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Incorporating haptic feedback in simulation for learning physics

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ABSTRACT

The purpose of this study was to investigate the effectiveness of a haptic augmented simulation in learning physics. The results indicate that haptic augmented simulations, both the force and kinesthetic and the purely kinesthetic simulations, were more effective than the equivalent non-haptic simulation in providing perceptual experiences and helping elementary students create multimodal representations of the movements of gears. However, in most cases, force feedback was needed to construct a fully loaded multimodal representation that helps students to comprehend later instruction with less sensory modalities. In addition, the force and kinesthetic simulation was effective in helping to transfer knowledge to new learning situations. These findings suggest that it is important to help elementary students make a solid cognitive grounding with the use of a perceptual anchor.

1. Introduction

We often observe people using their imagination to try to comprehend a physical system, rather than turning to an abstract rule. For example, given five gears that are arranged in a horizontal line, when asked which direction the fifth gear will turn when the first one turns clockwise, the first thing that people will do is try to imagine the real gear's movement and then trace that from the first to the fifth by mentally simulating the subsequent gears' movements (Schwartz & Black, 1996). As another example, when asked to make inferences on whether water in a thin or wide glass would reach the rim first, people were better at solving the problem by imagining the water's movement inside the glass than by applying abstract rules (Schwartz & Black, 1999). What if, however, people have never experienced seeing the movements of a gear or tilting glasses with water before? They would have a hard time imagining those objects' movements because there is no perceptual experience that can provide a ground for mental simulations.

Embodied cognition is a new area of research in cognitive psychology suggesting the importance of perception in conceptual learning by emphasizing the thought and knowledge which emerges from dynamic interactions between the body and the physical world (Barsalou, 2008; Barsalou, Niedenthal, Barbey, & Ruppert, 2003; Gibbs, 2005; Glenberg, 1997; Lakoff & Johnson, 1999; Smith & Gasser, 2005; Wilson, 2002). From this perspective, physical activity becomes a cognitive anchor to comprehend abstract concepts in learning situations. For example, when playing basketball in a physical education class, students know how forcefully they have to throw the ball to make it go a certain distance without calculating force and distance. However, when asked why or how they do what they do, students cannot explain the rationale of their behavior because they do not have the explicit language to describe it. The tacit knowledge that enables people to make judgments or predictions about certain physical phenomena is directly related to the object and their bodily experiences without mediating abstract symbols or knowledge that they learned from textbooks at school. This physically rooted knowledge later gets stimulated with appropriate instructional interventions when students learn about force, distance, or projectile motion in physics classes. While imagining throwing a basketball, students can link their perceptual experiences to abstract concepts. Without this imaginative grounding (Black, 2010), students cannot fully understand how an object would be propelled through the air in the real physical world.

This study examines how embodied cognition theory can be applied to an educational context to improve abstract concept learning in the domain of physics. More specifically, this study proposes that interacting with educational simulations based on multisensory input (visual, auditory, and haptic) can serve as the cognitive grounding needed. Current emerging technologies enable the feeling of a force that cannot be seen or heard and provides more embodied physics learning (Reiner, 1999). While this new technology seems promising in

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secondary or higher education settings, there is little research that examines the effectiveness of this new technology in relatively young students' learning. Thus, haptic augmented simulations were developed and their effectiveness in elementary students' learning was tested.

1.1. What is embodied cognition?

Embodied cognition is a relatively new approach to examining human cognition by emphasizing the importance of perception on conceptual learning. Traditionally, western philosophers assume that perception and conception are absolutely separated from each other. According to this dualism, perception has always been considered to be physical in nature while conception has been seen as purely mental and therefore independent of our abilities to perceive physical things. Along with this philosophical assumption, traditional theories of cognition assumed that knowledge is a network of abstract propositions stored in long-term memory in a format of semantic memory systems that are separated from our perception, bodily action and mental states. However, a growing number of researchers (Barsalou, 2008; Barsalou et al., 2003; Gibbs, 2005; Glenberg, 1997; Lakoff & Johnson, 1999; Smith & Gasser, 2005; Wilson, 2002) have claimed, under the name of "embodied cognition" that thought and knowledge emerge from dynamic interactions between the body and the physical world. Barsalou (2008), in particular, used the term of "grounded cognition" instead of "embodied cognition" in order to emphasize that the cognition is not only determined from physical states but can actually be drawn from multiple sources, including perceptual simulations, situated action, social interactions, emotional states, and the environment.

The ways of discussing the embodied nature of cognition have been different among researchers, depending on the disciplines they belong to and their perspectives. Cognitive linguists (Gibbs, 2003, 2005; Lakoff & Nunez, 2000; Lakoff & Johnson, 1980), for example, emphasize the role of the body itself in understanding abstract concepts. They view the whole body as a receptor of perceptual experiences and an image schema as a mental representation created by those experiences. Unlike cognitive linguists, cognitive psychologists define individual sensory modalities as a source of perceptual experiences and a multimodal representation as a mental representation created by those experiences. Thus, the frameworks for embodied cognition by cognitive linguists and cognitive psychologists are similar in that they both acknowledge mental representations (image schemata and multimodal representations) created by physical interactions as a cognitive grounding for understanding abstract concepts. However, they differ in explaining the mechanism of constructing those mental representations.

1.2. Embodiment in education

Embodied cognition theory suggests that people should have perceptual experiences first to construct multimodal representations in order to be able to mentally simulate what is being presented. So far, there are few studies which have examined the effects of perceptual experiences in terms of the embodied cognition framework. However, some inferences can be drawn from previous studies, one such inference is that physical manipulation of real objects or the addition of haptic feedback to a simulation is a possible way of providing more embodied instruction.

1.2.1. Physical manipulation in education

Physically manipulating objects using the hands while processing abstract concepts is one way of enhancing learners' comprehension. Many studies show the positive influence of physical manipulation in learning and memory (Bara, Gentaz, Cole, & Sprenger-Charolles, 2004; Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004; Lederman & Klatzky, 1987; Ramani & Siegler, 2008; Siegler & Ramani, 2008). Glenberg et al. (2004) found that physically manipulating toys while reading a story provides grounding for young children's reading comprehension. Similar results were found in younger children while learning the alphabet (Bara et al., 2004). The positive effects of physical manipulations were also observed in mathematics learning, it was shown that playing a numbers board game produces improvements in the understanding of numerical magnitude in preschoolers from low-income backgrounds (Ramani & Siegler, 2008; Siegler & Ramani, 2008). From the embodied cognition framework point of view, numerical board games help children to produce kinesthetic cues by physically moving the tokens, this creates a perceptual grounding that can be linked to abstract symbols (numbers) and eventually help children to comprehend the linear number line.

In contrast to the studies mentioned above, which show positive effects of physical manipulation in education, there are also studies that have not indicated the superiority of physical manipulation approach (Han, Black, & Hallman, 2009; Klahr, Triona, & Williams, 2007; Triona & Klahr, 2003; Triona, Klahr, & Williams, 2005; Zacharia & Olympiou, 2011). However, when considering the topics covered in these studies, we cannot conclude that physical and virtual materials provide perceptually equivalent experiences for all areas of learning. For example, Triona et al. (2005) investigated whether interacting either with physical instructional materials or virtual ones would make differences in learning based on embodied cognition. In this study, seventh- and eighth- graders designed mousetrap cars by assembling either physical components with their hands or virtual ones with mouse clicking. After running the cars, they had to determine the most effective properties of mousetrap cars. Unlike their hypothesis that the physical and the virtual manipulation would differently affect students' learning, both groups learned equally well from physical and from virtual materials. Also, in Zacharia and Olympiou's study (2011), 66 undergraduate students studied about heat and temperature with physical and virtual manipulations. While the physical manipulation group used real instruments and materials, such as thermometers, heaters, beakers, water, and etc., the virtual manipulation group used virtual ones. Even though, instruments and materials used were in different format, students in both groups learned equally well. These results might be due to the fact that physical objects used in these studies did not make an enormous perceptual difference from virtually clicking components on computer screens.

However, other subjects deal with content that is impossible to experience in a virtual space. For instance, when people hold two magnets repelling each other, they feel resistance between two magnets. This type of feeling, such as resistance, friction between surfaces, or forces that cannot be seen or heard is not perceptible by clicking a mouse button in a virtual space. Thus, if the learning topic had been different, the different perceptual experiences offered by the two instructional materials may have made a difference in the students' learning. Therefore, whether or not physical and virtual manipulations make a significant difference in learning still remains a controversial topic.

1.2.2. Haptic technologies in physics education

While the above studies show the positive effects of physical manipulation in younger children's learning, there are also studies exploring the effects of technological applications that incorporate haptic feedback at more advanced levels, from middle school through to graduate school, and mostly in the scientific domain, especially in physics. In schools, physics is typically taught in highly abstract ways that only promote the understanding of mathematical formulas for physical phenomena without giving students a chance to experience it. This results in students' lack of an understanding of the essential concrete concepts or principles of the subject (diSessa, 1993; Roschelle & Greeno, 1987; Roschelle, 1991, April; White, 1993). In contrast, embodied cognition theory suggests that instruction should be more focused on perception rather than concentrating purely on abstract rules, since conceptual understanding can only be achieved by first developing a perceptual grounding. Multimedia simulations accommodate this need by providing a more perceptually grounded education using visual and verbal stimuli. However, most of the simulations used in science use only visual and auditory feedback (Minogue & Jones, 2006), even though learners, especially novices, may benefit more from additional types of sensory feedback. In particular, in learning physics, learners can learn better from actually feeling the force that contributes to the actual physical motions observed. This understanding of force is at the heart of comprehension in physics. Thus, current emerging technologies are attempting to provide the feeling of the force that cannot be seen or heard through a haptic channel.

“Haptic” refers to manual interactions with environments, and this includes both exploration of the environment for extraction of information or manipulation of the environment (Srinivasan & Basdogan, 1997). These haptic interactions can cover many subjects such as reaction forces and tactile stimuli as well as temperature and motion (Dionisio, Henrich, Jakob, Rettig, & Ziegler, 1997). There are previous studies showing the benefit of haptic feedback in physics education. For example, technologies have enabled advanced haptic feedback for the study of forces that cannot be recognized by either visual or auditory channels. Examples of this include the study of the resistance between two molecules (Brooks, Ouh-Young, Battert, & Kilpatrick, 1990), magnetic forces (Reiner, 1999), and mechanical forces (Williams, Chen, & Seaton, 2003; Williams, He, Franklin, & Wang, 2007). Jones, Minogue, Tretter, Negishi, and Taylor (2006) investigated the impact of haptic feedback combined with computer visualizations on middle and high school students' ability to learn about viruses and nanoscale science. Also, incorporating haptic feedback with educational simulations had positive effects in a higher education setting. Brooks et al. (1990) found that experienced biochemists from a university research center benefited from using haptic feedback. In addition, Reiner (1999) examined the role of tactile perception in conceptual construction of forces and fields in graduate students who only had general high school science background by employing a modified trackball that transferred a simulated force applied by a field to the learner's hand.

Compared to the studies done to examine the effects of these emerging technologies in secondary and higher educational settings, fewer studies have been conducted in elementary science learning. Williams et al. (2003) developed a haptic augmented simulation to teach simple machines (levers, pulleys, inclined planes, gears, screws and wheel and axles) in elementary school. This haptic interface provides a sense of touch and force to the user from a virtual model on the computer and helps students learn about the transformation of forces created by each machine by actually letting the user feel those forces. Even though this simulation received positive feedback from the users as an educational tool, its effectiveness on elementary students' learning was not investigated. In order to learn how these technologies can enhance elementary students' science learning by providing more embodied experiences with the addition of haptic feedback, a thorough investigation is necessary.

While this technology has already showed its promise in a secondary or higher education settings, there is little research that examines the effectiveness of this new technology in relatively young students' learning. In order to fill the gap in previous literature, this study investigates the potential of haptic technology in the learning of elementary physics. For this study, a haptic augmented simulation was developed to provide both force and kinesthetic feedback through a commercially available force feedback joystick in conjunction with the normal visual and auditory information.

1.3. Instructional model for embodied understanding

This study proposes the *instructional model for embodied understanding* based on embodied cognition theory. When students learn certain concepts for the first time, they should be provided with a perceptually rich experience so that they can build a multimodal representation in their mind based on that experience. Once the multimodal representation is created, it becomes a reference point with which to interpret other types of instructional materials that explain the same concept but with different representational formats. According to the embodied cognition point of view, the interactions between the external representation of a concept and the internal representation occur countless times and gradually a higher-level categorical knowledge of the concept is gained from the accumulation of these interactions. However, in an educational setting, the number of interactions is limited due to time constraints. Thus, well-designed instructional sequences rather than random exposures to the perceptual experiences are necessary to enable students to get to the level of abstraction where it is possible to have a proper image schema for comprehending the corresponding abstract concepts.

In the instructional model proposed in Fig. 1, a sequential abstraction strategy is used for helping learners to form image schemata. The sequential abstraction strategy involves presenting instructional materials that sequentially contain fewer sensory modalities to use. For example, when students are first introduced to how gears work with a haptic simulation that can provide both force and kinesthetic feedback, they may construct a multimodal representation of which direction (haptic: kinesthetic), how fast two intermeshed gears rotate (visual), how much force is necessary to rotate a gear depending on size (haptic: force), how much force is generated by the interlocked gear (visual), and what is a physical principle behind it with narration (auditory). Once they create this multimodal representation with all three sensory modalities, when the second instructional material about a window winder is presented with only two modalities (e.g., visual and auditory), the perceptual simulation activates not only the visual and auditory representation but also the haptic representation that is related to the content presented. Again, if the third instructional material about a salad spinner is presented with only the auditory channel, the visual and haptic areas in the brain still become activated and the second multimodal representation is simulated. By sequentially removing one modality at a time, learners can practice imagining what is not explicitly presented and gradually develop mental image-like representations of the learning content, that is, the desired image schema. With these recurring experiences which gradually move from a full perceptual stage to an imagination stage, students are expected to create an image schema of the *trade-off*, which is when one factor increases (e.g., force), then another physically related factor should decrease (e.g., speed or distance), in simple machines. This image schema

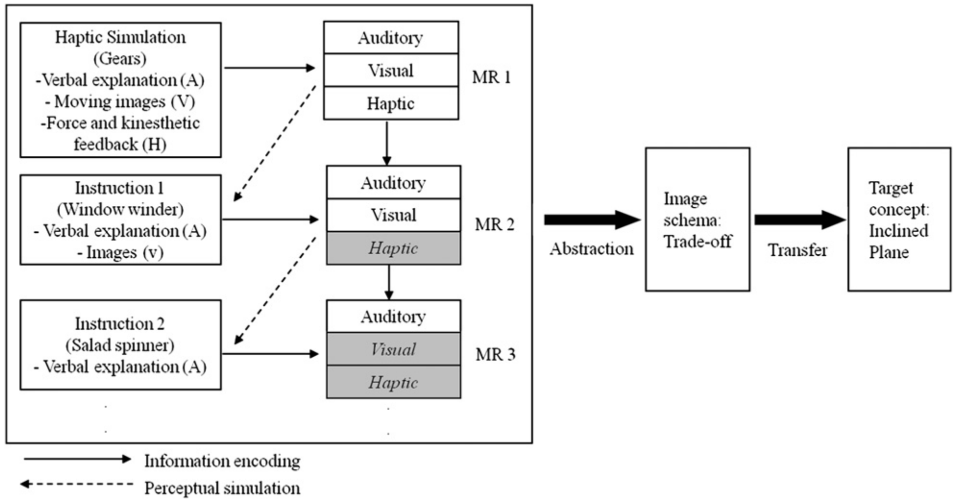

Fig. 1. Instructional model for embodied understanding of how simple machines work.

generated from perceptual experiences and perceptual simulations could be adapted to learn about other types of simple machines, such as an inclined plane.

In order to verify the first component of the proposed instructional model, that is creating an initial multimodal representation (MR1), three different types of simulations (force and kinesthetic, kinesthetic, and non-haptic simulations) were compared. The force and kinesthetic and the kinesthetic simulations were haptic augmented simulations with different haptic levels. The force and kinesthetic simulation was the highest haptic level simulation with both force and kinesthetic feedback. Force feedback provided the feeling of force while the kinesthetic feedback offers the feeling of direction or movement of hands. By having both alongside visual and auditory information, students were expected to create the most perceptually grounded multimodal representation and to better comprehend further instruction based on that representation. The kinesthetic simulation was also haptic augmented simulation but only provided kinesthetic feedback through visual and auditory information. The non-haptic simulation had no haptic feedback at all and delivered content only with visual and auditory channels. It was hypothesized that the haptic augmented simulation, especially the force and kinesthetic simulation, would be most effective in helping students create a multimodal representation that is the cognitive grounding to comprehend the following instructional contents which were presented in a more abstract way. The creation of a superior multimodal representation would result in better recall, inference, and transfer.

2. Methods

2.1. Participants

A simple machine is a mechanical device that changes the direction or magnitude of a force. By using a simple machine, people can get a mechanical advantage to multiply force. The New York City K-8 Science Scope and Sequence guidelines (2008) require teachers to introduce simple machines in the sixth grade. In order to control for prior knowledge, 220 fifth graders were recruited from eleven classes at three elementary schools located in lower socioeconomic status neighborhoods in the Bronx, New York, in the spring of 2009. Around two-thirds of the students in the three schools are Latino American and about one-third of them are African American. Also, more than 96% of the students are eligible for a free or reduced-price lunch program.

2.2. Dependent variables and test instruments

The dependent variables were students' creation of a multimodal representation, and adapting that representation to the new material being taught. These abilities were assessed with recall, inference, and transfer tests. The test instruments were revised from those used in the pilot study. In order to confirm the validity of the test instruments, all of the test items were reviewed and approved by two fifth grade elementary science teachers. Also, for reliability, four fifth graders with different academic levels (one high, two intermediate, and one low) were recommended by a homeroom teacher and interviewed about how they responded to the test instruments.

Creation of a multimodal representation was evaluated with the recall and the inference tests that collectively form the posttest. This posttest consisted of seven multiple-choice questions and four true or false questions. The seven multiple-choice questions were designed to test students' immediate recall by using the same images shown in the simulation. Students received one point for each correct answer. The four true or false questions were used to assess the inferential ability to predict the change in one factor that follows the change of another one. Once students chose their answers, they had to provide their rationale for why they thought it was true or false. Students received one point for each correct answer and an additional point for each correct explanation. It was assumed that once students create a correct multimodal representation about how gears work, they should be able not only to remember what they saw from the simulation but also to infer the movement of other machines.

Second, it was examined whether different types of simulations had different effects on forming a cognitive grounding to comprehend further instructions with the second posttest. As an immediate recall test two questions required students to fill out eight blanks in each question by choosing one of two words to complete the explanations. The questions concentrated on the real life machines presented earlier during instruction, a car window winder and a salad spinner. Students received one point for each correct answer. The second posttest also had the same four true or false questions as the inference test. Once students chose their answers, they had to provide their rationale for why they thought it was true or false. Students received one point for each correct answer and an additional point for each correct explanation. It was assumed that the multimodal representation created by previous perceptual experiences with simulations could serve as a cognitive grounding for future learning, and that those experiences could be activated by proper instructions. Thus, once students had created the multimodal representation about the machines, they should not only be able to remember what they learned from the instruction but also to infer the movement of those machines.

Third, the students' retention of knowledge was assessed with the same inference test for the gear session after a week of intervention. This inference test, again, contained the same four true or false questions. Once students chose their answers, they had to provide their rationale for why they thought it was true or false. Students received one point for each correct answer and an additional point for each correct explanation.

Finally, adapting previous understanding to new learning was assessed with the transfer test. This consisted of two multiple-choice, two short answer, four true or false, and one open-ended questions on the subject of an inclined plane. For the multiple-choice and short answer questions, students received one point for each correct answer. For the true or false question, once students chose their answers, they had to provide their rationale for why they thought it was true or false. One open-ended question required students to explain how a winding road helps a car to easily go up a mountain; both force and distance had to be mentioned in their description for two points. If only one factor was mentioned, one point was given. It was assumed that once students learned about the mechanism of simple machines with simulations and instructions, they should be able to transfer that knowledge to understand a different kind of simple machine.

Also, in order to determine students' prior knowledge about simple machines, a pretest was administered. The pretest assessed students' basic knowledge about the movement of gears, such as direction, force and speed, with three multiple-choice questions.

2.3. Materials

2.3.1. Gear instruction

A gear simulation was created for this study. The computer-based gear simulation utilized Adobe Flash software to create an interactive, animated interface. Adobe Flash was chosen for its versatility, universality, and end-user-friendly design. The simulation interface was designed with moving images in a Flash animation and also programmed to be interactive using ActionScript2. ActionScript2 takes input from the user and then triggers the force feedback device using the C++ programming language. The force feedback device used in the simulation was the Microsoft Sidewinder Force Feedback 2 Joystick, which was connected to the computer running the simulation through a USB interface. The API (application programming interface) used to program the force feedback between the simulation and the joystick was the Microsoft DirectX framework, version 10.

The gear simulation showed four gear combinations to illustrate how two intermeshed gears create mechanical advantages (see Fig. 2). The force and kinesthetic (FK) simulation, which was the force feedback simulation in the pilot study, provided information through visual, auditory, and fully loaded haptic feedback. Through the visual channel, information was delivered about how fast each gear rotates, how much input force was needed to rotate the gear on the left and how much output force was generated by the gear on the right. The haptic device, a Microsoft Sidewinder Force Feedback Joystick II, gave participants the actual feeling of the input force that they should use to rotate the gears, which was the force part of the haptic feedback. By rotating the joystick, participants were made aware of the positioning and arm movement that provided the information about the speed and the direction of gear rotation, which was the kinesthetic part of the haptic feedback. While participants interacted with the simulation, voice-over narration was played to explain related concepts. The kinesthetic simulation (K), which was the non-force feedback simulation in the pilot study, delivered the same scientific content with only the kinesthetic movement, without force feedback, along with visual and auditory information. The non-haptic simulation (NH) had only visual and auditory information without any haptic feedback and as such was a regular multimedia simulation that showed moving images with audio narrations.

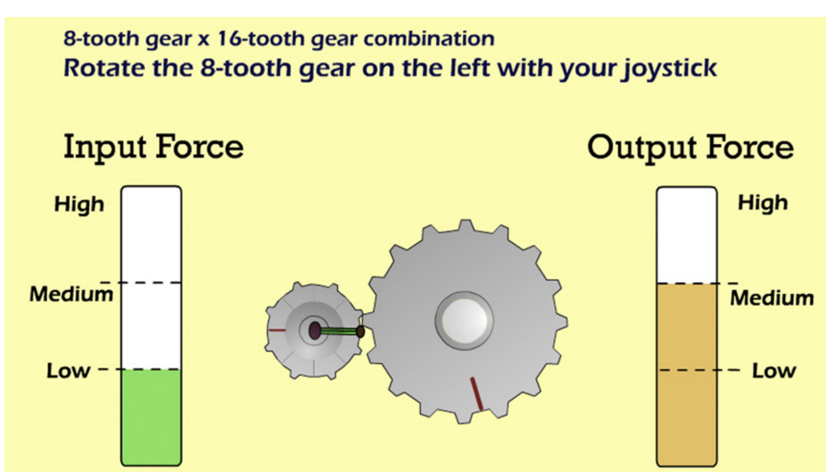

Fig. 2. Screenshot of gear simulation.

2.3.2. Transfer instruction

The instruction for transfer described how an inclined plane works to produce a mechanical advantage with a distance and force trade-off. Along with text explaining the mechanism of an inclined plane, the instruction contained pictures depicting a woman using a ramp and a man not using a ramp to lift a heavy box.

2.4. Procedure

This experiment was conducted over two sessions, one a week for two weeks. Fig. 3 illustrates the progression of the experiment.

Students were asked to fill out the pretest worksheet first. Then they learned about how two intermeshed gears work with one of the three simulations. As soon as individual students finished their simulation, posttests (recall and inference tests) were handed out for them to complete. Afterwards, they were provided instructional videos explaining how a window winder and a salad spinner work. Then, students were tested with the second posttest (recall and inference tests). In the second week, the delayed test was conducted. Finally, the third session was administered a week after the second session and was for learning about inclined planes. Students were provided a page-long instructional text that explained how inclined planes work. The experimenter briefly explained that an inclined plane is another type of simple machine and pointed out the picture of a woman using a ramp to lift a heavy box comparing with the picture of a man lifting a heavy box without a ramp. Following this, the class read the instructional text. Two volunteers took turns reading the text while the rest of the students followed along sentence by sentence. Afterwards, students were asked to fill out the transfer test to assess their understanding of how inclined planes work with the force-distance trade-off. Each session was forty-five minutes long.

3. Results

Among the 220 participants recruited, those who were absent from school when the first session was administered and those who did not complete all of the tests were excluded. Thus, the data from 175 participants was analyzed for the first session.

3.1. Effects of simulation type in the creation of a multimodal representation

Before evaluating the effects of each simulation type in terms of the students' ability to create a multimodal representation, a correlation analysis was conducted to examine whether the recall test was correlated with the pretest score. Pearson correlation ($r = 0.23$, $p < 0.01$) confirmed that there was a significant relationship between the pretest scores and the recall scores, meaning that the participants who got higher scores in pretest performed better in the recall test.

To eliminate this pretest effect on the recall test, a one-way ANCOVA with a covariate of the pretest was conducted. The dependent variable was recall test score (Table 1). The participants in the force and kinesthetic simulation group ($M = 3.93$) performed the best on the recall test, followed by the kinesthetic ($M = 3.85$) and the non-haptic ($M = 3.23$) simulation. These differences were statistically significant, F (2, 172) = 3.591, $p = 0.030$, $\eta^2 = 0.038$. The post-hoc analysis revealed that the difference between the force and kinesthetic simulation and the non-haptic simulation was significant, $p = 0.044$. However, the differences between the force and kinesthetic simulation and the kinesthetic simulation ($p = 1.00$) and between the kinesthetic simulation and the non-haptic simulation ($p = 0.11$) were not significant. This means that the force and kinesthetic simulation group outperformed the non-haptic simulation group but the kinesthetic group did not. The results for the ANCOVA indicate a significant main effect for simulation, F (2, 172) = 3.591, $p = 0.030$, $\eta^2 = 0.038$. Since there was a meaningful difference in the recall score among the three simulation groups, the pair wise comparisons using Bonferroni correction were performed to examine which pair of groups made the difference. This analysis revealed that the difference between the force and kinesthetic simulation and the non-haptic simulation was significant, $p = 0.015$ with the significance level of 0.017 (0.05/3). However, the differences between the force and kinesthetic simulation and the kinesthetic simulation ($p = 0.765$) and between the kinesthetic simulation and the non-haptic simulation ($p = 0.037$) were not significant. In short, the force and kinesthetic simulation group outperformed the non-haptic simulation group but the kinesthetic group did not.

Also, a one-way ANOVA was conducted to evaluate the effects of the simulations on the inference test. As shown in Table 1, the force and kinesthetic simulation group ($M = 3.12$) performed the best in the inference test, followed by the kinesthetic simulation group ($M = 2.54$) and the non-haptic group ($M = 2.50$). However these differences were found to be non-significant with F (2, 172) = 2.174, $p = 0.117$, $\eta^2 = 0.025$. These findings reveal that the simulation type did not make any difference in the results of the inference test.

Week 1: Gear session	*Week 2: Delayed test session*	*Week 3 : Transfer session*
- Introduction - Pretest (gear basic) - (Practice of using joystick for haptic group) - Simulation intervention - Posttest (recall, inference) - Instruction 1 for a window winder - Instruction 2 for a salad spinner - Posttest (recall 1, recall 2, inference) - Summary and announcement	- Retention test for gears - Summary and announcement	-Introduction - Reading the instructional text for an inclined plane - Transfer test - Summary

Fig. 3. Progression of experiment.

Table 1
Estimated marginal means and standard deviations for Recall and Inference test scores.

	Simulation	M	SD	n
Recall	FK	3.93 (56%)	1.62	59
	K	3.85 (55%)	1.43	54
	NH	3.23 (46%)	1.37	62
Inference	FK	3.12 (39%)	1.72	59
	K	2.54 (32%)	1.94	54
	NH	2.50 (31%)	1.76	62

Maximum score for Recall test is 7.
Maximum score for Inference test is 8.

3.2. Effects of simulation type in the comprehension of further instruction

The effect of simulation type in students' comprehending the instruction was tested. The participants who studied the window winder from the instruction with visual and auditory information after using the force and kinesthetic simulation performed the best ($M = 4.98$) on the recall test, followed by those using the kinesthetic simulation ($M = 4.82$) and the non-haptic simulation ($M = 4.24$) respectively (Table 2). A one-way ANOVA revealed a significant main effect for simulation, $F(2, 172) = 3.103$, $p = 0.047$, $\eta^2 = 0.035$. The post-hoc tests showed that there was a marginally significant difference between the force and kinesthetic simulation and the non-haptic simulation, $p = 0.056$ but non-significant differences between the force and kinesthetic simulation and the kinesthetic simulation ($p = 1.000$) and between the kinesthetic simulation and the non-haptic simulation ($p = 0.224$). In summary, the force and kinesthetic group outperformed the non-haptic group but the kinesthetic group did not.

In addition, the participants who studied the salad spinner with only auditory information after using the force and kinesthetic simulation performed the best ($M = 4.95$) on the recall test, followed by those using the non-haptic simulation ($M = 4.15$) and the kinesthetic simulation ($M = 4.00$) respectively (Table 2). A one-way ANOVA revealed a significant main effect for simulation, $F(2, 172) = 3.711$, $p = 0.026$, $\eta^2 = 0.041$. The post-hoc tests showed non-significant differences between the force and kinesthetic and the non-haptic groups ($p = 0.090$) and between the kinesthetic and the non-haptic simulations ($p = 1.000$) but a significant difference between the force and kinesthetic and the kinesthetic groups, $p = 0.041$. In short, the force and kinesthetic group outperformed the kinesthetic group and did not do better than the non-haptic group.

Lastly, the participants who studied an example of using gears, those using the force and kinesthetic simulation performed the best ($M = 2.98$) in the inference test, followed by those using the kinesthetic simulation ($M = 2.17$) and then the non-haptic simulation ($M = 2.05$) (Table 2). A one-way ANOVA revealed a significant main effect for simulation, $F(2, 172) = 5.039$, $p = 0.007$, $\eta^2 = 0.055$. The post-hoc tests showed significant differences between the force and kinesthetic and the kinesthetic groups, $p = 0.042$ and between the force and kinesthetic and the non-haptic groups, $p = 0.011$ but a non-significant difference between the kinesthetic simulation and the non-haptic simulation, $p = 1.000$. In short, the force and kinesthetic group outperformed the other two groups but the kinesthetic and the non-haptic group did not show any difference in their performances.

3.3. Effects of simulation type in the retention of knowledge

Among the 175 students who participated in the gear session, 152 students attended the second session for the delayed inference test. The participants who studied about gears using the force and kinesthetic simulation performed the best ($M = 2.26$) in the delayed recall test, followed by those using the non-haptic simulation ($M = 2.12$) and then the kinesthetic simulation ($M = 2.00$) (Table 3). A one-way ANOVA revealed a non-significant main effect for simulation, $F(2, 149) = 0.263$, $p = 0.769$, $\eta^2 = 0.004$. In short there was no difference in the delayed inference test scores depending on simulation type.

3.4. Effects of simulation type in transferring knowledge to new learning

Among the 220 participants recruited, only those who participated in all three sessions were included for the analysis. Thus, the data from 118 participants was analyzed for the transfer session. The participants who used the force and kinesthetic simulation ($M = 5.18$) performed the best in the transfer test, followed by the non-haptic simulation group ($M = 4.50$) and then the kinesthetic simulation group ($M = 4.15$) (Table 4). The one-way ANOVA results indicate a marginally significant main effect for simulation, $F(2, 115) = 3.622$, $p = 0.030$,

Table 2
Means and standard deviations for the Recall 1, Recall 2, Inference test scores.

	Simulation	M	SD	n
Recall 1	FK	4.98 (62%)	1.77	59
	K	4.82 (60%)	1.65	54
	NH	4.24 (53%)	1.72	62
Recall 2	FK	4.95 (62%)	1.91	59
	K	4.00 (50%)	1.97	54
	NH	4.15 (52%)	2.16	62
Inference	FK	2.98 (37%)	1.75	59
	K	2.17 (27%)	1.80	54
	NH	2.05 (26%)	1.69	62

Maximum score for Recall 1, Recall 2, and Inference test is 8.

Table 3
Means and standards deviations for delayed inference test scores.

Simulation	M	SD	n
FK	2.26 (28%)	1.61	47
K	2.00 (25%)	1.85	49
NH	2.12 (27%)	1.72	152

Maximum score is 8.

$\eta^2 = 0.059$. Further analysis was conducted to investigate which pair of groups contributed to that effect. The Turkey post-hoc tests revealed that there was a meaningful difference between the force and kinesthetic and the kinesthetic groups, $p = 0.027$. However, the differences between the force and kinesthetic and the non-haptic simulations ($p = 0.246$), and the non-haptic and the kinesthetic simulations ($p = 1.000$) were not significant. In short, the force and kinesthetic group only outperformed the kinesthetic group but did not do better than the non-haptic group.

Additional analysis was conducted to further examine the effects of simulation on transferring the previous knowledge to comprehend the core concept of trade-off in inclined planes. Three questions out of nine that were related to the trade-off between force and distance which is the foundation of understanding the mechanism of inclined plane were selected to investigate the simulation effects in-depth. When considering questions related to the core concept of trade-off, the differences among three groups became more dramatic. The force and kinesthetic simulation group ($M = 2.29$) performed the best in the transfer test, followed by the non-haptic simulation group ($M = 1.65$) and then the kinesthetic simulation group ($M = 1.60$) (Table 5). A one-way ANOVA revealed a significant main effect for simulation, $F(2, 115) = 5.112$, $p = 0.007$, $\eta^2 = 0.082$. The post-hoc tests showed significant differences between the force and kinesthetic and the non-haptic simulations ($p = 0.026$), and the force and kinesthetic and the kinesthetic simulations ($p = 0.014$) but non-significant difference between the kinesthetic and the non-haptic simulations, $p = 1.000$. In short, the force and kinesthetic group outperformed the other two groups but the non-haptic and the kinesthetic simulations did not result in any difference in students' performance.

4. Discussion

The purpose of this study was to examine the effectiveness of a haptic augmented simulation on elementary students' creation of a multimodal representation related to how gears work. Creating a multimodal representation based on perceptual experiences is a critical component in the embodied instructional model proposed earlier, since these perceptual experiences would become a basis for conceptual comprehension according to the embodied cognition theory (Barsalou, 2008; Barsalou et al., 2003; Gibbs, 2005; Glenberg, 1997; Lakoff & Johnson, 1999; Smith & Gasser, 2005; Wilson, 2002). For this study, computer simulations were developed with three different haptic levels (force and kinesthetic, kinesthetic, and non-haptic). Students' recall, inference and transfer abilities were evaluated as evidence of such cognitive processes.

The first finding of this study supports the previously mentioned research on the benefits of using haptic technology, especially force feedback technology, in learning science (Brooks et al., 1990; Jones et al., 2006). This study's results revealed that haptic augmented simulations, both the force and kinesthetic and the kinesthetic simulations, may be more effective than the non-haptic simulation in providing perceptual experiences and helping elementary students to create multimodal representations about machines' movements. In this study, it was found that participants who used the force and kinesthetic simulation performed better than those who used the non-haptic simulation but did not outperform the kinesthetic simulation group in recalling factual knowledge about gears' movements. This may be due to the fact that the haptic augmented simulation provides richer perceptual experiences to students by using three sensory inputs (visual, auditory and haptic) rather than using just two (visual and auditory) as in commonly used multimedia simulations (Chan & Black, 2006). Learning science involves comprehending abstract concepts that cannot be seen or heard in most cases. Especially in physics, understanding forces is at the heart of comprehension. In the haptic augmented simulation, haptic feedback is conveyed directly so that students can feel the force and/or kinesthetic movement while interacting with the simulation. Thus, students can encode information through three sensory modalities and capture them in their brains, this, in turn enables them to create a multimodal representation that is more perceptually grounded (Barsalou, 2008). This multimodal representation helps students to remember what they have seen from the simulation better than those who encoded the information through only two sensory modalities. However, the haptic augmented simulation was not better than the non-haptic simulation in improving students' reasoning about how machines work.

The second finding of this study revealed that in most cases, even though being haptic, using the purely kinesthetic simulation was not enough for elementary students to construct a complete multimodal representation that can serve as cognitive grounding for future learning. Force feedback was needed to construct a fully loaded multimodal representation that could be activated when the instruction with less sensory modalities was being given. In this study, it was found that participants who used the force and kinesthetic simulation better than those who used the non-haptic simulations in recalling factual knowledge from the instruction about how a window winder works that was delivered via visual and auditory channels. Similarly, in recalling factual knowledge from the instruction about how a salad spinner works that was delivered via only auditory channel, participants who used the force and kinesthetic simulation performed better

Table 4
Means and standards deviations for transfer test scores.

Simulation	M	SD	n
FK	5.18 (52%)	1.78	38
K	4.15 (42%)	1.66	40
NH	4.60 (46%)	1.76	118

Maximum score is 10.

Table 5
Means and standards deviations for core concept scores.

Simulation	M	SD	n
FK	2.29 (57%)	0.98	38
K	1.60 (40%)	0.98	40
NH	1.65 (41%)	1.19	40

Maximum score is 4.

than those who used the kinesthetic simulation. While the instruction is being given, students actively retrieve their memory about previous experiences which are relevant to the topic by mentally simulating it (Barsalou, 1999). This memory having been created with fully loaded representation, students can reactivate the full sensory experiences that they used to create that representation when the instruction is being delivered in a more abstract way with fewer sensory modalities. Thus when the instruction is presented through visual and auditory channels, students who had the experiences with the haptic augmented simulation, especially the force and kinesthetic simulation, retrieve and mentally visualize not only the visual and auditory information but also the haptic information relevant to the presented concept from their memory and actively compare it to the incoming content for revision. Going through this cognitive process of updating their mental representations helps students to internalize their understanding of a concept. However those who did not have an experience to feel the haptic sensation related to the concept have no cognitive grounding upon which to build their comprehension when the instruction explains about force and kinesthetic movements. Thus in this study, students who used the force and kinesthetic simulation remembered instructional content better than those who used the non-haptic simulation. Furthermore, when instruction was given in a more abstract way, that is only through the auditory channel, among the two haptic augmented simulations, the simulation with a higher augmentation that has both force and kinesthetic feedback was also more effective in helping students to recall the instructional content. This sequential abstraction in instruction provides the opportunity for students to gradually transform the perception-based knowledge to a conceptual knowledge, which, in this case, was the concept of trade-offs. Also, students who used the force and kinesthetic simulation performed better than the kinesthetic and the non-haptic simulation groups in reasoning about how machines work. As discussed earlier, students could not develop the ability of reasoning with only being provided perceptual experiences. However, after instructional support to activate their experiences and associate them with explicit knowledge, students in the force and kinesthetic simulation group could reason better than the other groups of students.

The third finding of this study provides empirical evidence for the theoretical claim that bodily rooted perceptual experiences can be a cognitive ground for reaching the conceptual level of comprehension (Barsalou, 2008; Gibbs, 2005; Lakoff & Johnson, 1999; Smith & Gasser, 2005; Wilson, 2002) This study revealed that the force and kinesthetic simulation may be effective in providing cognitive grounding to comprehend a new content based on the multimodal representation created with the enhanced force feedback. Once students constructed their own schematic knowledge (trade-offs), they should be able to transfer that knowledge to a new learning situation. Since the previous instructional process with haptic augmented simulation proved to be effective in creating a multimodal representation and in constructing a schema with sequential abstraction, it was expected that the haptic augmented simulation would also be helpful for knowledge transfer. In the transfer session, it was found that participants who used the force and kinesthetic simulation performed better in the transfer test than those who used the kinesthetic simulation but did not outperform the non-haptic simulation group. This is probably due to the fact that on the test there were general questions about inclined planes that were not directly related to the core concept of trade-offs and the simulation effect may have been counteracted. However, further analysis revealed that the force and kinesthetic group transferred and applied their schematic understanding to comprehend the core mechanism of force and distance trade-offs in inclined planes better than both the kinesthetic and the non-haptic simulation groups.

5. Conclusion

These findings suggest implications for successful instruction to learn abstract science concepts. It is important to help students to make a solid cognitive grounding by using a perceptual anchor. To this end, instructional tools should provide perceptual experiences related to learning content first before introducing concepts so that students can have a concrete cognitive base to refer to for comprehension. Haptic augmented simulation is unique in that it imitates the force and the kinesthetic movement that students can feel when they interact with physical objects (simple machines in this study) which might otherwise be difficult to experience with other instructional tools such as regular multimedia simulations or illustrations. By having this simulation, students not only have visual and auditory information, but also have haptic information and this is critical in creating a multimodal representation that is more perceptually grounded. Once the multimodal representation is created, it becomes a reference to absorb future learning.

The results of this study are limited in suggesting how the proposed instructional model would enhance students' learning, since this study only attempted to verify the first component of the proposed instructional model by investigating effectiveness of haptic augmented simulations in creating an initial multimodal representation. From the results of the study, we could learn that haptic augmented simulations would help students better encode information from simulation. However, activating perceptual simulation based on the multimodal representation created remained experimentally unproved and was only theoretically proposed. The activation of perceptual simulation is a key component of the mechanism of embodied understanding (Barsalou, 1999, 2008). Thus, it should be further examined in a follow-up study.

Being able to comprehend the mechanisms of machines is very important in learning science and understanding the physical world as well. To reach a conceptual understanding of physics, this study suggests emphasizing the perceptual stage. These results possibly offer important implications to current education where abstract knowledge acquisition is highly valued but first-hand experiences receive less attention. Specifically, this study provides evidence on how emerging technologies can help students' learning by providing a more embodied experience which allows students to internalize their understanding by imagining what is described in the instruction.

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