed here and here. The values for other variables on your data sheet will be displayed here. Make sure the webcam here is able to see this marker on the brick so it can keep track of its position (so stay off to the side). To run one trial, make sure it says "experiment stopped" here, and slowly pull the brick up the ramp. When it is at the top, keep the tension with the brick until it says "experiment stopped". It will freeze all of the values once the brick stops moving for a couple of seconds.

Now, please discuss your answers to the questions on this sheet. Do your best to explain your reasoning.

Height Experiment:

Now, you'll both complete an experiment on varying the *height* of an inclined plane. Use this data sheet to set up your experiment and record your results. Like the last experiment, I'll ask that you each perform the experiment once, the first person filling out trial 1 on the sheet and the second person filling out trial 2.

For Virtual-Only Condition:

For this experiment, you'll use the same simulation as before but change the height instead of the length. Use a ramp length of .90 meters for all trials.

For Physical-Only Condition:

For this experiment, you'll lift the brick to three different heights using the 90cm (medium) board from your last experiment. The short height is with only this platform, the medium height is with this support, and the tall height is with both. Like before, use the spring scale to record the amount of force it takes to lift the brick up the ramp, and calculate the other variables on the data sheet using the formulas at the bottom.

For Sequential Physical/Virtual Condition:

For this experiment, you'll use a simulation of an inclined plane to test lifting a block to different heights. Use the sliders on the left and the text boxes below them to input the variables, and drag the block up the ramp with your mouse to run the experiment. Clicking the reset button will allow you to start the experiment over.

For Integrated Physical/Virtual Condition:

For this experiment, you'll lift the brick to three different heights using the 90cm (medium) board from your last experiment. The short height is with only this platform, the medium height is with this support, and the tall height is with both. Otherwise, run the experiment the same way you did before.

Now, please discuss your answers to these questions. Do your best to explain your reasoning.

Post-Test:

(One person per group does test first, the other does interview first.)

Now you'll take a short test on what you have learned. Pick one of these computers and click on the link on the desktop that says "Post-test". Answer the questions to the best of your ability. Please let me know when you are finished.

Post-Interview:

Now I'd like to ask you a few questions about what you have learned. If it's ok with you, I'm going to video tape your responses for research purposes. (Start video. Show participant code to video camera.) Please answer these questions to the best of your ability and try to explain your reasoning for each question.

Thank you:

That's it. Thank you for participating in this study.

Appendix B: Laboratory Worksheets

Length Experiment Data Table

Directions: You will use this inclined plane environment to learn about how the length of an inclined plane affects different variables -- applied force, work, potential energy and mechanical advantage. Use this environment to collect your data in the table below, and discuss your answers to the questions below. Please conduct two trials for each length of ramp, with one of you performing the experiment for trial 1, and the other for trial 2.

Friction = .20, Load = 7.5 N

Ramp Length	*Distance (m)* ***(length of ramp)***	*Applied Force (N)*	*Work (J)*	*Potential Energy (J)*	*Mechanical Advantage*
Short Ramp	***.60 m***	***Trial 1:***	***Trial 1:***	***Trial 1:***	***Trial 1:***
		Trial 2:	***Trial 2:***	***Trial 2:***	***Trial 2:***
Medium Ramp	***.90 m***	***Trial 1:***	***Trial 1:***	***Trial 1:***	***Trial 1:***
		Trial 2:	***Trial 2:***	***Trial 2:***	***Trial 2:***
Long Ramp	***1.20 m***	***Trial 1:***	***Trial 1:***	***Trial 1:***	***Trial 1:***
		Trial 2:	***Trial 2:***	***Trial 2:***	***Trial 2:***

Work = Force x Distance

Potential Energy = Load x Height

Mechanical Advantage = Load / Applied Force

Length Experiment Observation and Analysis Questions

Discuss with your partner the following questions:

5. Using the data from this experiment, what do you notice about the relationship between *distance* and *applied force* in an inclined plane? Why do you think that occurs? Explain your reasoning.

6. Using the data from this experiment, what do you notice about the relationship between *distance* and *work* in an inclined plane? Why do you think that occurs? Explain your reasoning.

7. Using the data from this experiment, what do you notice about the relationship between *distance* and *potential energy* in an inclined plane? Why do you think that occurs? Explain your reasoning.

8. Using the data from this experiment, what do you notice about the relationship between *distance* and *mechanical advantage* in an inclined plane? Why do you think that occurs? Explain your reasoning.

9. How do you think the results of this experiment would change if there were *no friction?* Would any of the patterns in your data table change? If so, how and why?

Height Experiment Data Table

Directions:

You will use this inclined plane environment to learn about how the height of an inclined plane affects different variables -- applied force, work, potential energy and mechanical advantage. Use this environment to collect your data in the table below, and discuss your answers to the questions below. Please conduct two trials for each ramp height, with one of you performing the experiment for trial 1, and the other for trial 2.

Friction = .20, Load = 7.5 N

Ramp Height	*Height (m)* ***(height of ramp)***	*Applied Force (N)*	*Work (J)*	*Potential Energy (J)*	*Mechanical Advantage*
Short Height	***.10 m***	***Trial 1:***	***Trial 1:***	***Trial 1:***	***Trial 1:***
		Trial 2:	***Trial 2:***	***Trial 2:***	***Trial 2:***
Medium Height	***.25 m***	***Trial 1:***	***Trial 1:***	***Trial 1:***	***Trial 1:***
		Trial 2:	***Trial 2:***	***Trial 2:***	***Trial 2:***
Tall Height	***.35 m***	***Trial 1:***	***Trial 1:***	***Trial 1:***	***Trial 1:***
		Trial 2:	***Trial 2:***	***Trial 2:***	***Trial 2:***

Work = Force x Distance

Potential Energy = Load x Height

Mechanical Advantage = Load / Applied Force

Height Experiment Observation and Analysis Questions

Discuss with your partner the following questions:

1. Using the data from this experiment, what do you notice about the relationship between *height* and *applied force* in an inclined plane? Why do you think that occurs? Explain your reasoning.

2. Using the data from this experiment, what do you notice about the relationship between *height* and *work* in an inclined plane? Why do you think that occurs? Explain your reasoning.

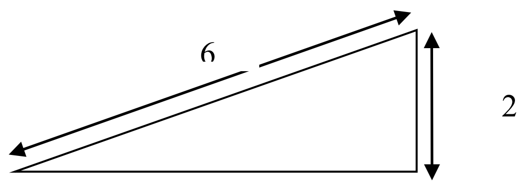
3. Using the data from this experiment, what do you notice about the relationship between *height* and *potential energy* in an inclined plane? Why do you think that occurs? Explain your reasoning.

4. Using the data from this experiment, what do you notice about the relationship between *height* and *mechanical advantage* in an inclined plane? Why do you think that occurs? Explain your reasoning.

5. How do you think the results of this experiment would change if there were *no friction?* Would any of the patterns in your data table change? If so, how and why?

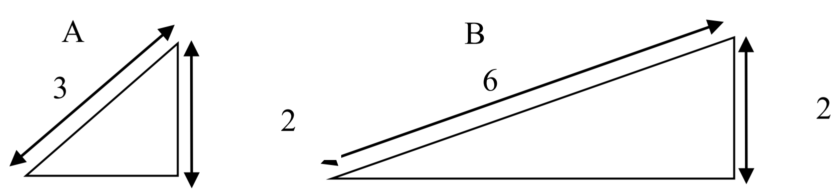
Appendix C: Pre and Post Concept Test Items

1. What will require *less force* to lift a box to a height of 2 meters – using the ramp shown or lifting the box straight up?



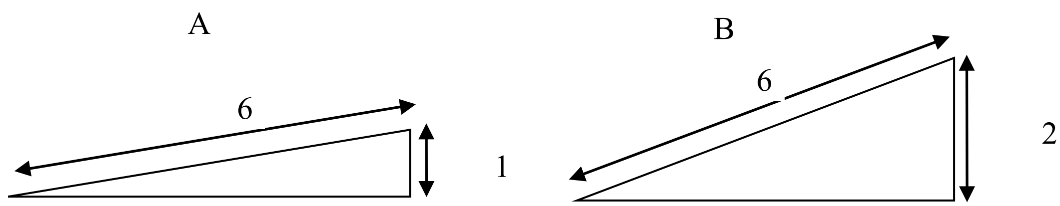
A.) Using the ramp
B.) Lifting it straight up
C.) Using the ramp or lifting it straight up will both require the same amount of force
D.) Not enough information to decide

2. If we ignore friction, which of the following two ramps will require *less applied force* to ride up?



A.) Ramp A
B.) Ramp B
C.) Both A and B will require the same applied force to ride up
D.) Not enough information to decide

3. If we ignore friction, which of the following ramps will require *less applied force* to ride up?



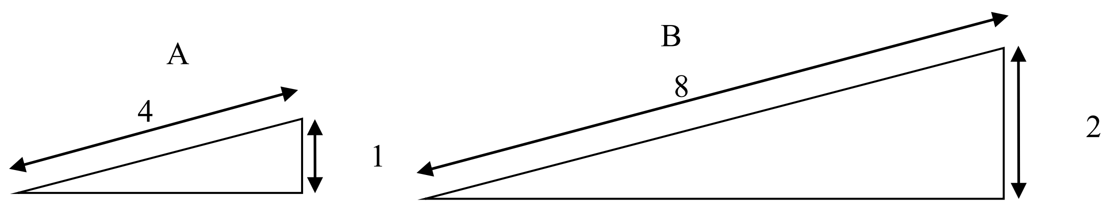
A.) Ramp A

B.) Ramp B

C.) Both A and B will require the same applied force to ride up

D.) Not enough information to decide

4. If we ignore friction, which of the following ramps will require *less applied force* to ride up?



A.) Ramp A

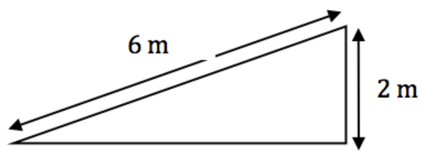
B.) Ramp B

C.) Both A and B will require the same applied force to ride up

D.) Not enough information to decide

4b. Explain your reasoning.

5. Jane is lifting a box straight up to a height of 2 meters. Mary is using the ramp shown below to lift the same box to the same height. If we ignore friction, what can you tell about the amount of *work* done by Jane and Mary?



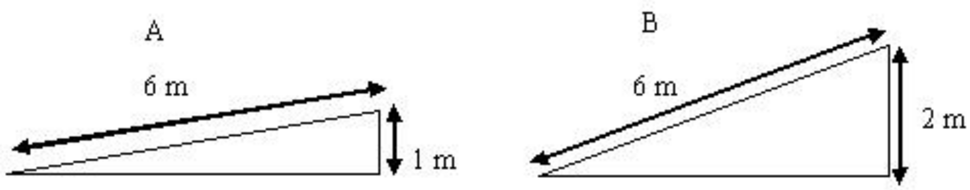
A.) Jane is doing more work

B.) Mary is doing more work

C.) Jane and Mary are doing the same amount of work

D.) Not enough information to decide

6. Alfred pushes a box to the top of Ramp A. Brenda pushes the same box to the top of Ramp B. What can you say about the amount of *work* being done?



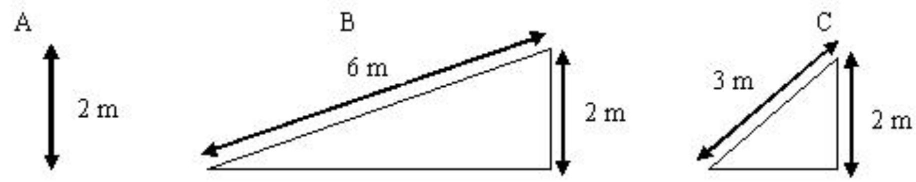
A.) Alfred is doing more work using Ramp A

B.) Brenda is doing more work using Ramp B

C.) Alfred and Brenda are doing the same amount of work

D.) Not enough information to decide

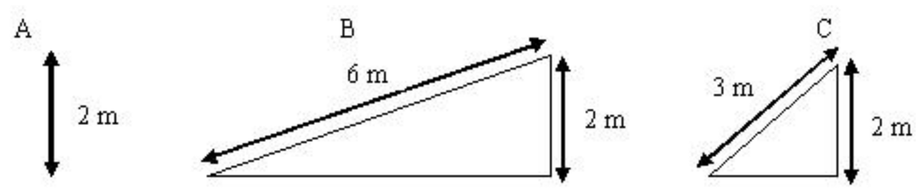
7. Ali lifts a box straight up by hand to a height of 2 meters. Brian pushes the same box to a height of 2 meters using Ramp B. Carlos pushes the same box to a height of 2 meters using Ramp C. If we ignore friction, what can you say about the amount of *work* being done?



A.) Ali is doing more work lifting the box by hand
B.) Brian is doing more work using ramp B
C.) Carlos is doing more work using ramp C
D.) Ali, Brian, and Carlos are doing the same amount of work

7b. Explain your reasoning.

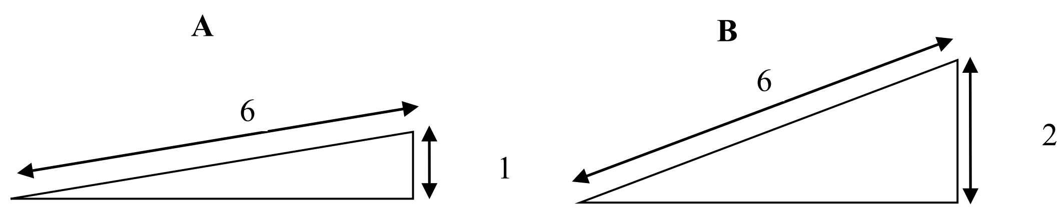
8. Ali lifts a box straight up by hand to a height of 2 meters. Brian pushes the same box to a height of 2 meters using Ramp B. Carlos pushes the same box to a height of 2 meters using Ramp C. *If there is friction*, what can you say about the amount of *work* being done?



A.) Ali is doing more work lifting the box by hand
B.) Brian is doing more work using ramp B
C.) Carlos is doing more work using ramp C
D.) Ali, Brian, and Carlos are doing the same amount of work

8b. Explain your reasoning.

9. Jacob is using ramps to lift two boxes of the same size and mass up to two different heights. He lifts one box to the top of Ramp A and then lifts the second box to the top of Ramp B. Ignoring friction, when lifting the box to the top of Ramp B Jacob is doing _______ *work* as/than when lifting the box to the top of ramp A?



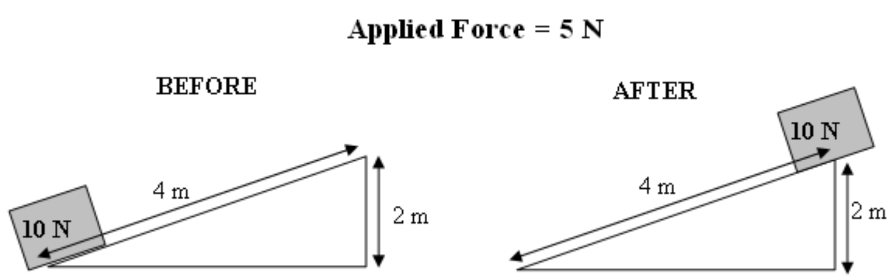
A.) More

B.) Less

C.) Same amount of

D.) Not enough information to decide

10. Below are before and after pictures of a load being lifted with the help of a ramp. Ignoring friction, calculate the *work* required to lift a load to the top of the ramp using the information from the picture below:



A.) 20 J

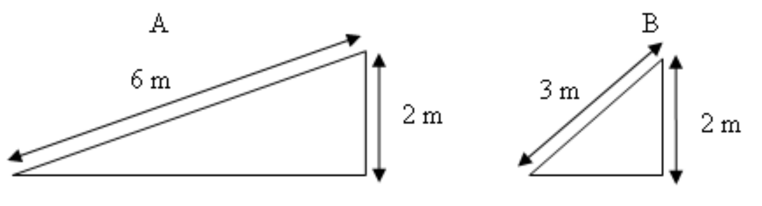
B.) 30 J

C.) 40 J

D.) Not enough information to decide

10b. Explain your reasoning.

11. Which of the following ramps will give more mechanical advantage?



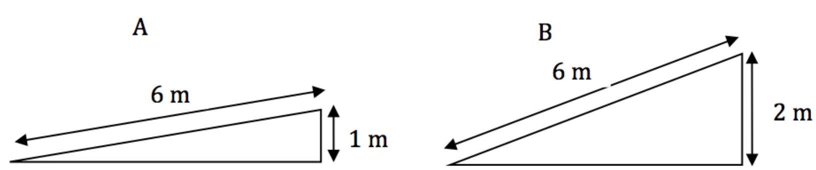
A.) Ramp A

B.) Ramp B

C.) Both A and B will give you the same mechanical advantage

D.) Not enough information to decide

12. Which of the following ramps will give more mechanical advantage?



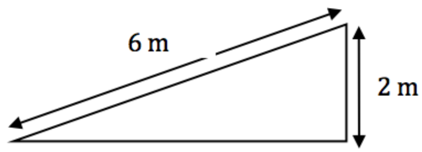
A.) Ramp A

B.) Ramp B

C.) Both A and B will give you the same mechanical advantage

D.) Not enough information to decide

13. If you ignore friction, how much *mechanical advantage* would this ramp give you?



A.) 2

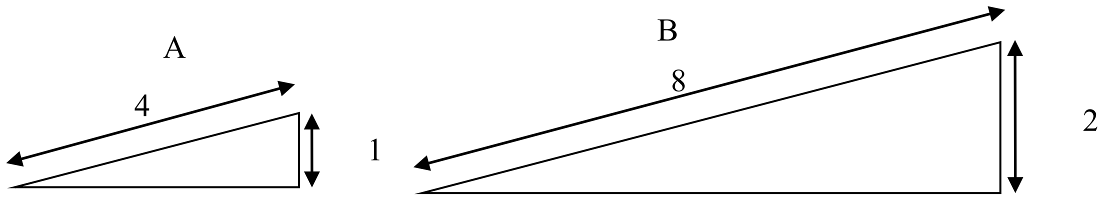
B.) 3

C.) 4

D.) 6

E.) Not enough information to decide

14. If we ignore friction, which of the following ramps will give more *mechanical advantage*?



E.) Ramp A

F.) Ramp B

G.) Both A and B will give you the same mechanical advantage

H.) Not enough information to decide

15. When lifting a heavy object to a height of 1 meter either straight up or using a 2 meter long ramp, under which condition does the object undergo a *greater change in potential energy*?

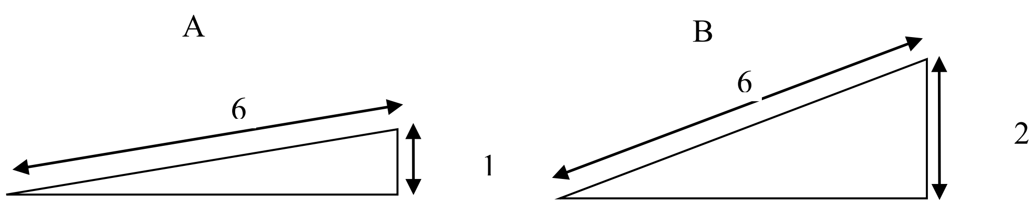
A.) Lifting the object straight up

B.) Lifting the object using the ramp

C.) The change in potential energy would be the same in both conditions

D.) Not enough information to decide

16. Diane pushes a box to the top of Ramp A. Fran pushes the same box to the top of Ramp B. Which box undergoes *a greater change in potential energy*?



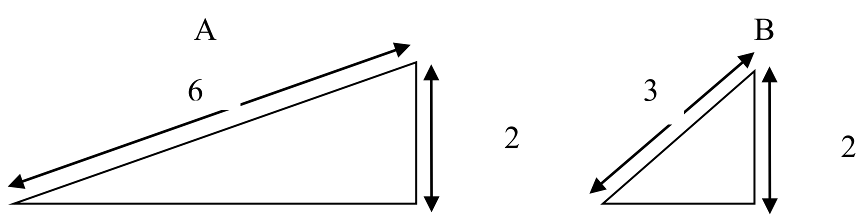
A.) The box on Ramp A

B.) The box on Ramp B

C.) Both boxes have the same potential energy

D.) Not enough information to decide

17. Louis pushes a box to the top of Ramp A. Toby pushes a box to the top of Ramp B. Which undergoes *a greater change in potential energy*?



A.) The box on Ramp A

B.) The box on Ramp B

C.) Both boxes have the same change in potential energy

D.) Not enough information to decide

17b. Explain your reasoning.

18. Henry slides a box up 1 meter high ramp. Ignoring friction, how does the amount of work compare to the change in potential energy of the box?

A.) The work needed is greater than the change in potential energy

B.) The work needed is less than the change in potential energy

C.) The work needed is the same as the change in potential energy

D.) Not enough information to decide

19. Gloria slides a box up a 1 meter high ramp. If there is friction, how does the amount of work compare to the change in potential energy of the box?

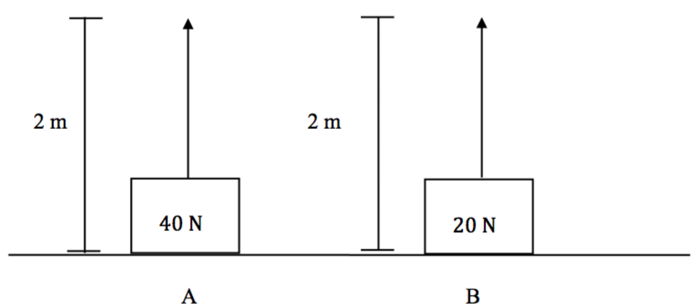
A.) The work needed is greater than the change in potential energy

B.) The work needed is less than the change in potential energy

C.) The work needed is the same as the change in potential energy

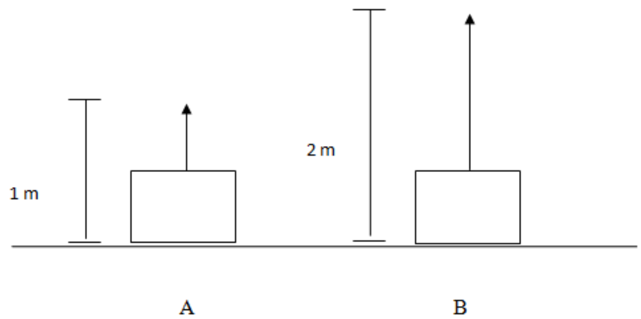
D.) Not enough information to decide

20. Anastasia lifts a box that weighs 40 Newtons to a height of 2 meters. Burt lifts a box that weighs 20 Newtons also to a height of 2 meters. Who needs to apply more *force* to lift their box?



A.) Anastasia needs to apply more force to lift her box
B.) Burt needs to apply more force to lift her box
C.) They need to apply the same amount of force to lift their boxes
D.) Not enough information to decide

21. Arnold lifts a heavy box a height of 2 meters. Ben lifts a box of the same weight to a height of 2 meters. Which box would require more force to lift?

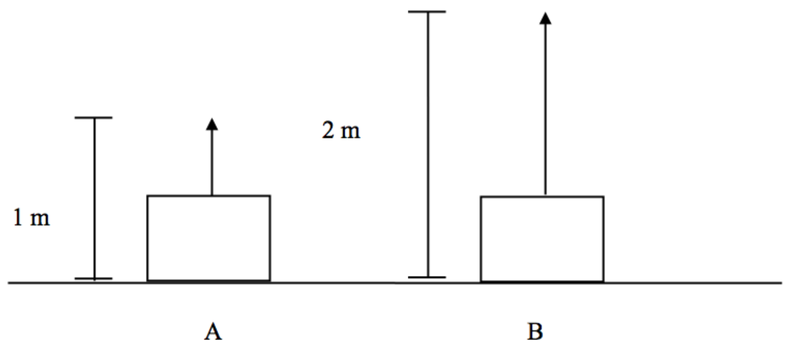


A.) Arnold's box
B.) Ben's box
C.) Both boxes would require the same amount of force to lift
D.) Not enough information to decide

22. Anushree drags a heavy rock along a flat surface along a distance of 20 meters. Boris drags the same rock along the same flat surface for 40 meters. Who has done more *work* when dragging the boulder?"

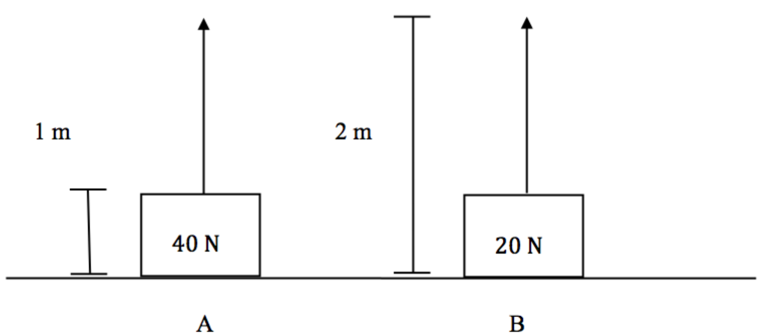
A.) Anushree has done more work
B.) Boris has done more work
C.) They have done the same amount of work
D.) Not enough information to decide

23. Arnold lifts a heavy box a height of 1 meters. Ben lifts a box of the same weight to a height of 2 meters. Who is doing more *work* when lifting their boxes?"



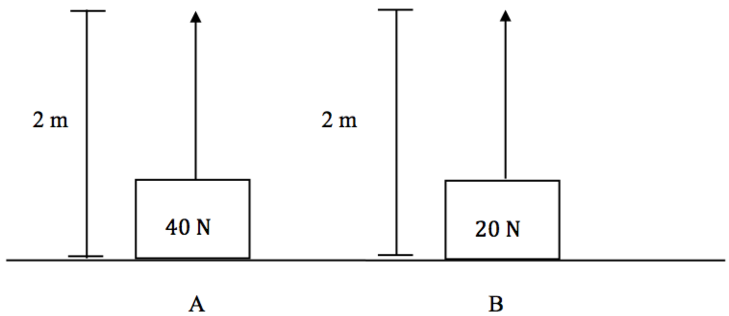
A.) Arnold does more work
B.) Ben does more work
C.) Ben and Arnold do the same amount of work
D.) Not enough information to decide

24. Anastasia lifts a box that weighs 40 Newtons to a height of 1 meter. Burt lifts a box that weighs 20 Newtons also to a height of 2 meter. Who is doing more work in lifting their box?"



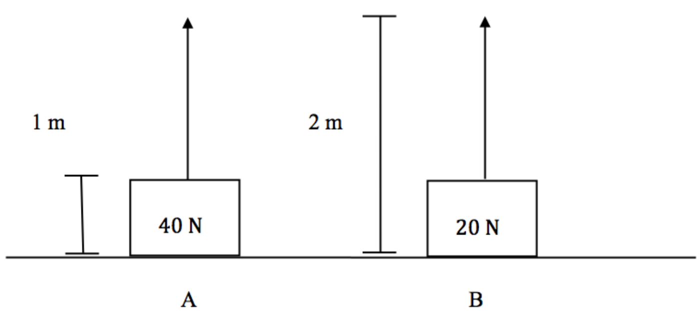
A.) Anastasia does more work
B.) Burt does more work
C.) They do the same amount of work
D.) Not enough information to decide

25. Anastasia lifts a box that weighs 40 Newtons to a height of 2 meters. Burt lifts a box that weighs 20 Newtons also to a height of 2 meters. Which box is undergoing a greater change in *potential energy?*"



A.) Anastasia's box is undergoing a greater change in potential energy
B.) Burt's box is undergoing a greater change in potential energy
C.) The boxes are undergoing the same change in potential energy
D.) Not enough information to decide

26. Anastasia lifts a box that weighs 40 Newtons to a height of 1 meter. Burt lifts a box that weighs 20 Newtons to a height of 2 meters. Which box undergoes a greater change in potential energy?



A.) Anastasia's box is undergoing a greater change in potential energy
B.) Burt's box is undergoing a greater change in potential energy
C.) The boxes are undergoing the same change in potential energy
D.) Not enough information to decide

Appendix D: Survey Questions

Pre-Laboratory Survey Questions

Age: ________

Gender: __________

Major: _________________________

Year in school: __________________________

On a scale from 1 to 10, how comfortable are you with physics concepts in inclined planes (10 being very comfortable)?

Have you ever covered simple machines in your educational career? _____

If yes, at what grade level(s)? ______

How many college-level physics classes have you taken? ______

On a scale of 1 to 7, how well do you know the person who came with you today (7 being very familiar)?

How often do you use the following technologies?

	Never	Less than Once a Month	Once a Month	2-3 Times a Month	Once a Week	2-3 Times a Week	Daily
Computers							
Computer Simulations							
Video Games							

Post-Laboratory Survey Questions

What about the laboratory environment(s) that you used today helped you to learn about physics concepts in inclined planes?

What improvements would you suggest for using this/these inclined plane laboratory environment(s) in the future?

In the moments when you were running each trial in your experiments (and not recording the results), what do you think you paid the most attention to? What were you typically looking at and thinking about?

If your participant code starts with an "S", do you think you learned more from doing the physical experiment or using the simulation? Please explain why. (If your code does not start with an "S", please skip this question.)

Appendix E: Interview Protocol

Script: I'd like to interview you about your current understanding of physics concepts in inclined planes. Your answers won't have any effect on your grade in the class, I just want to understand how you are *thinking* about these ideas now [*if pre-interview*: and what you already know about them].

I would like to videotape our conversation to help me remember what you say. Is that okay with you?

Okay, thank you. If at any time you want me to stop the video, just tell me.

Do you have any questions before we start?

4. Describe in your own words, the relationship between *force* and *distance* in an inclined plane.

    The next two questions are probes, to be asked IF students can't answer Q1.

    a. Probe: What happens to the applied force if the *distance* is longer?
    b. Restated: What happens to the applied force if the *ramp* is longer?

5. How much *force* would you need to raise something using a ramp versus lifting it straight up by hand? Would you need more, less, or the same amount of force?
    a. *then,* Why?

6. If you are using a ramp, as you are lifting an object up the ramp, do you think the force you need to apply increases, decreases or stays the same during that time?
    a. *then,* Why?

4. Describe in your own words, the relationship between *work* and *distance* in an inclined plane.

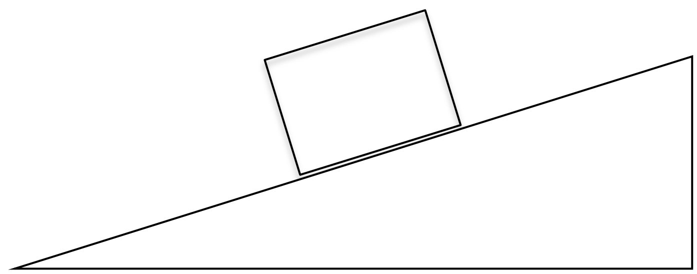
The next two questions are probes, to be asked IF students can't answer Q3.

a. Probe: What happens to the work if the *distance* is longer?
b. Restated: What happens to the work if the *ramp* is longer?

5. How much *work* would it take to raise something <u>with a ramp</u> versus <u>lifting it straight up by hand</u>? Would it take more, less, or the same amount of work?
    a. *then,* Why?

6. If you are using a ramp, as you are lifting an object up the ramp, do you think the work you are doing increases, decreases or stays the same during that time?
    a. *then,* Why?

7. In the following diagram, imagine that a block is being pulled up a real-world ramp. Draw what forces you think are acting on the block, including the direction of each force. Explain, in your own words, what each force is.

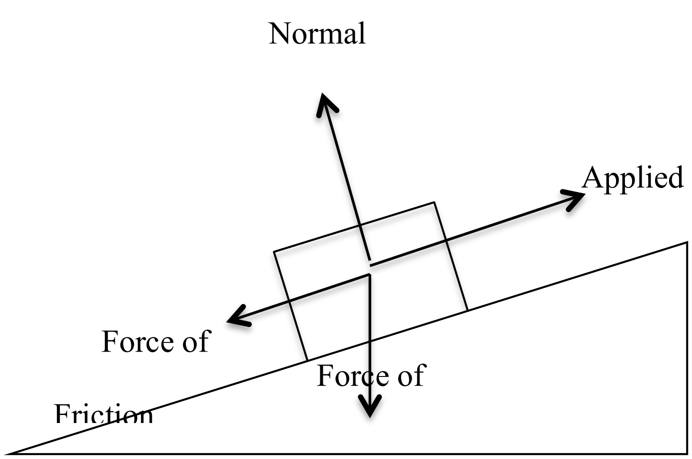


Prompts:

1. For each force, if they only name it: "Could you describe more about that force?"

2. If their drawing is incomplete or incorrect:

"Here are all of the forces acting on the block. You missed _____. What do you think this force does?"



8. [*Post-interview only]* What about the laboratory environment(s) that you used today helped you to learn about physics concepts in inclined planes?

    Follow-ups:

    If sequential physical-virtual condition:

    a. Did you enjoy using the physical laboratory environment or the computer simulation more? Why?
    b. Which one do you think you learned more from?

    If other condition:

    Follow up:

    a. What did you like about using this laboratory environment(s)?
    b. What about this laboratory environment do you think could be improved?

Note: The following *calorie-free* questions can be asked at any time:

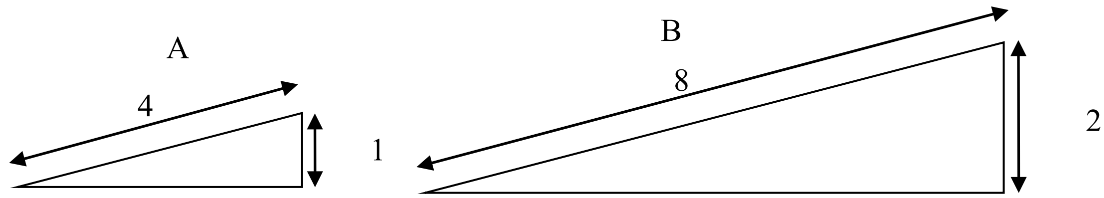
1. You may repeat the question
2. Is there anything else?
3. Tell me more.
4. What does that mean to you?

What are some thoughts you have?

Appendix F: Coding Rubrics

Open-Ended Pre and Post-Test Items

4. If we ignore friction, which of the following ramps will require *less applied force* to ride up?



A.) Ramp A

B.) Ramp B

C.) Both A and B will require the same applied force to ride up

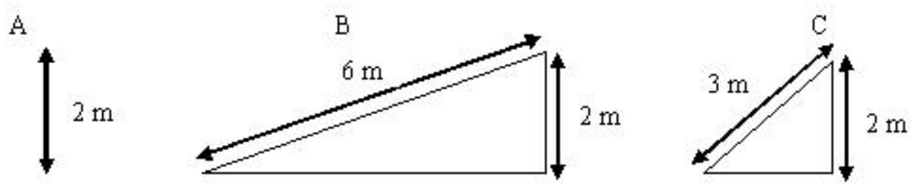
D.) Not enough information to decide

7. 4b. Explain your reasoning.

Score	Description	Example
0	Incorrect response OR Restatement of what they chose for the multiple-choice response without further explanation.	“Ramp a is shorter so it requires more applied force.”
1	Vague response saying that the applied force will be the same.	“While the second ramp may be higher, they distance of the ramp is longer so therefore they would end up equal in the end.”
2	Talks about similarity in terms of *steepness, slope* or *angle* of the two ramps.	“The distance was doubled in both directions.” “MA=length/height. Ramp A\'s MA would be 4/1, which equals

	OR Recognizing that the problem is dealing with ratio. May talk about the relationship with MA.	Ramp B\'s MA would be 8/2, which is 4. So, therefore, their MA would be the same.”

7. Ali lifts a box straight up by hand to a height of 2 meters. Brian pushes the same box to a height of 2 meters using Ramp B. Carlos pushes the same box to a height of 2 meters using Ramp C. If we ignore friction, what can you say about the amount of *work* being done?



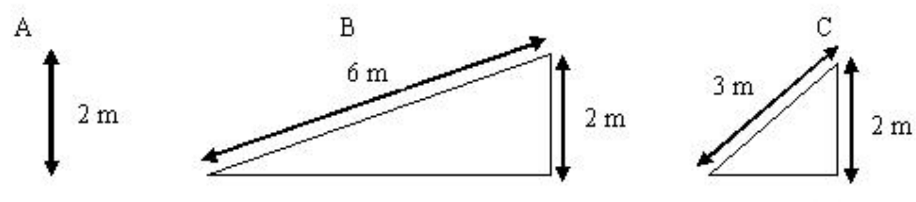
A.) Ali is doing more work lifting the box by hand
B.) Brian is doing more work using ramp B
C.) Carlos is doing more work using ramp C
D.) Ali, Brian, and Carlos are doing the same amount of work

7b. Explain your reasoning.

Score	**Description**	**Example**
0	Incorrect response OR Restatement of what they chose for the multiple-choice response without further explanation.	“If the ramp was 10 meters long the work would increase.” “Work stays the same.”
1	Discuss one aspect of work: applied force or distance Or	“Force x distance is = work.” “if there is no friction, then the

	Write the formula W=FxD Or says that work stays the same because there is no friction.	amount of work being done is the same"
2	Say that work stays the same because you are doing the same job or task or lifting to same height OR Discusses relationship between force, distance and work. OR Equate work with potential energy	"When length goes up, applied force goes down and when length goes down, applied force goes up. That means that work stays the same for any length." "Less efort but longer ramp means same work."

8. Ali lifts a box straight up by hand to a height of 2 meters. Brian pushes the same box to a height of 2 meters using Ramp B. Carlos pushes the same box to a height of 2 meters using Ramp C. *<u>If there is friction</u>*, what can you say about the amount of *work* being done?

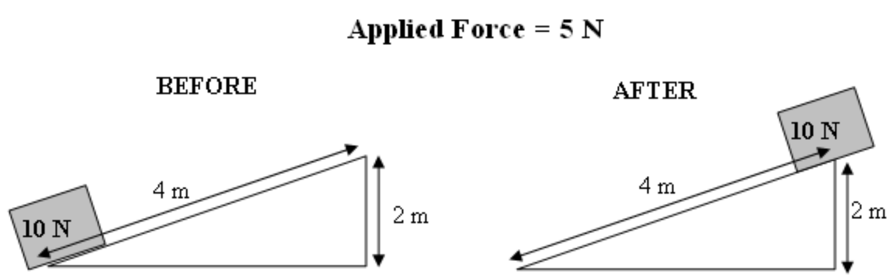


A.) Ali is doing more work lifting the box by hand
B.) Brian is doing more work using ramp B
C.) Carlos is doing more work using ramp C
D.) Ali, Brian, and Carlos are doing the same amount of work

8b. Explain your reasoning.

Score	Description	Example
0	Incorrect response OR Restatement of what they chose for the multiple-choice response without further explanation.	
1	Discuss one aspect of work: applied force or distance Or Write the formula W=FxD	"Brain is doing the most work because he is applying force for a longer period of time."
2	Explain that work would be the same, but that friction affects the longer ramp the most. Equate work with potential energy	"Brian is doing more work because there is a further distance and there more friction on the further distance."

10. Below are before and after pictures of a load being lifted with the help of a ramp. Ignoring friction, calculate the *work* required to lift a load to the top of the ramp using the information from the picture below:



A.) 20 J

B.) 30 J

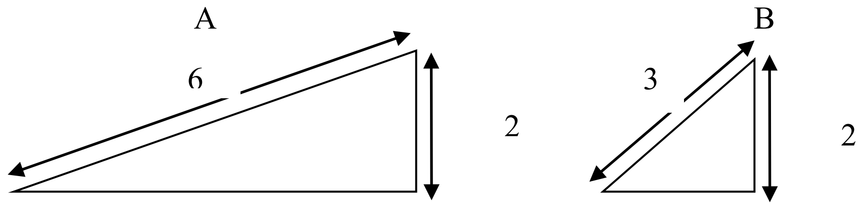
C.) 40 J

D.) Not enough information to decide

10b. Explain your reasoning.

Score	Description	Example
0	Incorrect response OR Restatement of what they chose for the multiple-choice response without further explanation. OR Giving equation for work while responding incorrectly for multiple choice portion.	"work is distance times the load"
1	Giving calculation (while responding correctly for multiple choice portion) without any explanation.	"because 10x2 =20"
2	Giving correct equation for work (while responding correctly for multiple choice portion).	"Work is force times distance which is 5 times 4 which equals 20 J."

17. Louis pushes a box to the top of Ramp A. Toby pushes a box to the top of Ramp B. Which undergoes *a greater change in potential energy*?



A.) The box on Ramp A

B.) The box on Ramp B

C.) Both boxes have the same change in potential energy

D.) Not enough information to decide

17b. Explain your reasoning.

Code	**Standard**	**Example**
0	Incorrect response OR Restatement of what they chose for the multiple-choice response without further explanation.	“It is steeper” “Its has a greater length”
1	Vague response indicating Lois and Toby are accomplishing the same task.	“They are doing the same thing”
2	Claim that potential energy is the same due to the same height	“Both have the same height, therefore having the same potential energy.”

Pre and Post Interview Questions

1. Describe in your own words, the relationship between *force* and *distance* in an inclined plane.

   The next two questions are probes, to be asked IF students can't answer Q1.

a. Probe: What happens to the applied force if the *distance* is longer?
b. Restated: What happens to the applied force if the *ramp* is longer?

Code	**Standard**	**Example**
0	Incorrect response	"The longer ramp would take more force"
1	Correct response but vague explanation	"The force will decrease, because it's not as hard because it's not as high."
2	Correct response that refers to the angle or steepness of the ramp as the key factor, or mentions balance between force and distance	"It would take less force to do the longer one because it's not as steep."

2. How much *force* would you need to raise something using a ramp versus lifting it straight up by hand? Would you need more, less, or the same amount of force?
a. *then,* Why?

Code	**Standard**	**Example**
0	Incorrect response	"They would take the same amount of force"

1	Correct response but vague explanation	"Probably less force. because you are going on the floor up vs going on an incline. it would put less strain on you."
2	Correct response that refers to the angle or steepness of the ramp as the key factor.	"If you use a ramp, you would have to use less force to get it up. Because you have a steady incline to get the object to the height that you need and not all of the forces that are acting on the object are acting on you when you pull it up. like, it's also balanced out by the ramp."

3. Describe in your own words, the relationship between *work* and *distance* in an inclined plane.

The next two questions are probes, to be asked IF students can't answer Q3.

a. Probe: What happens to the work if the *distance* is longer?
b. Restated: What happens to the work if the *ramp* is longer?

Code	**Standard**	**Example**
0	Incorrect response	"They would take the same amount of force"
1	Correct response but vague explanation (Note: because their data was in a frictionless environment, claiming that work increases with distance is a correct explanation. Also that they would stay about the same is a correct answer.)	"More work, because you're pushing it more than you would have to if you used the shorter ramp."
2	Explicitly stating that distance increases and force decreases, so they stay about the same.	

4. How much *work* would it take to raise something with a ramp versus lifting it straight up by hand? Would it take more, less, or the same amount of work?
a. *then,* Why?

Code	**Standard**	**Example**
0	Incorrect response	“A ramp would be less work because it helps you”
1	Correct response but vague explanation (Note: because their data was in a frictionless environment, claiming that work increases with distance is a correct explanation. Also that they would stay about the same is a correct answer.)	“More work. Because it's the greater distance.”
2	Explicitly stating that distance increases and force decreases, so they stay about the same.	“It'd be the same, wouldn't it? Because it's force times distance, so you're using a smaller force on the ramp, but you're going a greater distance.”

5. Let’s say you’re lifting something up an inclined plane. *As you are lifting the object,* what do you think happens to the amount of *force* needed as you go? Does it increase, decrease or stay the same?
a. *then,* Why?

Code	**Standard**	**Example**
0	Incorrect response	“Force increases as you go up.”
1	Correct response that claims that force stays the same as you lift the object up the ramp, but no (or vague) explanation as to why.	“It stays the same, I don't know it's just what it did in there.”

2	Explicitly stating that the force stays the same because the ramp stays at the same angle or slope	"The force stays the same. nothing has changed about the object. it still has they same weight, you're still going at the same angle"

6. Let's say you're lifting something up an inclined plane. *As you are lifting the object,* what do you think happens to the amount of *work* done as you go? Does it increase, decrease or stay the same?

a. *then,* Why?

Code	**Standard**	**Example**
0	Incorrect response	"Force increases as you go up."
1	Correct response that claims that work increases as you lift the object up the ramp, but no (or vague) explanation as to why.	"The amount of work increases the longer you are pulling it up the ramp. I don't know why."
2	Explicitly stating that the work increases because the distance is increasing.	"I think the work would increase over time because of the distance pulling it."