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Using Makey-Makey for teaching electricity to primary school students. A pilot study

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Abstract

Primary school students find it difficult to grasp concepts related to electricity. On the other hand, tangible user interfaces, such as Makey-Makey, offer an interesting alternative for teaching this subject. In order to examine whether the above holds true, a pilot project was carried out, having as a target group 75 students aged 10–11, divided into three groups. Everyday materials for making circuit boards were used for the teaching of the first group, simulations were used in the second, and in the third Makey-Makeys were utilized. Bybee's 5Es was the teaching framework applied to all groups. The project lasted for eight two-hour sessions for each group. Data were collected using evaluations sheets and a short questionnaire. The results' analysis demonstrated that the learning outcomes of students that used Makey-Makey were better compared with the other two groups. This result suggests that students in this group established a solid base of functional as well as procedural knowledge regarding electricity. Then again, no significant differences were noted between the group that used simulations and the group that used Makey-Makey in terms of motivation and enjoyment. The findings point to the need of providing educators with software tools that will assist them in using Makey-Makey more efficiently. Furthermore, when intending to use it for teaching a subject, they should reflect on whether this device has clear advantages over other tools and what meaningful activities can be conducted. An appropriate teaching framework is also advised.

Keywords Electricity · Makey-Makey · Primary school · Simulations

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1 Introduction

The teaching of science courses in all levels of education is a challenging task. In fact, research spanning for decades demonstrated that students' pre-instructional beliefs and knowledge about natural phenomena are not only in conflict with their scientifically correct counterparts but they are also deeply rooted in students' minds, making conceptual change difficult (Duit and Treagust 2003). Students' own observations and interpretations of the world surrounding them, as well as family members, friends, and acquaintances, are the initial (and probably the most significant) sources for these false understandings (Kibuka-Sebitosi 2007; Pine et al. 2001). Inappropriate teaching methods (Levy Nahum et al. 2010) and errors in the textbooks (Zajkov et al. 2017) have also been identified as sources of students' problems in science-related subjects. Researchers have also reported that teachers (in all levels of education) sometimes lack knowledge as well as basic understanding of natural phenomena (Antink-Meyer and Meyer 2016; Cheung et al. 2009; Kaltakci-Gurel et al. 2016; Kilty and Burrows 2019). In fact, as they cannot offer scientifically appropriate explanations (Flynn 2011), their teaching is often shallow and they default to traditional instruction (Burden and Kearney 2016). As a result, students' performance is far from being considered as satisfactory (Forsthuber et al. 2011).

The teaching of topics related to electricity is not immune to the above problems. As we will further elaborate in the coming section, it seems that there is not a single concept related to electricity not causing some trouble to students and adults alike, rendering it one of the most problematic subjects in science learning (e.g., Lee 2007; Peşman and Eryılmaz 2010; Shipstone 1984). Since the situation does not seem to change much through the years, it is not an overstatement to say that it is still a pressing and worth examining issue. Moreover, as technology evolves, new tools emerge bearing the promise to ease existing problems. Then again, integrating any of these tools into instruction, requires studies that prove (or disprove) the feasibility of such an endeavor, provide evidence for their impact on the learning outcomes, and suggest instructional frameworks that exploit their advantages.

A much promising category of such technological artifacts can be described with the term "tangible user interfaces, TUIs." In short, TUIs are devices/interfaces that allow users to interact with digital information by manipulating physical objects/materials (Ishii 2008). Their educational use is grounded on Papert's views, as well as on the Embodied Cognition theory and its derivatives. Indeed, Papert (1980) accentuated the importance of students' active participation in the learning process, through the construction and sharing of artifacts. Similarly, the Embodied Cognition theory emphasized the need for tangibly engaging learners with objects, as this fosters the understanding of concepts related to these objects (Lindgren et al. 2016).

A device that falls into the TUI category, is Makey-Makey that is used quite extensively in education with noteworthy results (e.g., Abrahams 2018; Barrios et al. 2018; Palaigeorgiou et al. 2017). On the other hand, research involving the use of Makey-Makey in the teaching of subjects related to electricity is rather limited. Having the above in mind, the research question the study at hand sought to answer was: "Is Makey-Makey an effective tool for teaching concepts related to electricity to primary school students?" For answering this question, we designed and implemented a pilot project, details of which are presented in the sections to follow.

2 Background

Almost four decades of research accumulated irrefutable evidence that electricity is a learning subject infested with problems (Guisasola 2014). In fact, in an effort to systemize these problems, researchers grouped them into several models:

- The unipolar/non-recursive model. Students think that one wire is sufficient for providing power to a device, the other wire(s) have no current at all (Peşman and Eryılmaz 2010).
- The attenuation model. Students believe that the current loses its "power" as it travels in a circuit (McDermott and Shaffer 1992); the further a bulb is from a battery, the dimmer it will light (Tarciso Borges and Gilbert 1999), and less current will return to the source (Lee 2007).
- The source and sink model Quite often, students visualize electricity as some kind of liquid or water flowing from the power source (e.g., a battery) to the devices through the wires (Peşman and Eryılmaz 2010).
- The clashing current model. In serial circuits, students either believe that all the devices share equally the current (Shipstone 1984) or that the electricity flows from both sides of a source, collides inside a device, and the electric "matter" is converted to energy (Shipstone 1984).

Other problems related to the understanding of electricity include the following:

- Students view the battery as the container of electricity and not as a source of potential difference (Engelhardt and Beichner 2004). Moreover, very few understand the chemical reactions taking place inside a battery (Lee 2007).
- The understanding of short circuit is also problematic, as students believe that a device will still work despite the presence of a conducting wire short-circuiting it (Heller and Finley 1992).
- Insulators are understood in the context of preventing electrocution, while conductors are generally described as materials that allow the flow of current (Azaiza et al. 2006).
- Finally, it was found that there is a compartmentalization of knowledge; students cannot link concepts related to static electricity and concepts related to electrodynamics (Eylon and Ganiel 1990).

It seems that depending on students' age the prevailing models are different. For instance, kindergarten students view electricity as being static inside wires (Solomonidou and Kakana 2000), younger primary school students view electricity as a flow of a liquid, while, at an older age, they view it as moving particles but they still mix electrons, protons, and neutrons (or they just refer to particles) (Azaiza et al. 2006). Others found that the unipolar model is common among eight-year-olds, the clashing current model prevails at ages nine to ten, and at ages eleven to twelve the decreasing current model is the most common (Azaiza et al. 2006). On the other hand, certain problems persist into adulthood. A typical example is that of a video recording which shows MIT and Harvard graduates not being able to make a simple circuit using batteries, wires, and bulbs (Schneps and Sadler

1997). University students also have a limited understanding of basic concepts such as Ohm's law, even if they have the necessary mathematical skills to solve the relevant problems (McDermott 1991). Finally, the clashing current model was evident even in pre- or in-service teachers (Lee 2007).

Several reasons cause this situation. Whether students' knowledge prior to instruction is to blame remains debatable. That is because some argued that students do not know much about electricity before coming into class; therefore, the way we teach them is problematic (Maharaj-Sharma 2011). Others suggested that the curriculum at the primary level has to be rearranged; concepts related to electric current should be at the forefront rather than the concepts related to energy (Osborne 1983). Regardless of which of the above holds true, the multitude of students' difficulties indicate that they have trouble understanding electricity's core concepts (i.e., conceptual "building blocks" that advance the understanding of a subject), as well as mastering threshold concepts (i.e., concepts which, when understood, transform a person's perception for a given subject or phenomenon) (Meyer and Land 2003). It seems that electricity is somehow "alien" to students or even intellectually absurd, resulting to what Perkins (1999) described as "troublesome knowledge." What is more, not being able to grasp the basics, their performance is negatively affected, initiating yet another cycle of limited understanding in the concepts to follow (Choi and Chang 2004). Probably, most problems emerge from the fact that the electric current is invisible; merely seeing a bulb to turn on, does not mean that students can imagine or understand the flow of the electric charge. As Chapman aptly put it: "much of the science takes place inside the wire" (Chapman 2014, p. 5); such an abstract concept requires better visualization technics (Choi and Chang 2004).

Making simple circuit boards and conducting experiments using everyday materials is the prevailing visualization method when teaching electricity. Besides that, computer simulations are also powerful visualization tools. Simulations are the interactive, manipulable digital representations of real or hypothetical situations/phenomena (Plass et al. 2009). The use of simulations in courses related to electricity is not new. Then again, they are most commonly used by high-school students, college/university students, and teachers (e.g., Aktan 2012; Kollöffel and de Jong 2013; Zacharia and de Jong 2014); fewer studies examined the use of simulations in primary school (e.g., Falloon 2019; Jaakkola et al. 2011). However, it is generally accepted that simulations assisted knowledge building, as they helped the visualization of otherwise abstract and invisible phenomena (Wang and Tseng 2018). Conceptual change, as well as a decrease in students' misconceptions regarding electricity, has also been noted (Ramnarain and Moosa 2017).

3 Makey-Makey

Makey-Makey is a simple device implementing the Human Interface Device protocol easily connected to any computer using a USB port, no additional software or drivers are required (Fig. 1). With the provided alligator clips, it can be linked with conductive materials/objects making closed circuits. Because it uses high resistance switching (22MΩ pull-up resistors), it can sense closed switches even if the materials' conductivity is very low (e.g., skin, leaves, and food). When a switch is closed, this action is translated into a mouse or a keyboard click that can be used as an input command by any software. As a result, any material able to conduct even the slightest electric current is turned into an input device, a nature-based TUI (Collective and Shaw 2012).

Several theories and views on cognition provide the framework for the use of Makey-Makey in teaching/learning. For Papert (1980), active engagement in artifacts' construction, which are later shared and criticized by others, fosters learning. In Human-Centered Design (HCD) the focus shifts from the (technological) artifacts to the human factor, emphasizing individuals' needs, skills and abilities; in short, technology has to adapt to the individual and not vice-versa (Norman 2005). HCD instruments make things better for humans (UNICEF 2016) and society regards them as valuable resources (OECD 2017). HCD views computers and other digital artifacts not as productivity tools but as the means to fulfill tasks that are sophisticated and exceptional (Stephanidis 2001). In an educational context, HCD enhances creativity, provides rich learning experiences, and encourages collaboration (UNICEF 2016).

The Grounded Cognition theory postulated that situated action, modal simulations, and bodily states, trigger cognition (Barsalou 2008). Extending this idea, the Embodied

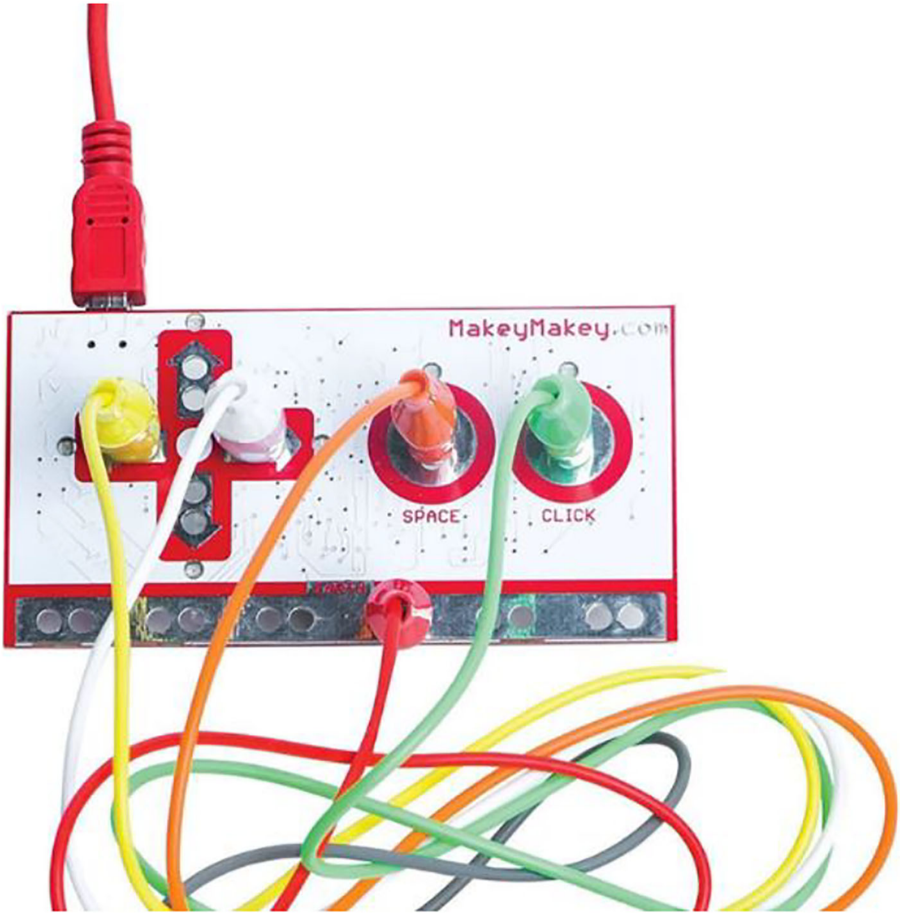

Fig. 1 A Makey-Makey board

Cognition theory (as well as several closely connected frameworks) suggested that when individuals are tangibly engaged with objects, there is an impact on the way they think about them; physicalizing processes and relationships provide the conceptual foundation upon which new knowledge is built (Lindgren et al. 2016). To put it differently, physical interaction with objects, besides increasing learners' engagement by immersing them into meaningful/authentic activities, helps them to understand even abstract concepts (Atmatzidou and Demetriadis 2016; Eguchi 2016) and even if they belong to "difficult" learning domains such as maths and science (Manches et al. 2010). Others put more emphasis on manipulability rather than on physicality, as they argued that overly rich physical activities may distract students, thus, learning is negatively affected (Zacharia and Olympiou 2011). Nonetheless, there is an agreement that practice through physical manipulatives has a positive impact on problem-solving skills, collaboration (even between individuals with mixed skill-levels) (Johnson et al. 2016), as well as on knowledge retention and transfer (Carbonneau et al. 2013).

Putting into practice the above, Makey-Makey has been used in a quite large number of occasions and countries, either in the context of organized scientific projects examining its potential or in real-life conditions (e.g., school projects). Indeed, the multiplicity of research reporting the results from the use of Makey-Makey either by itself or together with other devices/applications (e.g., augmented reality and programming languages) and in terms of target groups and learning domains, is hard to fit in a literature synopsis. For example, in a creativity workshop, elderly people (up to 90 years old) used Makey-Makey for being involved in music-making (Rogers et al. 2014). At the other end of the age spectrum, it was used by preschoolers for artistically expressing themselves with food traces (Chen et al. 2019) or for creating paper prototypes of rockets and paper circuits for launching them (Hershman et al. 2018). Primary school students learned about time (Palaigeorgiou et al. 2017). Making tangible games using Makey-Makey (together with Scratch) for fostering programming skills and computational thinking seems to be a rather common practice in both primary and secondary education (e.g., Lee et al. 2014; Vasudevan et al. 2013). The same applies to arts/music (for enhancing creativity) (e.g., Abrahams 2018; Chen and Lo 2019) and maths (Barrios et al. 2018). Makey-Makey was also used, having as target group younger students, in the context of special education (Calleja et al. 2015; Lin and Chang 2014), for fostering higher-order thinking skills (Lozano Mahecha et al. 2016) and for stimulating language skills (Choosri et al. 2017). Teachers also benefited as they learned how to gamify the learning process (Xefteris and Palaigeorgiou 2019) and developed skills in using technology during their teaching (e.g., Matthews et al. 2018; Scaradozzi et al. 2019).

Almost uniformly, the relevant studies reported positive results in terms of skills learned, knowledge acquisition, motivation, fun, and engagement. Then again, our literature review revealed just a handful of studies involving the use of Makey-Makey for teaching concepts related to electricity to primary school students (e.g., Davis et al. 2013; Smith and Smith 2016). It seems that most researchers try to find innovative and flamboyant applications of Makey-Makey, neglecting the most basic one; by default, Makey-Makey is the ideal tool for teaching electricity. Not only that, but the use of TUIs is an emerging study area while the research is spread too thin across an assortment of subjects and target groups. As a result, research in this field is not adequately systematized; we still need empirical evidence for Makey-Makey's usefulness. In addition, we observed that a considerable volume of the research projects we reviewed based their conclusions on small sample sizes and few teaching interventions, raising questions for their results' generalizability. Finally, we noticed that a quite a large number of projects utilized a pre-post study design and did not compare the outcomes with other tools or instruments (e.g., lab simulations or actual circuit boards). As a result, we decided to set forth the following hypotheses:

- H1. The use of Makey-Makey for teaching concepts related to electricity to primary school students yields better learning outcomes compared with the use of other tools and applications.
- H2. Students consider Makey-Makey as more effective and easier to use tool, are more motivated to learn, and enjoy their teaching more, compared with the use of other tools and applications.

4 Method

On the basis of the gaps and uncertainties we identified in the preceding sections and the research hypotheses that emerged, we designed and implemented a pilot project. We chose a quasi-experimental design with two control groups and one experimental as we collected data from whole classrooms. The project lasted for eight two-hour sessions for each class (a total of twenty-four two-hour sessions), from mid-November 2018 to mid-February 2019.We present further details for the project in the coming sections.

4.1 Participants

According to the Greek program of study for primary schools, students are taught subjects related to electricity in the fifth grade (ages ten to eleven). Logically enough, our target group was students of this age. We applied the following set of criteria, so as to achieve a "typical" and "ordinary" sample" (Creswell and Poth 2017): (i) students to have never used Makey-Makey, (ii) classes to reflect the spread of ability of a typical fifth-grade class, and (iii) the ratio of girls and boys to be, once again, close to that of a typical fifth-grade class. After contacting a number of public primary schools in Preveza, we selected three classes having twenty-five students each and we randomly assigned to them a teaching tool described in the "Materials" section. In order to comply with the rules for conducting research with minors, we took the following measures: (i) we applied and we were granted a research approval from the University's ethical committee, (ii) we briefed students' parents and we asked for their written agreement for their children's participation, and (iii) we also briefed the schools' headmasters and the classes' teachers for the study's objectives. In addition, we asked the teachers to follow the teaching procedure we presented to them during this meeting (described in the "Procedure" section).

4.2 Materials

The fifth grade's Physics school textbook was the basis for the teaching/learning material we used. We wrote a booklet in which, in essence, we re-arranged the textbook's sections for electricity and we added supplementary content, so as (i) to thoroughly cover all aspects of the subjects discussed in these sections and (ii) to deal more effectively with students' problems on electricity (as presented in the "Background" section). Therefore, we formed a total of four discrete units, each having two sub-units: (i)"Why the lights turn on?" including concepts related to electrons, electricity (e.g., static electricity, alternating and direct current), historical facts, and definition of terms, (ii) "A simple circuit and switches" also including concepts related to batteries and generators, (iii) "Conductors, insulators, and semiconductors" also discussing diodes, transistors, and electronics, and (iv) "Parallel and serial circuits" also including electrical appliances at home and safety precautions (e.g., guideless for avoiding electrocution). Given the large number and multiplicity of students' problems related to electricity, as already presented, we decided to place "reminders" of basic concepts and ideas throughout the booklet when the topic discussed in a sub-section was related with concepts discussed in a previous one.

It was essential to us to engage students in a "learning by doing" process, namely by conducting experiments. That is because we believe that students' active engagement in situations in which their knowledge is applied, results in better learning outcomes (Ertmer and Newby 2013). Indeed, the textbook suggests a quite large number of such activities using everyday materials. For example, students can make simple circuit boards using pieces of wire, batteries, bulbs, and clips (for switches). Thus, we decided one class/group of students to use such materials (Fig. 2).

Given that simulations are also used when teaching electricity, we searched for software with which the same experiments as the ones included in the textbook could be carried out. One such is Physics Education Technology (PhET) simulations (https://phet.colorado.edu/). In fact, PhET is a whole suite of research-based simulations for teaching/learning chemistry, maths, and physics. It was developed by Laureate and Wieman at the University of Colorado Boulder and it is an open educational resource project for improving how science is learned (Wieman et al. 2008). While PhET simulations are more suitable for high school students, they can be used by primary school students as well. Therefore, PhET simulations for electricity was our study's second tool, assigned to a second group of students (Fig. 3).

The last group of students used Makey-Makey (Fig. 4). We wrote short programs using Scratch, for making the experiments with Makey-Makey more interactive and more fun. For example, students were asked to find ways to make a closed circuit using different materials, so as drums to start playing or Scratch's cat to start dancing (instead

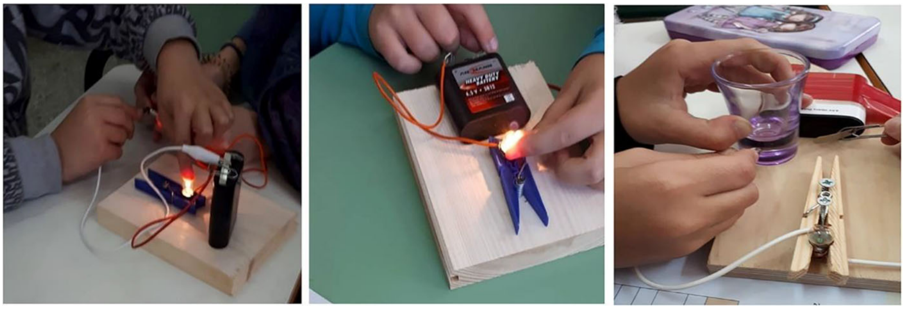

Fig. 2 Experiments using everyday materials

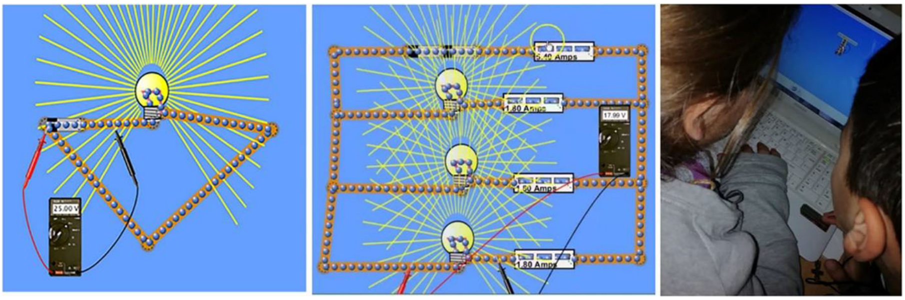

Fig. 3 Experiments using PhET

of just lightning bulbs). More importantly, we decided to take full advantage of this device's potential to invoke the principles of Embodied Cognition. Thus, most experiments were conducted using students' bodies or unusual/unexpected objects (e.g., bananas, shoes, and snacks/foods), as electricity conductors/insulators. By doing so, we theorized that students will be able to have a deeper understanding of how electricity works.

We have to note that students in the first group also used their bodies as part of the circuits they created, although the results were the opposite compared with that in the third group. That is because in the former group the batteries' low current and low conductivity of the human body did not allow the bulbs to light up, while in the latter group, Makey-Makey's sensitive electronics (as we presented in a preceding section) allowed students' bodies to act as electrical conductors. To both groups, the necessary clarifications were provided, so as to avoid misinterpretations of the experiments' results.

Finally, we wrote a series of worksheets in which students could record their thoughts and opinions. Additionally, the worksheets included supplementary experiments with electricity and in-classroom activities. For instance, students were given the roles of wires, switches, bulbs, and various objects (either insulators or electricity conductors) and were asked to simulate closed/open or serial/parallel circuits.

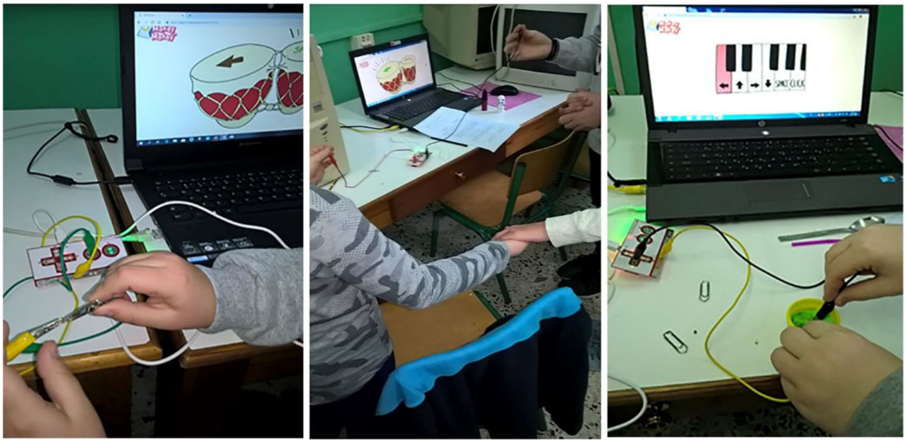

Fig. 4 Experiments using Makey-Makey

4.3 Procedure

Given that the experiments, as well as the in-classroom activities, required a considerable amount of time and as it was important to provide students with enough time to assimilate the learning material, we decided to allocate two teaching hours for each subunit. We decided students to work in groups of three. That is because a general rule of thumb when teaching science-related subjects is students to work in small groups (Harlen and Qualter 2014). Out of the various models for teaching science, we deemed that Bybee's 5Es (Bybee et al. 2006) was the most well-suited for our needs. In detail:

- The Engage stage provides the initial stimulus for what students are about to learn and excites their interest, so as to be personally involved in the upcoming activities. The teachers made a short introduction, provided examples from everyday life, and initiated the first round of discussions between students.
- During the Explore stage, as its name implies, students, through activities, explore their ideas on the subject. The students' groups used their booklets, studied the relevant material, performed the corresponding experiments, and recorded their views or explanations for the experiments' results (in the provided worksheets).
- Following that, the Explain stage urges students to communicate their ideas and/or what they think they have learned. Each group presented the outcomes of the previous stage, discussed them with the rest of the class. If necessary, they re-assessed their ideas prior to recording their final views for the concept they encountered.
- The purpose of the Extend stage is to allow students to further explore the implications (practical or otherwise) of what they have learned. We considered this stage as the most important part of the teaching procedure, because it allowed students to gain procedural knowledge (e.g., to know how to make new types of circuits) and functional knowledge (e.g., to adapt what they have learned so as to make predictions and explain how other types of circuits work). The participating students performed the in-classroom activities and conducted the supplementary experiments. As in the previous stage, students recorded their views in the worksheets, presented their ideas, and discussed them with the other groups.
- Finally, the Evaluation stage assesses how much learning was achieved. The teachers presented problems or applications related to the unit's subject and, following group discussions, students presented their ideas.

During sessions, the teachers facilitated the learning process; they started or joined in students' debates, they draw their attention to what was significant/relevant, and they provided guidelines/hints (without enforcing their views or giving direct answers).

To summarize, three groups of students were taught the same subjects/units related to electricity, for the same number of sessions, with the same teaching method. On the other hand, each group used a different tool.

4.4 Instruments

In order to collect data for each group's learning outcomes, we devised a total of six evaluation sheets (one Pre-test, one for each teaching unit-four in total, and one

Delayed post-test). The Pre-test examined students' prior knowledge in subjects related to electricity, so as to determine whether there were initial differences between groups which might affect the study's results. We administered the Delayed post-test three weeks after the end of all sessions in a group, having as an objective to examine knowledge retention (in all subjects). Students completed the rest of the evaluation sheets right after the end of a teaching unit (i.e., at the end of the second, fourth, sixth, and eighth session). All the evaluation sheets followed the same logic and structure: (i) they had fill-in-the-blanks, multiple-choice, yes-no, and open-ended questions, (ii) in most cases students were urged to provide an explanation for their answer in a question, (iii) they thoroughly examined all the material included in a unit, (iv) the ratio of difficult to easy questions was two to one, and (v) about a third of the questions examined declarative knowledge (e.g., facts and definitions of terms/concepts), most questions' objective was to examine whether procedural and functional knowledge was gained; they were "tricky" (as they required attention to details and critical thinking), they asked students to give their own examples (by making their own circuits), and to apply what they have learned to new situations. Figure 5 presents an example of such questions. We have to note that all the evaluation sheets were the result of a collaborative process involving both the participating teachers and our team. Each member of this expanded team was asked to suggest -as many as possible- questions to be considered for inclusion in the evaluation sheets, following the guidelines presented above. A series of email exchanges and face-to-face meetings followed, in which these questions were discussed in terms of their wording, logic, applicability/necessity, and difficulty level. Draft evaluation sheets were assembled (at least three versions for each evaluation sheet), discussed, and questions were added or removed. Out of these drafts, six were selected during one last face-to-face meeting.

For examining H2, we selected four out of the twelve factors included in a validated, modular scale, designed for examining digital educational applications (Authors 2019). Specifically, we selected fun/enjoyment (six items), subjective learning effectiveness (six items), ease of use (six items), and motivation (three items). All questions were presented in a five-point Likert-type scale (anchored at "strongly disagree" to "strongly agree"). The questionnaire's items are presented in the Appendix Table 5.

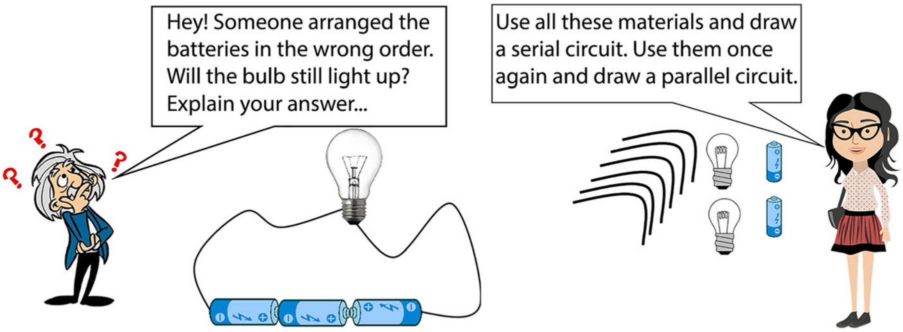

Fig. 5 Sample questions

5 Results

As we already stated, the sample size was seventy-five students (thirty-five boys and forty girls), divided into three groups (twenty-five students each). In each group a different tool was used; Group1 used everyday materials, Group2 used PhET simulations, and Group3 used Makey-Makey. As all the participating students attended all session and as all filled the questionnaire, we did not exclude any of them from the study. We graded students' evaluation sheets and we imputed the data into SPSS 25 for further analysis. Table 1 presents descriptive statistics for the evaluation sheets.

As we were going to conduct one-way ANOVA tests for determining whether the above scores were statistically significantly different, we checked whether the data were suited for this type of analysis. We found that: (i) the three groups had an equal number of participants ($N = 25$ each), (ii) no outliers were found, (iii) Shapiro's-Wilk's test and Q-Q plots indicated that the data were normally distributed with one exception (Evaluation sheet 4), and (iv) the homogeneity of variance (assessed using Levene's test) was violated in the Delayed post-test. We determined that the deviation from normality in the Evaluation sheet 4 was not an issue since one-way ANOVA is quite robust to moderate violations of this assumption (Lix et al. 1996). For the Delayed post-test, we used the Brown-Forsythe test (Brown and Forsythe 1974), as suggested when heteroscedasticity is an issue. The results of the one-way ANOVA tests are presented in Table 2.

In order to examine the differences between pairs of groups, we used the Tuckey HSD test for conducting post-hoc comparisons, excluding the results in the pre-test, as there were no statistically significant differences. In the Delayed post-test, we used the Games-Howell test (Games and Howell 1976) (Table 3).

Summarizing Tables 2 and 3, we can note the following:

- All groups had the same prior knowledge, given that we found no statistically significant differences in the Pre-test. Thus, we can support that all the differences found in the subsequent tests can be attributed to the tool that was used.
- Group1 did not outperform the other groups in any case. As a result, we can infer that the corresponding tool was the least effective.

Table 1 Means and standard deviations per evaluation sheet and per group

Evaluation sheet	Group1 ($N = 25$)		Group2 ($N = 25$)		Group3 ($N = 25$)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	15.10	2.63	15.49	1.96	15.05	3.08
Evaluation sheet 1	35.55	4.23	38.27	4.84	42.65	4.47
Evaluation sheet 2	36.50	5.16	38.74	4.87	42.83	5.14
Evaluation sheet 3	40.41	3.54	41.32	4.38	46.00	3.45
Evaluation sheet 4	39.22	4.03	40.14	5.06	45.18	3.37
Delayed post-test	32.19	2.33	35.88	4.53	38.42	3.64

The maximum score in all evaluation sheets was 60

Table 2 One-way ANOVA results

Evaluation sheet	Result	Interpretation
Pre-test	$F(2, 72) = 0.14$, $p = .867$	Groups' mean scores were not statistically significantly different
Evaluation sheet 1	$F(2, 72) = 11.06$, $p < .001$	Groups' mean scores were statistically significantly different
Evaluation sheet 2	$F(2, 72) = 7.08$, $p < .001$	Same as above
Evaluation sheet 3	$F(2, 72) = 10.95$, $p < .001$	Same as above
Evaluation sheet 4	$F(2, 72) = 10.34$, $p < .001$	Same as above
Delayed post-test	Brown-Forsythe $F(2, 69.77) = 9.16$, $p = .001$	Same as above

- Group2 outperformed Group1 in one case (Delayed post-test) and was outperformed by Group3 in three out of five cases. Thus, the corresponding tool was marginally more effective than that of Group1 and less effective than that of Group3.
- Group3 outperformed Group1 in all five cases. Together with the above outcome, we conclude that the tool this group used was the most effective one.
- Considering these results, H1 can be accepted. The use of Makey-Makey for teaching concepts related to electricity to primary school students produces better learning outcomes compared with the use of simulations and everyday materials.

Table 3 Post-hoc comparisons

Evaluation sheet	Group	Group	Mean Difference	Std. Error	p	Effect size (Cohen's d)
Evaluation sheet 1	1	2	−2.72	1.55	.195	–
	1	3	−7.11	1.53	< .001	1.94 (very large)
	2	3	−4.39	1.53	.016	0.94 (large)
Evaluation sheet 2	1	2	−2.24	1.74	.409	–
	1	3	−6.33	1.71	.002	1.23 (very large)
	2	3	−4.10	1.71	.053	–
Evaluation sheet 3	1	2	−0.91	1.31	.766	–
	1	3	−5.60	1.29	< .001	1.60 (very large)
	2	3	−4.68	1.29	.002	1.19 (large)
Evaluation sheet 4	1	2	−0.93	1.44	.796	–
	1	3	−5.97	1.42	< .001	1.60 (very large)
	2	3	−5.04	1.42	.002	1.17 (large)
Delayed post-test	1	2	−3.69	1.24	.036	1.02 (large)
	1	3	−6.23	1.03	< .001	2.04 (extremely large)
	2	3	−2.54	1.39	.179	–

The highlighted rows indicate statistically significant differences

Prior to analyzing the results in the questionnaire, we examined its internal consistency using Cronbach's alpha. We found that the internal consistency was good ($\alpha = .836$) and the same applied for the reliability scores of the four constructs ($\alpha = .816$ to $\alpha = .894$). Table 4 presents descriptive statistics for the four factors.

As with the evaluation sheets, we conducted a series of one-way ANOVA tests and post-hoc comparisons, in order to examine the differences in students' responses. We found that:

- There were no differences in subjective learning effectiveness [$F(2,72) = 1.42$, $p = .249$] and ease of use [$F(2,72) = 2.22$ $p = .116$].
- Differences were noted in fun/enjoyment [$F(2,72) = 30.02$, $p < .001$]. The pairwise comparisons revealed that students in Group1 gave the lowest ratings in this factor compared with the other two groups, while responses in Group2 compared with the ones in Group3 were not different [Group1-Group2, $p < .001$, $d = 1.41$ (very large); Group1-Group3, $p < .001$, $d = 2.15$ (extremely large); and Group2-Group3, $p = .186$].
- Finally, there were differences in motivation [$F(2,72) = 3.79$, $p = .027$]. As previously, motivation received -marginally- the lowest score in Group1 compared with the other groups, while responses in groups 2 and 3 were almost identical [Group1-Group2, $p = .050$, $d = 0.57$ (medium); Group1-Group3, $p = .050$, $d = 0.57$ (medium); and Group2-Group3, $p = .999$].
- Given the above, we can conclude that students regarded the three tools as equally effective in terms of learning and equally easy to use. The everyday materials were considered the least motivating and fun to work with. Then again, there were no differences between the use of PhET simulations and Makey-Makey. Thus, H2 is partially accepted. The use of Makey-Makey for teaching primary school students concepts related to electricity is more enjoyable and motivating only when compared with everyday materials.

6 Discussion

For examining whether Makey-Makey is an effective tool for teaching concepts related to electricity to primary school students, we conducted a series of teaching interventions. The results confirmed that it certainly has potential, but also some rather perplexing outcomes emerged, as discussed in the coming paragraphs.

Table 4 The questionnaire's results

Factor	Group1		Group2		Group3	
	M	*SD*	*M*	*SD*	*M*	*SD*
Subjective learning effectiveness	4.67	0.58	4.75	0.46	4.89	0.33
Fun/enjoyment	4.00	0.53	4.70	0.46	4.91	0.29
Ease of use	4.26	0.74	4.33	0.52	4.60	0.52
Motivation	4.50	1.00	4.92	0.29	4.92	0.28

The first observation worth mentioning is related to the results in the pre-test. As it is evident in Table 1, students' scores in this test (all groups considered) were extremely low; only a quarter of the questions were answered correctly. A closer examination of students' answers revealed not only that their prior knowledge was limited, but the explanations they provided reflected an assortment of wrong ideas all falling into the categories we presented in the "Background" section. Although we did not examine the underlying reasons that led to this result, a logical assumption is that students were not systematically taught subjects related to electricity at an earlier stage, allowing for students' wrong interpretations to take roots. Indeed, the Greek program of study does not include even a single unit related to electricity until the fifth grade. Thus, prior instruction, or, more correctly, the complete lack of it, bears a great deal of responsibility for this situation, as previous research suggested (Maharaj-Sharma 2011).

The results in the evaluation sheets were much better; 60% to 77% of the questions were answered correctly, depending on the evaluation sheet and the group of students (i.e., the tool that was used). Whether these results can be characterized as satisfactory is debatable. Our view is that, while not being impressive, they are good, given that researchers agree that electricity is not an easy learning subject (Lee 2007; Peşman and Eryılmaz 2010; Shipstone 1984). In this respect, the three tools proved their usefulness as they all had a considerable positive impact on students' learning. The importance of this conclusion is highlighted even further if one takes into account that our objective was not just the acquisition of declarative knowledge (e.g., definition of terms) but we mostly focused on procedural and functional knowledge (the "why" and "how" things work and the application of knowledge to new situations) (see sections "Instruments" and "Procedure").

Thus, a question that has to be answered is which of the three tools produced the best results. The answer to this question comes from Table 3. Only in one evaluation sheet Group3 (Makey-Makey) did not outperform the other two groups (everyday materials and PhET simulations). What is more, the effect sizes were mostly large, meaning that the distance between the results of the three groups was considerable. Given that, we can conclude, with a certain confidence, that students, with the help of Makey-Makey, were able to develop a rather solid base of both procedural and functional knowledge on subjects/concepts related to electricity. This conclusion gives further support to the findings of previous studies (e.g., Davis et al. 2013; Smith and Smith 2016), expanding the rather limited literature on this matter. What stresses, even more, the significance of our findings is that, unlike previous studies that were mostly based on pre-post research design, in our study, we compared the results with the two most commonly used tools when teaching electricity. On the other hand, the results suggest that, as far as knowledge retention is concerned, there was no difference between Makey-Makey and simulations and that there was a decline in students' scores (see Tables 1 and 3, delayed post-test). The latter was, more or less, expected. It would be unrealistic one to expect that a relatively small number of interventions could have had a long-lasting positive impact. As for the former, possible explanations are debated in the coming paragraphs.

What has to be discussed are plausible explanations for the study's results. Regardless of the tool that was used, the same teaching method was applied, which is considered effective in the teaching science-related subjects (Bybee et al. 2006). In addition, students collaborated, as it is, once again, recommended when teaching science courses (Harlen and Qualter 2014). Both the above are good explanations for the results as a whole, but they do not elucidate us on why the results were better in the group that used Makey-Makey. One might suggest that compared with everyday materials and simulations, it was easier for students to use Makey-Makey. This explanation has to be ruled out because of the results in the questionnaire; there were no statistically significant differences in this factor. The same applies to subjective learning effectiveness; the participating students regarded all tools as equally effective. The literature suggested that students were motivated to learn when they used Makey-Makey (e.g., Hershman et al. 2018; Palaigeorgiou et al. 2017; Rogers et al. 2014; Xefteris and Palaigeorgiou 2019). Although students' responses in this factor were extremely positive ($M = 4.92$, $SD = 0.28$), meaning that they were indeed highly motivated, they were almost identical with the responses of students in the simulations group and marginally better than those of students in the everyday materials group. Thus, Makey-Makey had a slight advantage in terms of motivation compared with everyday materials, but none compared with PhET simulations. Fun and enjoyment were also considered as Makey-Makey's strong points (e.g., Abrahams 2018; Chen and Lo 2019; Hershman et al. 2018; Lee et al. 2014). Again, our results suggest that students enjoyed using Makey-Makey more compared with everyday materials, but they equally enjoyed using PhET simulations. It seems that the most obvious explanations were partially rejected in our study; increased motivation and enjoyment can explain why the results were better compared with everyday materials, but cannot explain the difference between Makey-Makey and PhET simulations.

While Makey-Makey and PhET simulations are technology-based teaching tools, the former adds a layer of realism/verisimilitude as others advocated (Hershman et al. 2018), not present in the latter. Not only that, but simulations add a layer of abstraction which is absent in Makey-Makey. For example, when students used simulations, they had to rely on the computer for seeing whether the circuit they designed functioned or not; the wires and switches were imaginary and it was the computer that lighted the bulbs. In essence, in addition to electricity being the sum of abstract and difficult to grasp concepts, students had to imagine that all they were seeing, while not real, do apply in reality. On the other hand, when students used Makey-Makey, they were tangibly engaged with real objects and saw "science" happening in front of their eyes. If something was not working it was because they did something wrong and they were the ones who had to fix it not through the computer.

We believe that the above were the key advantages of Makey-Makey that led to better learning outcomes compared with simulations. Indeed, as the theory of Embodied Cognition postulated, individuals' tangible engagement with objects allows the creation of mental representations of concepts related to these objects, which, in turn, helps individuals to understand these concepts and to acquire new knowledge (Atmatzidou and Demetriadis 2016; Eguchi 2016; Lindgren et al. 2016). The students in the Makey-Makey group were able to acquire more procedural and functional knowledge compared with students in the other groups; thus, we can support that they were able to tackle electricity's threshold concepts better. We have to note that following the literature's suggestions regarding threshold concepts (Cousin 2006), (i) we extensively revised/re-organized the teaching material without making any assumptions whatsoever regarding students' prior knowledge and (ii) the teaching method we followed, encouraged students to explore, by themselves, electricity's concepts. In this respect, we can assume that Makey-Makey is better aligned with the teaching procedure we followed and the way we organized the teaching material, at least when compared with the other two tools. Finally, given that students' collaboration was fostered due to their group work with tangible devices, we can assume that this also helped in achieving better learning outcomes, as previous research suggested (Johnson et al. 2016).

6.1 Implications for practice

We made the assumption that the results would be better if the experiments with Makey-Makey were more enjoyable. For that matter, we wrote a series of rather simplistic programs using Scratch. In fact, they were just a few lines of code, far from being comparable with professionally developed applications. While the learning outcomes were indeed better compared with the other tools, students equally enjoyed the experiments with PhET simulations. In a way, this can be viewed as a "failure" to effectively utilize Scratch. Although Scratch is not that difficult to learn, time and some expertise are needed in order to develop complex applications using it. Given the above, it is questionable whether educators will be willing to become skillful programmers just for the needs of some experiments. Therefore, they need either ready-made software packages or software tools that will make the application developing process more efficient and appealing to novice programmers.

Students' satisfactory learning outcomes render the use of Makey-Makey for teaching electricity an interesting teaching aid. In this respect, educators can consider integrating it into their everyday teaching. Then again, the use of this device, by itself, does not guarantee positive learning outcomes; the context as well as how a tool is going to be used are important. In our study we relied on the experiments suggested in the official textbook not only because they could be -relatively- easily implemented using Makey-Makey but, mainly, because they were well-suited for teaching electricity using this device. Therefore, for any given subject, educators have to reflect whether Makey-Makey has an advantage over other tools (digital or otherwise) and what meaningful activities can be conducted using it. Given the novelty of this device, at least in the eyes of students, we were also concerned that it may act as a distraction. To avoid that, we strongly advise educators to use it in the context of a well-defined teaching framework, such as the one suggested in our study. Moreover, as with most digital devices used by young students, a familiarization period and some training sessions are also advised (Fernández-López et al. 2013).

The cost for acquiring enough Makey-Makeys for a class is probably not an issue, given that: (i) students can work in groups, (ii) it can be used in many other subjects/courses and not just for teaching electricity, and (iii) very cheap Makey-Makey clones are available in the market. On the other hand, time is a crucial factor. We allocated two teaching hours for each sub-unit so as students to have enough time to conduct the experiments and the activities. Consequently, education administrators and policymakers have to make adjustments to the primary school's curriculum/timetable and dedicate more teaching hours to subjects/courses in which Makey-Makeys are going to be used.

6.2 Limitations and future work

Though interesting results were brought into light regarding the use of Makey-Makey for teaching electricity to primary school students, the study is not without certain limitations that need to be considered. First, the sample size, even though sufficient for ANOVA testing, it could have been larger, allowing for greater confidence for the results' generalizability. One could argue that the number of sessions was limited, given the subject's complexity. On the other hand, the schools' rather strict timetables did not allow us to add more sessions. Also, we could have focused on a few specific concepts instead of teaching all the textbook's units regarding electricity. Probably our study's most significant limitation is that we did not check whether there was a change in students' misconceptions. Both the above limitations are due to the study's exploratory nature. Given the limited literature on the matter, our primary concern was to obtain some hard evidence for the pros and cons of Makey-Makey and, depending on the results, to plan our next moves. Indeed, given that Makey-Makey is an easy to use device, it would be interesting to test whether it is suitable for teaching electricity to even younger students. Older students are also an interesting target group, given that complex circuits can be implemented using Makey-Makey. Finally, although testing the potential impact of this device on misconceptions requires careful planning (and equally intricate methods for testing the outcomes), it is in our immediate plans to conduct a series of studies targeting specific wrong ideas each time.

7 Conclusion

In sum, considering the aforementioned results and limitations, we feel that the study provided a quite comprehensive idea about if and how Makey-Makey can be an effective tool for teaching concepts related to electricity to primary school students. That is because we presented evidence that, through the use of Makey-Makey, students can gain not only declarative but also procedural and functional knowledge. What is more, we suggested and tested an instructional framework for integrating this device into teaching. In conclusion, the study's findings might prove useful to researchers and educators in understanding the impact and successfully utilizing Makey-Makey in primary education.

Compliance with ethical standards

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

Appendix

Table 5 The questionnaire's items

Factor	Item
Enjoyment	I think the tool* that was used was fun I felt bored while using this tool** I enjoyed using this tool I really enjoyed studying with this tool It felt good to successfully complete the tasks using this tool

Table 5 (continued)

Factor	Item
	I felt frustrated**
Perceived learning effectiveness	I felt that this tool can ease the way I learn This tool was a much easier way to learn compared with the usual teaching This tool made learning more interesting I felt that this tool helped me to increase my knowledge I felt that I caught the basics of what I was taught with this tool I will definitely try to apply the knowledge I learned using this tool
Perceived ease of use	I think it was easy to learn how to use this tool I found this tool unnecessarily complex** I imagine that most people will learn to use this tool very quickly I needed to learn a lot of things before I could get going with this tool** I felt that I needed help from someone else in order to use this tool because It was not easy for me to understand how to use it** It was easy for me to become skillful at using this tool
Motivation	This tool did not hold my attention** When using this tool, I did not have the impulse to learn more about the learning subject** The tool did not motivate me to learn**

* = the word "tool" was replaced by "everyday materials", "PhET simulations", and "Makey-Makey", depending on the group of students; ** = item for which its scoring was reversed

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