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# Understanding the Notion of Friction Through Gestural Interaction with a Remotely Controlled Robot

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**Abstract**

Embodied interaction with tangible interactive objects can be beneficial for introducing abstract scientific concepts, especially for young learners. Nevertheless, there is limited comparative evaluation of alternative interaction modalities with contemporary educational technology, such as tablets and robots. In this study, we explore the effects of touch and gestural interaction with a tablet and a robot, in the context of a primary education physics course about the notion of friction. For this purpose, 56 students participated in a between-groups study that involved four computationally enhanced interventions which correspond to different input and output modalities, respectively: (1) touch-virtual, (2) touch-physical, (3) hand gesture-virtual, and (4) hand gesture-physical. We measured students' friction knowledge and examined their views. We found that the physical conditions had greater learning impact concerning friction knowledge compared to the virtual way. Additionally, physical manipulation benefited those learners who had misconceptions or limited initial knowledge about friction. We also found that students who used the more familiar touchscreen interface demonstrated similar learning gains and reported higher usability compared to those using the hand-tilt interface. These findings suggest that user interface familiarity should be carefully balanced with user interface congruency, in order to establish accessibility to a scientific concept in a primary education context.

**Keywords** Embodied learning · Educational robotics · Human-robot interaction · Science education · Gestural congruency · Surrogate embodiment · Physicality

## Introduction

It is widely agreed that abstract concepts can be hard for children to learn (Resnick et al. 1998; Zuckerman et al. 2005). In contrast to concrete objects that can be touched, seen, smelled, or heard, abstract concepts are entities with no physical substance in the real world (de Koning and Tabbers 2011). However, scientists of cognitive semantics assume that mental representations of abstract concepts are always rooted in sensorimotor experiences and are typically understood, via conceptual metaphor, in terms of more concrete concepts (Lakoff and Johnson 2008; Lakoff and Núñez 2000). As Barsalou (1999) points out "abstract concepts are grounded in complex simulations of combined physical and introspective events." From this perspective, formation and comprehension of abstract concepts rely on our interactions with the physical world.

As stated in the conceptual metaphor theory (Lakoff and Johnson 2008; Lakoff and Núñez 2000), image-schemas are used to metaphorically map concrete concepts perceived through physical interaction of the body with the environment onto abstract concepts. An illustrative example of how embodiment leads to the creation of conceptual metaphors and how abstract materials can be understood comes from the field of mathematics (Lakoff and Núñez 2000). For instance, through the metaphor "The Arithmetic Is Object collection" mapping from the

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concrete domain of physical objects to the abstract domains of numbers is created. Based on our previous physical activity on adding and taking away objects from collections, we can talk about adding and subtracting numbers respectively. Apart from mathematics, the claims of the conceptual metaphor theory have been extensively applied in the fields of cognitive linguistics and science education. Especially in physics, the development of ideas about motion and forces comes from image-schemas that transform previous physical experiences into abstract knowledge. On this account, embodiment of knowledge by getting students to act out the abstract concepts physically makes the conceptual metaphors employed by our brains a real-life experience.

Additionally, with the rapid development of digital technologies, such as mobile devices and touchscreens, a wide gamut of interfaces is provided to users. Hence, children can interact with computers more naturally and physically (Jacob et al. 2008). Putting forth the notion of "embodied interaction" (Dourish 2004), touch and hand gestures can be employed as input for the interaction (Lindgren and Johnson-Glenberg 2013), besides the conventional keyboard and mouse interfaces. Recently, there has been a strong push to exploit these interfaces in science education. Moving beyond the traditional desktop metaphor, the development of digital manipulatives (Resnick et al. 1998) and their use in education enabled students to explore a broader range of abstract scientific concepts (Zuckerman et al. 2005) by interacting with tangible objects, such as robots, that exist in the real world.

Motivated by the embodied cognition framework, highlighting the significance of physical experiences in the development and comprehension of abstract concepts, with the current study, we set out to explore the potential educational synergy between mobile interfaces and educational robotics. We aimed to investigate whether diverse input interaction modalities, such as touch and hand gestures and different outputs, such as virtual and physical robots, can assist students in comprehending abstract scientific concepts. Thus, the central research question of this study is:

> RQ: How different input and output interaction modalities can affect students in exploring the concept of friction?

The rest of the paper is structured as follows: in the next session, we present the related work and outline the various hypotheses; in the "Materials and Methods" section, we describe the methodology; in the "Results" section, we present the results; in the "Discussion" section, we discuss the findings and limitations; and finally, in the "Conclusion" section, we summarize the conclusion and future work.

## Related Work and Research Hypothesis

### Embodied Learning

Theories of embodied cognition (Barsalou 2008; Gallese and Lakoff 2005; Wilson 2002) emphasize the importance of perception in conceptual learning by suggesting that knowledge is intimately tied to sensorimotor actions. The mind no longer has been treated as separate from the body, and its perceptual rich experiences that lend support to the cognitive processes of the mind (Wilson 2002) and allow individuals to construct meaning and understanding of the world (Dourish 2004). Gallese and Lakoff (2005) add to this view by claiming that "conceptual knowledge is embodied" and "the sensory-motor system not only provides structure to conceptual content, but also characterises the semantic content of concepts in terms of the way that we function with our bodies in the world."

An issue is how precisely perceptual rich experiences contribute to knowledge. Evidence about the mechanisms underlying embodied learning can be drawn from the theories of working memory and cognitive load (Zacharia et al. 2012). It is thought that not only each sensorimotor modality (visual, auditory, and tactile) has its working memory (Millar 1999) but also acts as an individual source of perceptual experiences (Han and Black 2011). Specifically, when multiple modalities are employed stronger memory traces are produced, and more abundant knowledge structures are created, compared to the use of a single modality. Hence, learners would be able to retrieve the multimodal knowledge representations more efficiently in the future. Secondly, by combining the tactile channel with the visual and auditory ones, the mental energy required to process a given amount of information is distributed across the modalities, and thus the cognitive load imposed to the learner is reduced. In summary, perceptual rich experiences not only may help individuals learn the conceptual content faster and easier but also in a more in-depth manner.

Educational and developmental learning theories have also acknowledged the importance of sensory and motor actions of the human system in the construction of knowledge (de Koning and Tabbers 2011). For example, Maria Montessori (1966) believed that through movement learners interact with the environment, and it is through these interactions that they eventually acquire even abstract ideas. From a theoretical perspective, embodied learning is also related to learning theories favoring hands-on activities and child interaction. According to Piaget (2013) and Papert (1980), a fundamental tenet of learning is peoples' actions, as they construct knowledge and form the meaning of the world by actively interacting with learning objects. Likewise, Vygotsky (1980) emphasized the role of interaction with physical and symbolic artifacts in learning. Similarly, Bruner (1966) believed that learning begins with an action-touching, feeling, and manipulating.

However, what distinguishes embodied learning from other hands-on learning theories is the dimension of "gestural congruency" (Lindgren and Johnson-Glenberg 2013); that is in order a perceptually rich learning experience to be effective, actions of the body need to be congruent to the mental operations and representations of the concepts to be learned (Oviatt et al. 2012; Segal 2011; Johnson-Glenberg et al. 2016). A representative example that highlights the significance of "gesture congruency" is Johnson-Glenberg et al.'s (2016) study for learning about centripetal force. Specifically, having participants swing a trackable object overhead instead of using a mouse interface to control the simulation is a movement that maps coherently onto the learning domain (Lindgren et al. 2016) but also coincides with real-life experiences (Johnson-Glenberg et al. 2016). It is essential therefore to consider not only methods that make use of physical interactions but also how meaningful are the interactions to the teaching content.

## Utilizing the Body for Conceptual Development

Based on this premise, an increasing number of researchers and educators have shifted their focus to perception apart from conception, implementing interventions where the learner is able to develop a "feel" for the learning material, referred to as "the perceptual simulation," in addition to "knowing," cited as "the symbolic representation" (Black 2010). The embodied approach (Barsalou 2008; Gallese and Lakoff 2005; Pouw et al. 2014; Wilson 2002) has been used to cover the learning of abstract materials in a wide range of topics that extend from reading comprehension (Glenberg et al. 2004), and mathematics (Abrahamson 2014; Alibali and Nathan 2012; Nemirovsky et al. 2012; Ramani and Siegler 2008; Tran et al. 2017) to science (Han and Black 2011; Johnson-Glenberg et al. 2016; Johnson-Glenberg and Megowan-Romanowicz 2017; Kontra et al. 2015; Lindgren et al. 2016), technology, engineering and computational thinking (Fadjo 2012; Parmar et al. 2016).

Clearly, the domain of physics (Kontra et al. 2015) is an obvious choice for applying the embodied approach since we begin to develop a "feel" for basic physics concepts, like force and motion, from the moment our brain and body starts to experience the world. According to Enyedy et al. (2012), students do not enter school as a blank slate, but they develop intuitions about physical phenomena through continuous observations and interactions with the environment. Physicality plays an essential role in the development of students' ability to think and reason about formal physical laws and later as they enter school. For instance, in physical laboratories, learners do not passively observe the effects of physical phenomena, but they are expected to test their intuitions by engaging actively, through their senses, in various hands-on and embodied activities.

Apart from physical laboratories, computer simulations that make use of gestures and touch sensorimotor input (Chan and Black 2006; Han and Black 2011; Minogue and Borland 2016) have been considered as an innovative approach to support the teaching of abstract scientific concepts within the embodied framework. Specifically, in a study conducted by Chan and Black (2006) students investigated the functional relationship between the gravitational and kinetic energy through a roller coaster simulation. Participants assigned in the direct manipulation condition were asked to control the position-height of a roller coaster car and at the same time observed the changes in its kinetic and potential energy. They demonstrated better recall, problem-solving and transfer abilities than the students, assigned to more disembodied conditions, who just watched the animation without user control. Similarly, Han and Black (2011) utilized simulations augmented with haptic feedback to enhance elementary students' understanding of the movements of gears. Results of their study indicate that the augmented haptic simulations (force and kinesthetic and purely kinesthetic) provided richer perceptual experiences to students than the equivalent non-haptic simulation. Thus, information about the relevant physics concept was presented to participants not only through the visual and auditory channels but also through the haptic channel, helping them to create a multimodal representation of the gears' movements and offload cognition.

A practical learning approach, known as direct embodiment (Black et al. 2012), is to have students physically enact though natural movement the learning material. The notion of acting out is a core characteristic of the embodied process, and Gallagher and Lindgren (2015) refer to this as the "enactive metaphor." For example, Enyedy et al. (2012) reported how augmented reality embodied simulations could be used effectively to assist students to build meaningful connections between perceptuomotor activity and mental representations of Newtonian force and motion. The use of full-body interaction for learning physics principles, such as gravity force and planetary motion, through a mixed reality simulation, was the subject of research conducted by Lindgren et al. (2016). Results of the study indicate that students who used a full-body mixed reality simulation game obtained more knowledge about force and motion, showed higher levels of engagement, and more positive attitudes towards science compared to students who used the desktop version of the same simulation game. Similarly, Johnson-Glenberg et al. (2016) used a mixed reality simulation to facilitate college-age participants' understanding of centripetal force. The authors found higher long-term learning gains in physics for the subjects assigned to the "high embodiment" condition (swinging a tangible trackable object overhead) compared to those assigned to the "low embodiment" condition (using a mouse as interaction tool).

However, there is also the view that physicality does not always facilitate learning and in some cases might lead to cognitive overload and thus to lower learning gains (Pouw et al. 2014; Song et al. 2014; Skulmowski et al. 2016; Skulmowski and Rey 2018). Researchers, embracing this view favor the use of virtual laboratories over the physically enhanced ones for the development of conceptual knowledge. They do not regard physicality as a prerequisite for science learning (Zacharia et al. 2012) and draw an explanation from the fact that students might have already gained the necessary knowledge about a physical phenomenon through their previous sensorimotor experiences. Thus, the presence or absence of physicality in a simulation would not have a significant impact on the learning process. Evidence on these claims can be found in a study conducted by Zacharia et al. (2012) where students explored the concept of mass by observing its effect on a balance beam. Students with incorrect preconceptions of how a balance beam works profited more in the physical manipulative condition (real weights were used) compared to the virtual manipulative condition (virtual weight were used). As for students with correct preconceptions, the different conditions (physical vs. virtual) did not make any difference in their understandings about mass, as participants have already grounded the associated knowledge in their previous tactile experiences.

The above sample of embodied research studies highlights the need to further explore the positive learning effects of embodiment in science education. In response to this necessity, we set out to investigate whether diverse input interaction modalities (touch and hand gesture) with a different level of congruency, will make any difference in learning about friction.

H1: Students will acquire more knowledge about friction, using hand gesture as input interaction modality.

Hand gestures for triggering the movement of a tangible or virtual object seems to coincide with students' prior experiences because in real life when an individual wants to throw an object and observe its movement in space, he/she uses some hand gesture. Therefore, we believe that this type of input is more congruent to determine the initial velocity with which an object will move on a surface. Additionally, a more muscular movement will engage more sensorimotor systems that might lead to higher learning gains (Johnson-Glenberg et al. 2016), compared to touch.

## Virtual and Physical Surrogates

Apart from direct, another type of embodiment is surrogate where learners manipulate and observe an external representative (Black et al. 2012). The external surrogate might be a virtual character (Fadjo et al. 2009; Khan and Black 2014), a physical object (Glenberg et al. 2004), or a person (Lu et al. 2011), such as a student (Enyedy et al. 2012) or a teacher (Li et al. 2009). Specifically, Fadjo et al. (2009) introduced mathematical concepts (positive and negative numbers, and Cartesian coordinates) to children by asking them to manipulate virtual surrogates as they developed a video game in Scratch. Glenberg et al. (2004) found out that having students simulate the stories (about farms) they read using a set of toy manipulatives (farmers, animals) enhanced their reading comprehension. The stories describe in the text made more sense to students when they were actively manipulating representational objects, and consequently, this increased their understanding and memory of the text material. Finally, in Li et al.'s (2009) study, students participated in role-playing activities where they observed the teacher acting out the moves of a robot, before creating the program.

Besides virtual characters, toy manipulatives, or persons "digital manipulatives" (Resnick et al. 1996) can also be used as surrogates in scientific investigations. "Digital manipulatives" (Resnick et al. 1998) are computationally enhanced versions of traditional toys that enable children to explore mathematical, technologic, and scientific concepts through direct physical manipulation that would have been otherwise difficult to learn. Resnick (2001) believes that digital manipulatives can provide children with "conceptual leverage." A significant advantage is that children can interact with computers and learn in a more natural, familiar, and immediate way, engaging multiple senses (touch, vision, auditory) (Zuckerman et al. 2005). Digital manipulatives can communicate and interact with each other, but most importantly, they are programmable so students can determine for themselves how the toys should behave. For instance, BitBall (Resnick et al. 1998) is a computationally enhanced version of a traditional ball toy that enables students to explore scientific concepts in the domain of kinematics such as acceleration. Similarly, Curlybot (Frei et al. 2000) is a robot with kinetic memory and a pen attached to it. Curlybot can be utilized to teach mathematical and computational concepts as it can record and replay its movements drawing various geometric shapes. Topobo (Raffle et al. 2004) follows the same logic as it is a construction toolkit that enables the building of robotic creatures from parts that have kinetic memory. Topobo can be used as an external physical surrogate to help children explore the concepts of movement, balance, and gravity. It seems that the use of digital manipulatives, and especially robots, as physical surrogates in the learning process, is an innovative way to support scientific explorations. A notable example is an investigation by Han (2013). In her study, students enhanced their learning about physics (how gears work) by physically or virtually manipulating a physical (Lego robot) or virtual robot respectively. Thus, an additional issue of our research is studying the aspects of embodied learning with the use of a physical or virtual surrogate.

A number of empirical studies have previously compared the use of physical manipulatives and virtual manipulatives in the domain of science education (Jaakkola et al. 2011; Triona and Klahr 2003; Zacharia et al. 2012; Zacharia and Constantinou 2008; Zacharia and De Jong 2014; Zacharia and Olympiou 2011). Clearly, physical and virtual manipulatives vary in their affordances and each has its advantages (De Jong et al. 2013) over the other in supporting the development of conceptual knowledge. An obvious advantage of virtual laboratories is "that reality can be adapted to serve the learning process" (Zacharia and De Jong 2014). On the other hand, with the use of concrete materials, the learning process builds on the existing knowledge and experiences that students have acquired through their observations and interactions with the real world (Triona and Klahr 2003). Secondly, the cognitive activity is embedded in the physical environment (Pouw et al. 2014) and as learners are able to use extensively touch sensorimotor, the cognitive load imposed on them can be alleviated. Based on the above, we hypothesized that:

> H2: Using a real robot as an output modality will benefit the learning of friction concept more than using a virtual one.

We assumed that manipulating and observing a physical surrogate will benefit students more than a virtual one. The interplay between the individual, the physical robot and the environment may support more efficient the cognitive activity of the learner and facilitate the acquisition of conceptual knowledge.

## Materials and Methods

Kolb (1975) argued "that the learning process often begins with a person carrying out a particular action and then seeing the effect of the action in this situation. The second step is to understand these effects in the particular instance so that if the same action was taken in the same circumstances it would be possible to anticipate what would follow from the action. Using this pattern, the third step would be to understand the general principle under which the particular instance falls" (Kirschner et al. 2006). In our case, the objective was to have students carry out actions, such as touch and hand gestures, and then observe the consequences of their actions in the kinematics of a virtual or physical surrogate (Table 1). We measured students' views with a questionnaire. Furthermore, we applied pre-test and post-test questionnaires for the assessment of students' understanding regarding friction.

**Table 1** The four conditions of input-output interaction modalities

| Modalities | | Output | |
|---|---|---|---|
| | | Virtual | Physical |
| Input | Touch | Tap-screen | Tap-robot |
| | Hand gesture | Tilt-screen | Tilt-robot |

### Materials

We created four computationally enhanced conditions that corresponded to the different input and output interaction modalities used in our study (Table 1). For the physical conditions, we placed two similar robots in two trails with different friction coefficient, so students interacted with the physical surrogates observed their movement and drew conclusions about friction. For the virtual conditions, we replaced the real robots with virtual ones (Fig. 1). The physical were considered to be the conditions with a higher level of physicality as the physical actions of the user transformed into physical reactions on the kinematics of the robots. On the other hand, the virtual were the conditions with a lower level of physicality as users' physical actions respectively affected the kinematics of the virtual surrogates (Melcer and Isbister 2016).

Ollie robot[1] from Sphero supported the physical conditions. The Ollie robot was selected because it was cheap to obtain but the primary criterion for its selection was the availability of a blocks-based visual programming environment (Tynker[2]) on a tablet.

The input interaction modalities for triggering the movement of the virtual or physical objects, varied in the amount of kinesthetic and gestural congruency (Johnson-Glenberg et al. 2016) and were supported by tablet devices with an embedded accelerometer sensor (Fig. 2). Additionally, they varied in the amount of sensory engagement as tapping the screen has a different sense than tilt. Oviatt et al. (2012) believe that the keyboard and mouse have limited capabilities when interacting with animated characters and robots. However with mobile technologies, as tablets or smart devices, the interaction space is expanded "to more physical and embodied modalities" (Lindgren et al. 2016) as touchscreen and accelerometer-based interfaces that can be used to interact with digital information (Jacob et al. 2008).

We used tablets in all cases as the control devices. However, the virtual and physical conditions differ in the spatial location of the output in relation to the input, referred to as mapping (Melcer and Isbister 2016). Explicitly, the mapping in the physical conditions was considered to be discrete as the actions for triggering the effect were performed in the tablet, separately from the tangible robots where the movement took

[1] Ollie Sphero Robot: http://www.sphero.com/ollie
[2] Tynker: https://www.tynker.com

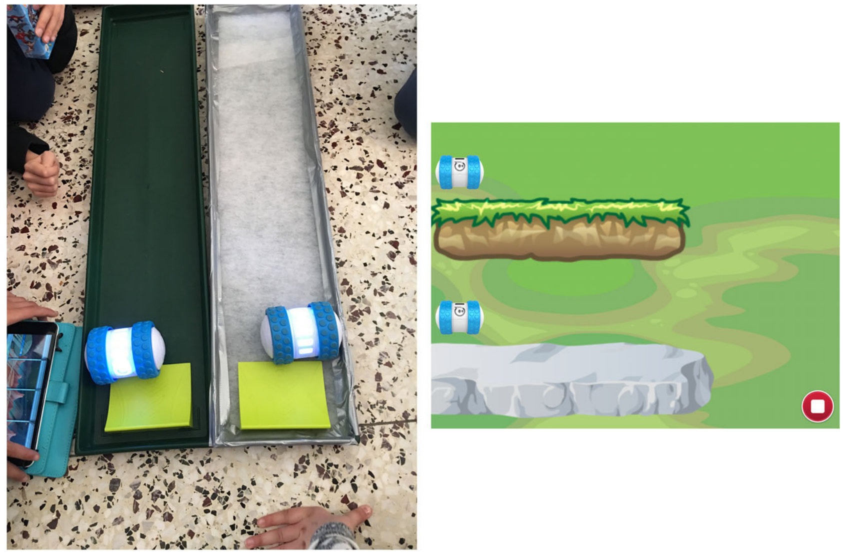

Fig. 1 The output modalities: physical (left) and virtual (right)

place. It should be noted that as children manipulate a digital or physical manipulative, their actions trigger effects on the same object, so input and output are embedded in the manipulative (Melcer and Isbister 2016). The difference in our approach is that participants manipulated an object (tablet) and their actions triggered reactions on another object (robot), so they controlled the surrogates through teleoperation. On the other hand, the mapping in the virtual conditions was assumed to be collocated as actions in the tablet triggered reactions in the virtual robots that moved on the tablet's screen (Fig. 3).

For each condition, we had to create the respective instructional material. Its creation was guided by the need to represent the same concept (friction) and a time constraint of completing the scenario in 45 min for each group. A 1-month pilot study guided the overall preparation. The activities were tested in an authentic classroom environment by 20 students, who were selected from the sixth-grade class of an elementary school, aged between 11 and 12 years. Students worked in pairs, and their feedback helped us refine the instructional material and the measuring instruments. The same researcher conducted both the preparation of the instrumental material and the tutoring of the courses.

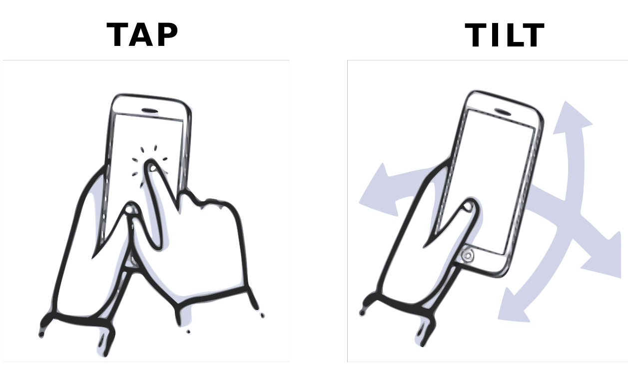


Fig. 2 The input modalities: touch (left) and hand gesture (right)

## Subjects

The participants were 56 students, who were randomly selected from the fifth-grade class (aged between 10 and 11 years) of four public elementary schools in central Athens. The sample was White; 50% were children of immigrants, equally divided by sex (28 girls and 28 boys) from lower to middle socioeconomic statuses. We created four independent groups, one for each condition: the tap-screen, the tilt-screen, the tap-robot, and the tilt-robot each with 14 children (Table 1). The decision for selecting this specific age group was guided by the fact that none of the students had previously received teaching regarding the concept of friction as part of previous formal education. Students worked in pairs in each of the activities. The criteria for matching the pairs of students were their skills, expertise, and existing friendships. By working in pairs, students were able to collaborate and support each other across the activities. Students voluntarily participated in the study. Nevertheless, their parents were informed and asked to give their permission by signing the necessary consent form.

## Measuring Instruments and Procedure

Firstly, we employed a five-level Likert demographic questionnaire to record the participants' engagement with technology. This questionnaire was given to students before the study and was filled in together with their parents. At the beginning of the experiment, we used a pre-test multi-choice questionnaire to measure students' preconceptions concerning friction. Participants completed the pre-test questionnaire individually. Afterward, students assigned in the tap-screen group were asked to program a virtual robot appearing on the tablet's touchscreen.

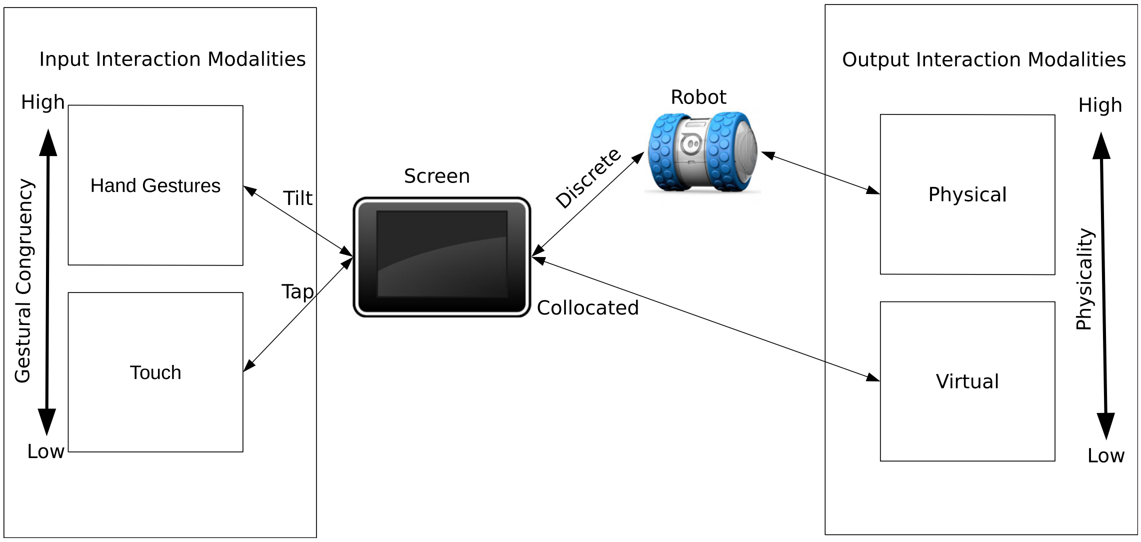


**Fig. 3** Block diagram showing overview of the interaction modalities, the conditions, and mapping

We gave them a basic program with two virtual robots placed in two different virtual trails, one with grass and one with ice. Students examined the program and made small changes by modifying some blocks, to create a simulation of the robots' movement on soil with different friction coefficient. A touchscreen interface with buttons was used to control the virtual robots. So students engaged touch sensorimotor in navigating the robots. In the second condition, the output was the same (virtual robots), but the input modality was different. Instead of using touch by tapping the buttons, students engaged hang gesture tracked by the tablet's accelerator. We asked the students to modify a program that applied a virtual force to the robots appearing on the screen depending on the movement of the tablet (tilt). In the third and fourth conditions, physical robots replaced the virtual ones and students assigned to these groups were asked to program the robots and control it using touch and hand gesture respectively. After the activity, we gave two post-test questionnaires to students, and they answered their questions individually. The first multi-choice post-test questionnaire included questions similar to the ones in the pre-test, allowing us to make a director comparison between the knowledge students had before and after the experiment and assess the learning gains of each treatment. The second was a five-level Likert questionnaire that recorded students' views towards the input and output interaction modalities.

Cronbach's alpha was computed as a measure of the internal consistency of the scales. Reliability of the knowledge assessment questionnaires was good: pre-test $a = .68$, post-test $a = .70$. The difference in the alpha level between pre-test and post-test can be explained by the fact that students' knowledge about friction before the treatment was less accurate than after (Jaakkola et al. 2011). Furthermore, an item discrimination analysis was conducted to check how each multi-choice question was related to the overall assessed performance. Specifically, the point-biserial correlation coefficient, for each question of the pre-test compared to the overall test score performance, was between $r_{pb} = 0.375 - 0.561$, with significant values. Similarly, for the post-test questionnaire, the point-biserial correlation coefficient for each question was between $r_{pb} = 0.273 - 0.556$, with significant values.

## Results

The mean averages of the participants' answers in the demographic questionnaire can be found in Table 2. Since they were randomly selected from the fifth-grade, we expected that the independent groups would be equivalent before any treatment. The Kruskal-Wallis non-parametric test was used to assess statistical differences on the answers' given in the demographic questionnaire, due to the relatively small sample size (14 per group) and the fact that the data were not normally distributed. The Kruskal-Wallis tests verified that no significant difference

**Table 2** Descriptive statistics from the demographic questionnaire

| | | | Engagement with technology | |
|---|---|---|---|---|
| | Group | *n* | *M* | SD |
| 1 | Tap-screen | 14 | 3.00 | 1.359 |
| 2 | Tilt-screen | 14 | 3.07 | 1.207 |
| 3 | Tap-robot | 14 | 3.00 | 1.177 |
| 4 | Tilt-robot | 14 | 2.86 | 0.864 |

was found in students' engagement with technology ($H(3) = 1.485$, $p = .683$) between the independent groups.

## Students' Knowledge About Friction

The Kruskal-Wallis test was also applied to determine whether there were differences in students' knowledge improvement between the conditions (Table 3). The results indicated that no significant difference, $H(3) = 6.459$, $p = .091$, was found between the groups.

Additionally, four Wilcoxon signed-rank tests were applied to verify whether there was a significant statistical difference in the learning impact of each condition. Concerning the tap-screen group, students' knowledge about friction after the treatment (Mdn = 3.36) was significantly higher than knowledge before the treatment (Mdn = 1.36), $T = 78$, $p = 0.002$, with large effect size ($r = 0.58$). A substantial increase, $T = 75.5$, $p = 0.004$, $r = 0.54$, was also found in students' knowledge about friction after (Mdn = 3.29) and before the treatment (Mdn = 1.57), in the tilt-screen group. Regarding the tap-robot group, student's friction knowledge after the treatment (Mdn = 3.86) was significantly higher than knowledge before the treatment (Mdn = 0.79), $T = 105$, $p = 0.001$, $r = 0.62$. Finally, in respect of the tilt-robot group, students' friction knowledge after the treatment (Mdn = 3.21) was significantly higher than knowledge before the treatment (Mdn = 1.00), $T = 66$, $p = 0.003$, $r = 0.55$.

### Knowledge Improvement Using Touch vs. Hand Gesture

First, we investigated whether the students who used hand gestures for triggering the movement of the virtual or physical robots acquired more knowledge compared to those that used touch ($H1$). The mean improvement of participants' knowledge according to the input interaction modalities can be found in Table 4. The Mann-Whitney $U$ test was used to compare the differences between the two independent conditions. For students who used touch for triggering the movement of the robots the improvement (Mdn = 2.54) was similar to those who used hang gestures (Mdn = 1.96), $U = 305$, $z = -1.455$, $p = 0.146$, $r = -0.20$.

### Knowledge Improvement Using Physical vs. Virtual Surrogates

Furthermore, we examined whether the physical conditions supported students to acquire more knowledge compare to the virtual ones ($H2$). The mean improvement of participants' knowledge according to the output interaction modalities can be found in Table 5. The Mann-Whitney $U$ test was used to compare the differences between the two conditions. For students who used the physical surrogates, the improvement (Mdn = 2.64) was significant greater than those using the virtual surrogates (Mdn = 1.86), $U = 509$, $z = 1.956$, $p = 0.050$, $r = 0.26$.

Afterwards, we investigated students' improvement about friction based on their preconceptions. According to Fig. 4, it seems that the use of a physical surrogate benefited more students with limited initial knowledge about friction, as recorded in the pre-test questionnaire. For instance, participants with zero correct answers in the pre-test improved more in the physical condition (Mdn = 4.25) than in the virtual (Mdn = 3.83). Similarly, the improvement was higher for participants that initially gave only one correct answer in the pre-test. However, for participants that initially gave two correct answers, the opposite was true: higher improvement with the use of a virtual surrogate (Mdn = 1.58) than with the use of a physical (Mdn = 1.00).

## Students' Views About the Interaction Modalities

We also examined students' views by comparing the input to the output interaction modalities. Three aspects were measured and compared: how accurate, how fun, and how easy to use each condition was.

Initially, the comparison had four perspectives due to the possible conditions of input-output modalities used in our study (Table 6). First, we compared touch (tap) to the output modalities and hand gesture (tilt) to the output modalities. No significant statistical difference was found in students' views when dealing with touch input and the different outputs (virtual and physical). Respectively, the inductive statistical analysis showed no difference in the students' views when dealing with hand gesture input and the different outputs. Then, we

**Table 3** Descriptive statistics and effect sizes for students' knowledge about friction

| | | | Before | | After | | Improvement | | |
|---|---|---|---|---|---|---|---|---|---|
| | Group | n | M | SD | M | SD | M | SD | Effect size |
| 1 | Tap-screen | 14 | 1.36 | 0.842 | 3.36 | 1.008 | 2.00 | 1.301 | 0.58 |
| 2 | Tilt-screen | 14 | 1.57 | 1.222 | 3.29 | 0.914 | 1.71 | 1.590 | 0.54 |
| 3 | Tap-robot | 14 | 0.79 | 0.579 | 3.86 | 0.864 | 3.07 | 1.269 | 0.62 |
| 4 | Tilt-robot | 14 | 1.00 | 0.877 | 3.21 | 1.222 | 2.21 | 1.626 | 0.55 |

**Table 4** Students' knowledge improvement according to the input modalities

| | Modalities | $n$ | Mean improvement | SD |
|---|---|---|---|---|
| 1 | Touch | 28 | 2.54 | 1.374 |
| 2 | Hand gesture | 28 | 1.96 | 1.598 |
| | Total | 56 | 2.25 | 1.505 |

compared virtual to the input modalities and robotic to the input modalities. No significant statistical difference was found in students' views when dealing with different input (touch and hand gesture) and the same virtual output. Similarly, students' positive views assigned to the group with touch input and robotic output did not differ significantly from the views reported by students assigned to the group with hand gesture input and robotic output.

As a final step, we compared touch and hand gesture input regardless of the output modalities (Table 7). Three Mann-Whitney $U$ tests applied to verify whether there was a significant statistical difference in students' views when dealing with different input modalities. Students found touch (Mdn = 3.32) significantly easier to use than hand gesture (Mdn = 2.68), $U = 261$, $z = -2.265$, $p = 0.024$, $r = -0.30$. However, students reported that touch interface was not more accurate (Mdn = 2.64) than hand gesture (Mdn = 2.36), $U = 321.5$, $z = -1.200$, $p = 0.230$, $r = -0.16$. Finally, participants did not find using touch input (Mdn = 2.64) more fun than tilt (Mdn = 2.64), $U = 314$, $z = -1.360$, $p = 0.174$, $r = -0.18$.

## Discussion

The purpose of this study was to investigate how different input and output interaction modalities can affect students in exploring the concept of friction. We asked students to carry out actions, such as touch and hand gestures, and then observe the consequences of their actions in the kinematics of a virtual or physical surrogate. Four independent groups that corresponded to the possible conditions of input-output modalities were created. Our results suggest that students' knowledge about friction in all groups was increased significantly (Table 3).

**Table 5** Students' knowledge improvement according to the output modalities

| | Modalities | $n$ | Mean improvement | SD |
|---|---|---|---|---|
| 1 | Virtual | 28 | 1.86 | 1.433 |
| 2 | Physical | 28 | 2.64 | 1.496 |
| | Total | 56 | 2.25 | 1.505 |

### Balancing Congruency with Familiarity

As we were interested in the learning impact of the input interactions modalities, we hypothesized that students who used hand gestures for triggering the movement of the virtual or physical robots would acquire more knowledge about friction compared to those that used touch ($H1$). Usually, a hand gesture is required to trigger the movement of an object. Thus, hand gesture was assumed to be more congruent to the learning task. Moreover, higher sensorimotor engagement (Johnson-Glenberg et al. 2016) as moving the tablet with your hand would be more efficient than using just your fingers to touch the tablet's screen. However, the current study did not support this hypothesis, as the analysis revealed that the mean improvement was higher in the touch conditions (Mdn = 2.54) than in the hand gesture (Mdn = 1.96). Nevertheless, no significant statistical difference was found in the learning impact of the input modalities.

A possible explanation is that students are more familiar using the touchscreen interface for the operation of the tablet device than the accelerometer-based interface. Besides students' prior perceptional experiences with the learning content (Han 2013), participants' familiarity with mobile devices may have influenced their understanding. Thus, using a more complex interface (Skulmowski et al. 2016) in the hand gesture task is likely to impose a higher cognitive load on students than the touchscreen task. The additional load might overwhelm students, hindering their learning performance. This finding is concurrent with results from previous studies, embracing the cognitive load theory that higher interactivity might lead to lower learning outcomes (Skulmowski et al. 2016; Song et al. 2014). Additionally, if we take into account that students found the touchscreen interface significantly easier to use (Table 7), hand gesture might have required additional motor coordination and the involvement of bigger muscle group (Zhai et al. 1996) than fingers. This substantial effort for achieving adequate motor precision to control the robot might have also added cognitive load to students influencing their understanding (Skulmowski et al. 2016). The affordances of specific input devices may affect an individual's ability to perform optimally at some tasks (Card et al. 1978; Zhai et al. 1996). Hence, it may be important to consider balancing congruency and user interface familiarity to gain better access to conceptual scientific knowledge.

### Physicality's Contribution to Learning

The utilization of a virtual or physical surrogate for enhancing learning was another aspect of our study. We hypothesized that the use of a physical surrogate as an output modality would be more efficient regarding knowledge transfer than the use of a virtual one ($H2$). The statistical analysis revealed that the learning gains in the physical conditions were

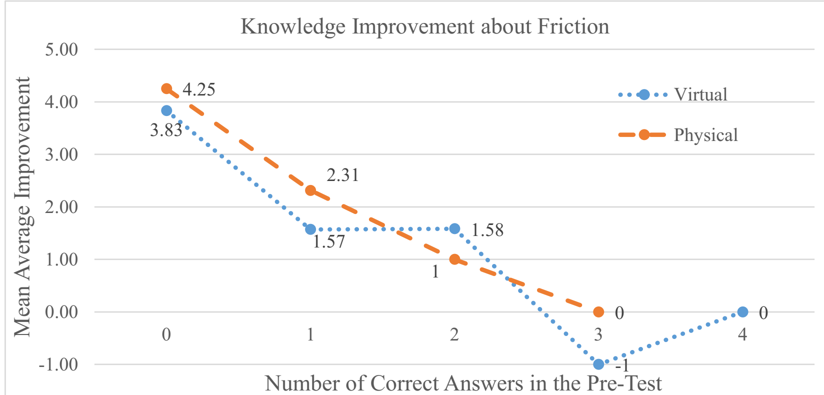


**Fig. 4** Students' knowledge improvement about friction according to the number of correct answers given in the pre-test and the output modalities

significantly higher than the gains in the virtual ones. This finding contradicts results that show that the use of virtual manipulatives is more or equally educationally effective as the use of physical manipulatives (Han 2013; Triona and Klahr 2003; Zacharia and Olympiou 2011). However, it is consistent with previous research emphasizing the importance of digital manipulatives in the learning process (Resnick et al. 1996; Zuckerman and Gal-Oz 2013). Additionally, the physical conditions benefited those learners who had misconceptions or limited initial knowledge about friction. This finding concurs with Zacharia et al.'s (2012) findings that physicality has a significant impact only on students with incorrect preconceptions. For students with correct preconception, physical manipulations were as effective as the virtual ones in learning physics concepts.

The question raised is why the physical conditions were more conducive to learning than the virtual ones. The answer may lie not only in the physicality of the surrogate agent, but also in the affordances of the environment, either virtual or real, where the agent acts. Although our intention was to create a virtual simulation as similar as possible to the physical representation, some of the affordances of the real world might not have been included. Specifically, it was not possible to incorporate in the virtual simulation environment properties such as the actual "look and feel" of the two trails' surface or the sense of the robot's weight (Zacharia et al. 2012). Thus, the model of the simulation was, to an extent, simplified. As a result, in the physical conditions novice students had better access to observations as the perceptual and interactive richness highlighted different aspects of the content being learned (Jaakkola et al. 2011). Maybe the virtual conditions would be more or equally conducive to students' learning if we have adapted the virtual model to provide learners with a more comprehensive view of the underlying scientific mechanism (Jaakkola et al. 2011).

Previous well-established educational practices promote either the physical enactment of the learning material (direct embodiment) or the manipulation of an external physical or virtual representative (surrogate embodiment). With our approach, participants carried out actions on a tablet and observed the effects on virtual or physical agents. Compared to direct manipulation where the input and output are embedded in the same object, in the physical conditions, the input and output were discrete. Hence, we adopted a form of surrogate embodiment that involved manipulation of the robots from a distance. Teleoperation enabled students to control the experiment flexibly, using devices that are appealing to them. This form of surrogate embodiment could be further applied in educational settings where the experimenter explores scientific phenomena that cannot be observed easily through direct manipulation. For example, controlling the behavior of a robot underwater (Phamduy et al. 2015) or in the air.

## Limitations

A limitation of the current study was the relatively small number of participants in each condition (14 students). A second limitation is that time restriction (45 min) was imposed on each treatment as we conducted the study in an authentic

**Table 6** Descriptive statistics for students' views about the interaction modalities

| | How accurate | How fun | How easy | | | |
|---|---|---|---|---|---|---|
| Group | Screen | Robot | Screen | Robot | Screen | Robot |
| Tap | 2.71 | 2.57 | 3.00 | 3.36 | 3.50 | 3.14 |
| Tilt | 2.29 | 2.43 | 2.36 | 3.00 | 3.00 | 2.36 |

**Table 7** Descriptive statistics for students' views about the interaction modalities

| | How accurate | | How fun | | How easy | |
|---|---|---|---|---|---|---|
| Modalities | *M* | SD | *M* | SD | *M* | SD |
| Touch | 2.64 | 1.062 | 3.18 | 0.983 | 3.32 | 0.819 |
| Hand gesture | 2.36 | 1.026 | 2.68 | 1.362 | 2.68 | 1.090 |

classroom environment. A third limitation of our study is that the assessments used may not have been sufficient or sensitive enough to measured students' understanding about friction. More embodied-oriented approaches and methods for the evaluation of the acquired knowledge should be adopted (Lindgren and Johnson-Glenberg 2013). Additionally, we did not measure the long-term learning gains, although there are clues (Lindgren and Johnson-Glenberg 2013) that "high embodiment" conditions are likely to lead to more significant long-term conceptual benefits. Thus, the above factors limit the ability to generalize the findings of our study.

## Conclusion

The contribution of this paper is to provide additional insight into the synergy between embodiment and the use of computationally enhanced objects for promoting conceptual development. We attempted to measure the learning effect of employing different modalities for interacting with virtual and physical robots instead of exploring the learning outcomes by comparing a tangible interface to a virtual one (Zhu et al. 2016). The results suggest that students with misconceptions can gain a better understanding of friction when they have the opportunity to use a physical instead of a virtual surrogate. Overall, the current findings provide a number of practical implications for teaching abstract concepts and for applying the embodied approach to the field of science education. Specifically, teachers are encouraged to design and incorporate embodied activities in their classes where the learner is able to interact with various types of manipulatives and with diverse modalities (touch, movement, speech, vision). It is essential to acknowledge that each type of manipulative, due to its unique affordances, may provide alternative learning opportunities to all students, regardless of their mental status. For instance, novice students could take advantage of the interactive richness of computationally enhanced concrete materials, while more advanced students could proceed to more disembodied learning stages within a virtual learning environment. Others (Jaakkola et al. 2011; Zacharia and De Jong 2014) have already advocated the importance of combining virtual and physical manipulatives. This synergy not only may offer the optimal affordances to students for their scientific explorations (Zacharia and De Jong 2014) but can also make it easier for them to bridge the gap between the real and the virtual, thereby leading to a deeper understanding of scientific phenomena.

A further study is needed with more significant numbers of participants and additional activities to confirm and generalize the findings of our research. Additionally, more nuanced and embodied-oriented assessment methods should be used, measuring not only the short-term but also the long-term learning gains (Lindgren and Johnson-Glenberg 2013) and the ability to transfer the acquired knowledge in related domains (Han 2013). As a future investigation, it would also be interesting to manage the cognitive load imposed on students by controlling their familiarity with a particular interaction interface and examine their learning performance. Besides touch and hand movement, we intend to employ diverse input modalities as speech and full-body movement (Malinverni and Pares 2014), so we can have a more nuanced understanding of the attributes that facilitate particular user interaction styles. Instead of using virtual or physical robots as surrogates it would be interesting to utilize a direct embodiment approach where students could have the opportunity to feel friction through full-body interaction in a virtual or mixed reality environment (for example playing with a skateboard simulation). Also, we should take special consideration for children with physical limitations by providing them the appropriate interaction modalities in the learning process. Finally, future research might also examine the use of different target platforms (Merkouris et al. 2017), such as wearables, or drones, for the execution of code as a means to introduce abstract concepts related to movement in three dimensions, orientation, and gravity.

## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

**Ethical Approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed Consent** Informed consent was obtained from all individual participants included in the study.

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