Chapter 12
Using Physical and Virtual Manipulatives to Improve Primary School Students' Understanding of Concepts of Electric Circuits

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12.1 Introduction

Research on science experimentation has been growing over the years. In fact, several studies have been conducted to investigate and document the value of experimenting through the use of physical manipulatives (PM; real world physical/concrete material and apparatus) and/or virtual manipulatives (VM; virtual apparatus and material which exist in virtual environments, such as computer-based simulations) in science (for a review see [4, 34]).

Given that both VM and PM were found to offer unique affordances to students when experimenting, many researchers have argued in favor of combining PM and VM [15, 26, 31, 34]. However, up until recently, a detailed framework depicting how PM and VM could be blended was proposed in the literature of the domain [15].

This framework takes into consideration the PM and VM unique affordances and specifically targets the content of each lab experiment separately. According to Olympiou and Zacharia [15], the PM and VM are blended and used in conjunction in the context of each experiment in a way that they match the needs of each experiment separately. This is the first time a framework suggests to target each experiment separately. Up until recently, researchers were assigning the use of PM or VM to a number of experiments before switching the mode of experimentation (PM or VM) (e.g., [5, 10, 24, 31]).

More specifically, the Olympiou and Zacharia [15] framework involves a series of steps that need to be followed in order to reach a fine blending of PM and VM. According to this framework, an educator or a researcher who is about to blend VM and PM for teaching purposes should take into consideration the overarching

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general learning objective of the experiments at task, students' prior knowledge and skills, the identification of the PM and VM unique affordances, the matched learning objectives with the corresponding PM and VM unique affordances, students' ability to switch manipulatives (PM to VM and vice versa), and researchers or teachers knowledge and skills (e.g., they need to know which PM and VM are available, how these PM and VM could be used, what affordances and limitations PM and VM carry, and whether their students have the knowledge and skills to use them) (for more details see [15]).

This framework has been tested successfully among undergraduate students [15, 16]. In particular, in these studies it was found that the use of a blended combination of PM and VM enhanced students' conceptual understanding in physics more than the use of PM or VM alone. However, no data are available concerning the effectiveness of this framework in enhancing the conceptual understanding of younger students. In fact, no unconfounded research study exists, at the primary school level, that examines how PM and VM could be combined for optimizing students' learning in science. Moreover, comparative studies concerning the use of PM and VM among young learners (i.e., Pre-K through K-6) is quite scarce [33, 35]. Therefore, the goals of this study was: (a) to examine comparatively the effect of using PM and VM (alone and blended) on primary school students' conceptual understanding, (b) whether any possible differences in the effect relate to the processes that students engage in during PM or VM experimentation, and (c) to investigate whether the use of blended combinations of PM and VM, which are created according to the Olympiou and Zacharia [15] framework, have a similar positive effect on primary school students conceptual understanding as it was the case with the undergraduate students.

For answering these questions, we followed the same research design as in our previous two studies [15, 16], in which three conditions were used (PM alone, VM alone, and a blended combination of PM & VM), but implemented them this time among primary school students. Finally, we situated this research design in the subject domain of electric circuits.

12.2 Theoretical Background

12.2.1 PM and VM Affordances

PM and VM have a significant overlap in terms of the affordances they could offer for experimentation purposes, such as the manipulation of material, the provision of direct observations, and the exposure to experimentation skills [6]. On the other hand, they carry affordances that differ. These differing affordances are what make PM and VM unique for teaching and learning purposes, and explain the need for using both in a leaning environment and selecting one of them over the other, according to which learning objective is better served by a PM or VM affordance.

In the case of PM, examples of such unique, advantageous affordances are the presence of touch sensory input, the acquisition of psychomotor skills, and the presence of measurement errors. Touch sensory input is advantageous because it was found to form the basis for conscious memory and learning [1, 11, 13]. Zacharia et al. [33, 35] concluded that touch is a prerequisite for science learning when it is the only modality that can provide the necessary sensory feedback for building knowledge related to the physical phenomenon being investigated and when the student does not already have this knowledge available from prior tactile experiences.

In conjunction with touch sensory input, students acquire and develop psychomotor skills, which are vital for interacting with the natural and human-made world. For instance, students using PM grab and heft with their hands for manipulation purposes, whereas basic VM users point, drag, and click with the mouse or touch the screen with their hands [26, 32].

A third example of a beneficial affordance of PM is the presence of measurement errors, which are usually ignored in VM environments. The reason behind the intentional absence of measurement errors in VM is to have students focus on the variables under study than the errors per se. In other words, the idea is to minimize the possibility of having the students being distracted when new concepts are introduced. This does not mean that the students won't focus on errors when experimenting. On the contrary, the idea is to do so right after they get a good picture of the newly introduced concepts. It is crucial for the students to experience measurement errors and acquire knowledge and skills in dealing with them because they are part of the world they are living in [24]. Moreover, measurement errors are an important reminder to the students that real life phenomena and systems are not perfect and that restrictive forces exist, such as friction, that affect their outcomes. Moreover, they reveal the "messy" nature of science and thus enable students understand the true nature of science [34].

In the case of VM, more unique, advantageous affordances exist. This is because VM were designed to surpass the inherent limitations of PM (which admittedly are many within the context of school science experimentation). Such unique and advantageous VM affordances are, the provision of the option for (a) allowing students to change variables, such as amplifying or reducing temporal and spatial dimensions, which are impossible to change in real life [27]; (b) using multiple dynamically linked representations at the same time [7, 17]; (c) allowing students to visualize objects and processes that are normally beyond perception [28] or conceptual/abstract in nature [17]; (d) receiving immediate feedback about errors and thus offering to the students the opportunity to fix the experimental set up immediately, which result in saving valuable experimental time [8, 20]; and (e) allowing students to perform a wide range of experiments faster and more easily and thus experience more examples within a given time framework [3, 8, 29, 30].

In the context of electric circuits, at the university level, it was found that the use of VM was more conducive to students' conceptual understanding than the use of PM, when certain unique VM affordances were present. Specifically, the VM affordances that were found to positively affect students' conceptual understanding were: (a) allowing students to visualize conceptual/abstract objects, namely the electron flow in electric circuits [5, 34]; (b) receiving immediate feedback about errors and thus offering to the students the opportunity to fix the experimental set up immediately [34]; (c) allowing students to perform a wide range of experiments faster and more easily and thus experience more examples within a given time framework [29, 30]; and (d) providing always observable outcomes, no matter how complex is the electric circuit [34].

Given these findings, it was also of our interest to examine whether these affordances could be found as beneficial to our primary school participants' conceptual understanding as it was for the students of prior studies at the university level.

12.2.2 The Effect of PM and VM Experimentation on Primary School Students' Conceptual Understanding: Theoretical and Empirical Underpinnings

The use of PM and VM for experimentation purposes more or less follows the same pattern across K-16. Students at all levels are expected to conduct an experiment, if not to design and set it up, as well. In this context, independent of PM or VM use, students are expected to identify the variables involved (e.g., which is the independent and dependent variables), form their hypotheses, alter the values of variables in a way that the experimental procedure is valid (i.e., run a fair experiment), observe the outcomes (the effect on the dependent variable), and initiate processes for taking data/measurements.

Given that PM and VM experimentation provide students empirical evidence through observations, researchers have argued about experimentation's potential to promote students' conceptual understanding at all levels [15]. Tao and Gunstone [23] characterized experimentation as a cognitive conflict model of instruction, because it allows students to make observations, compare these with their own (prior) conceptions, and attempt to reconcile any discrepancy between their conceptions and the observations from the experiment. In this way, PM and VM experimentation provide grounds for promoting conceptual change through *meaningful* cognitive conflicts and thus, enhance students' conceptual understanding (for details on how to achieve *meaningful* cognitive conflicts and conceptual change see [12]).

Research among primary school students, even though it is limited, has shown that experimentation through the use of PM alone and VM alone can enhance students' conceptual understanding in science (e.g., [2, 22]. However, for understanding how to combine/blend PM and VM, these studies are not very informative, because they do not reveal the relative value of each mode of experimentation (PM or VM) as opposed to the other. Comparative studies are needed in this respect, which examine the comparative effect of PM and VM on students' learning. From our literature review, we identified only three such studies [9, 10, 26], two of which concerned the subject domain of electric circuits at the primary school level [9, 10]. These latter two studies also involved a combination of PM and VM, which was parallel in nature (students were using first VM to conduct an experiment and then PM to conduct the same experiment).

Triona and Klahr [26] compared physical materials (springs, weights, and ramps in the transfer task) and virtual materials (a simulation with digital representations of the same materials) in the context of designing simple unconfounded experiments using the control of variables strategy. The sample comprised 92 fourth- and fifth-graders. The study carefully controlled for factors such as instructional format and adopted a range of outcome measures including: designing unconfounded experiments (student's understanding of the need to control variables), deriving correct predictions from these experiments, and making explicit reference to the need for experiments to be unconfounded. Both types of materials (PM and VM) were found to be equally effective in achieving these instructional objectives.

Jaakkola and Nurmi [9] examined whether combining PM and VM (first use VM to conduct an experiment and then PM to conduct the same experiment) would be more conducive to students' learning than using PM and VM alone. The sample of the study comprised of 66 elementary school students, who were placed into the aforementioned three conditions. The curriculum of the study focused on electric circuits. The results showed that the VM&PM condition led to statistically greater learning gains than the use of either PM or VM alone. There were no statistical differences between VM alone and PM alone. The authors highlighted the benefits of using in parallel VM and PM to promote students' understanding of electricity. Among others, they argued about the success of their parallel combinations that VM can help students to first understand the theoretical principles of electricity, whereas PM is necessary to challenge further students' intuitive conceptions by demonstrating through real life enactments that the theory discovered through PM applies in reality.

Along the same lines, the same research group [10] compared the learning outcomes of students using VM with the outcomes of those using VM in parallel with PM in the domain of electric circuits. Moreover, the authors examined how the learning outcomes in these environments are mediated by implicit (only procedural guidance) and explicit (more structure and guidance for the discovery process) instruction. The participants of the study were 50 elementary school students, who were randomly separated in the study's conditions: simulation implicit, simulation explicit, combination implicit, and combination explicit conditions. The results revealed that elementary school students can gain better conceptual understanding about electric circuits when they have an opportunity to use VM in parallel with PM than when using VM alone, even in the case when the use of VM is supported with explicit instruction.

Despite the encouraging results coming from the parallel use of VM and PM, this work [9, 10] has been criticized about the fact that the time-on-task was not controlled [15]. In particular, the critique focused on the fact that it is not possible to attribute the positive results on students' learning solely on the parallel combination of VM and PM, since the students in the VM&PM condition were repeating each experiment, which increased considerably their time-on-task (more than that of VM or PM alone users). Therefore, this critique brings us back to the fact that there is no solid framework in this research domain depicting how PM and VM could be combined in order to enhance students' learning. As mentioned in the Introduction, the purpose of this study, among others, was to shed light towards this direction.

12.3 Methodology

12.3.1 Participants

The participants were 55 sixth graders coming from three different classes of a public, primary school in Nicosia, Cyprus. The school is a typical public school that shares same demographics as most public primary schools in Cyprus. The sixth graders of the three classes selected from this school were also typical in terms of their performance in science compared to other primary schools. None of the students had a class on electric circuits before.

The students of all three classes/conditions were taught about electric circuits during their science classes by the same teacher for 3 weeks (80-minute periods per week). The teacher is a holder of two Bachelor's degrees; one in educational sciences and one in physics. Moreover, the teacher had a 6-year experience in teaching science at the primary school level.

The first class/condition involved the use of PM (PM condition, 18 students), the second class/condition involved the use of VM (VM condition, 18 students), and the third class/condition involved the use of a blended combination of PM and VM (PM&VM condition, 19 students) throughout the study.

The students in all conditions were randomly assigned to subgroups of three as suggested by the curriculum of the study [14].

12.4 Materials

The curriculum materials used were derived from the Electric Circuits module of the Physics by Inquiry curriculum [14] and adopted to serve the needs of sixth graders. In particular, we used material from Part A of the module of Electric Circuits of the Physics by Inquiry curriculum (pp. 382–454). Part A (Sections 1 and 2) involves only basic circuits, namely one- and two-bulb circuits, and targets the development of a qualitative, conceptual model for electric circuits in the context of one- and two-bulb circuits. In Section 1, the brightness of bulbs that are connected to a battery in different configurations is examined, and simple electric circuit concepts are introduced that will enable learners to account for relative brightness of the bulbs that they observe. In Section 2, students are encouraged to construct a conceptual model about the *behavior of electric circuits* from direct experience with batteries and bulbs.

In terms of the experimental material used, PM involved the use of physical objects [identical batteries, wires, switches, and resistive elements (e.g., bulbs)] in a conventional physics laboratory. The students were responsible for setting up their experimental set-ups (electric circuits) on their own. During PM experimentation, feedback was available to the students through the behavior of the actual system (e.g., bulbs' brightness).

In the case of VM, the Virtual Labs Electricity [19] was used. It was selected because it retained the features and interactions of the domain of Electric Circuits as

PM did, but also because it carried unique affordances that PM did not (e.g., it provided feedback when setting-up a circuit). In Virtual Labs Electricity, students were able to design and test any DC circuit mentioned in the curriculum by using the "same" instruments and circuit parts (batteries, wires, switches and resistive elements, such as bulbs) as when experimenting with PM. Circuits were created by clicking on icons representing electrical parts and moving the parts to the desired position in the circuit.

12.4.1 Data Collection

Data from four different sources were collected, namely a conceptual knowledge test, instructor's reflective journal, video data (including screen-captured data for all the VM conditions), and interviews. The conceptual knowledge tests were used to assess students' understanding, and the instructors' reflective journals and video data were used to gain insight into students' experimentation processes. The interviews were used for triangulation and clarification purposes. However, for the purposes of this paper we used only the video data and the data collected through the conceptual knowledge test.

12.4.1.1 Conceptual Knowledge Tests

The study's research design was a pre-post comparison study design. Thus, a test was administered to assess students' understanding of concepts concerning the electric circuits both before and after the study. The items included on the conceptual knowledge test were developed and used in previous research studies by our own research group. The test included seven open-ended items and took students about an hour to complete it. Five of them were paper-and-pencil items and asked conceptual questions, all of which required explanations of reasoning, and two of them involved a practical task, as well (students had to build the electric circuits in addition to answering questions about them on paper). The practical part of the latter two items were taken in the form of an interview and for each student separately (all students were videotaped). All items of the test consisted of subitems (each subitem corresponded to one question). We always required an answer and an explanation or reasoning for each subitem.

12.4.1.2 Video Data

For the purposes of this study, we randomly selected three groups from each condition for analysis of their discourse and actions in order to identify whether students engage in different processes during PM or VM experimentation. The selection of these groups was done after students completed the pretest. In particular, we randomly selected three groups per condition and compared their pretest scores to the scores of the remaining students in the same condition. This was to ensure that the students in the selected groups had similar levels of prior knowledge on electric circuits to the other student groups coming from the same condition. We used the Mann–Whitney test and found no significant differences across all comparisons ($p > .05$).

Video and audio data were collected from each group throughout the study. In the case of PM, we used camcorders, and in the case of VM, we used the screen-capture plus video–audio software (River Past Screen Recorder Pro) to capture actual computer work activity (e.g., actions, sounds, movements that take place on the computer monitor).

After capturing student discourse and actions for each of the selected groups of each condition throughout the study, we intentionally selected and analyzed only certain episodes that involved the critical events that interested us [18]. We watched the videos of the three conditions and identified the events in which a condition was diverting from the other conditions (e.g., repeating an experiment, arguing whether a circuit was built correctly). We then located and isolated the (video) episodes that included the experiments that involved these critical events (points of differentiation across the groups) and proceeded with transcribing the corresponding dialogues and with coding students' actions and activities. The idea was to check whether these instances of variation differentially affected students' discourse and actions and therefore also affected the students' processes in experimentation and their level of understanding of the electric circuits concepts introduced in these experiments. A total of about 270 min of student conversations were transcribed and coded. The corresponding actions of the students, within these 270 min of video, were also coded.

12.4.2 Data Analysis

12.4.2.1 Conceptual Knowledge Tests

The tests were analyzed both quantitatively and qualitatively. In the case of the quantitative methods, all participants' tests were first scored. The scoring of each subitem was performed through the use of a scoring rubric that included preset criteria (expected correct answer and expected correct explanation of reasoning), which were used to score whether the elements of the participant's overall response (answer and its accompanying reasoning) were correct. The scoring of the accompanying reasoning was based only on whether students provided specific concepts or evidence that were needed to support their answer, as prespecified in the scoring rubrics. A correct answer to a subitem received one point, and its corresponding reasoning was scored in accordance with how many of its preset criteria were met. Each prespecified concept or evidence present in the reasoning received a half point. However, it should be noted that students received points only when they provided a correct answer and a corresponding correct or partially correct reasoning. All tests were scored and coded blind to participant condition. We took the individual student as the unit of analysis.

The maximum score for each subitem varied according to the number of pre-specified elements required to be present. However, the scales for the items on a test were about the same. Finally, all participants total scores were adjusted it to fit on a 100-point scale. An independent coder reviewed about 20 % of the data. The reliability measure (Cohen's kappa) for scoring of the conceptual knowledge test was .88.

The statistical analysis of the scored tests involved (a) one-way ANOVA for the comparison of the pretest scores of the three conditions, (b) paired samples t-test for the comparison of the pretest scores to the posttest scores of each condition, and (c) one-way ANCOVA for the comparison of the posttest scores of the three conditions on the study's test.

The qualitative analysis involved the identification and classification of students' Scientifically Acceptable Conceptions (SACs) and Scientifically Non-Acceptable Conceptions (SNACs) concerning current in the context of circuits that included up to five bulbs connected in series or in parallel. This analysis followed the procedures of open coding [21], in which the researchers first underlined the most important sentences in each student's pre- and posttest and marked keywords that characterized the student's conceptions with respect to *behavior of electric circuits* (e.g., which bulbs will and which will not, which will be the brighter bulb, why some bulbs are brighter than others). By comparing the sentences underlined and the keywords derived from the tests, the content-specific similarities and differences in students' test responses about the *behavior of electric circuits* were explored and summarized. Then, the researchers constructed qualitatively different subcategories of description, across rather than within the responses, that were used to classify the conceptions of *behavior of electric circuits*. By comparing the similarities and differences between the students of each condition, subcategories of conceptions emerged (for an example of such subcategory, see Table 12.2). The purpose of the open coding analysis was to reveal the subcategories of description that could characterize the qualitatively different perspectives in which *behavior of electric circuits* was conceptualized or experienced by the students of each condition.

In addition, the prevalence for each of the resulting subcategories was calculated, as well the mean frequencies and standard deviations of SAC and SNAC in the three conditions and on the study's test (see Table 12.3). The aim of the latter calculation was to compare whether students' conceptions changed over the course of the study. This procedure was essential because it clarified whether students with similar scores also shared the same ideas, either SAC or SNAC conceptions.

For internal consistency reliability purposes, a second independent rater reviewed about 20 % of the data. The reliability measures (Cohen's kappa) for identifying subcategories of SAC and SNAC as described above for the conceptual knowledge test was .84. The reliability measures (Cohen's kappa) for classifying students' conceptions according to the resulting subcategories was .91.

12.4.2.2 Video Data

For the video, audio and screen-captured data analysis, we also followed open coding from grounded research methodology [21] and took the group as the unit of analysis. In the case of the audio material, we transcribed the selected conversations and coded what the students were talking about (e.g., about the experimental setup, about their observations). After all transcribed conversations were coded and the list of codes was finalized, all coded transcripts were reviewed once more for consistency reasons. Interreliability data were collected as well. A second coder who did not have access to the first round of coding repeated the whole coding process. Cohen's kappa was calculated at .85. Differences in the assigned codes were resolved through discussion.

For analyzing the data related to what the students were doing with PM or VM, we coded the video and screen-captured data for students' actions (e.g., building a circuit, playing with the material, repeating an experiment). The codes emerged through open coding and aimed at capturing the students' actions during their work with the PM or VM. After the list of codes was finalized, all coded transcripts were also reviewed once more for consistency purposes. Interreliability data were collected as well. A second coder who did not have access to the first round of coding repeated the whole coding process. Cohen's kappa was calculated at .87. Differences in the assigned codes were resolved through discussion.

The analysis of these data involved contrasting the resulted codes for both discourse and actions and identifying the differences that existed among the three groups, over time. The idea was to discover when the three conditions deviate, if they deviate at all, and why. The purpose of such an analysis was to identify the cause behind any deviations found in terms of students' conceptual understanding.

12.5 Findings

12.5.1 Conceptual Understanding

The one-way ANOVA procedure indicated that the three conditions did not differ in pretest scores across all of the study tests, $F < 1$,ns. The paired samples *t*-test showed that all three conditions improved students' understanding of the electric circuits concepts at task after the study ($p < 0.001$ for all comparisons). However, the ANCOVA procedure revealed differences among the study's three conditions (for mean scores and *SD* on the posttest, see Table 12.1). Bonferroni-adjusted ($p < 0.01$) pairwise comparisons suggested that students' posttest scores in the PM alone and VM alone conditions were significantly lower than those of the students in the blended combination PM&VM condition. The pairwise comparisons did not show any significant difference between the students' posttest scores of the PM alone and VM alone conditions.

The qualitative analysis on students' conceptions (SAC and SNAC) revealed, for the category of *behavior of electric circuits*, a number of subcategories (for an

Table 12.1 Participants' mean scores and SD on the posttest

Condition	*N*	Mean	SD
PM	18	62	4.49
VM	18	65	3.55
PM&VM	19	87	6.28

Table 12.2 Example of a subcategory of student conceptions of behavior of electric circuits and the corresponding SAC and most prevalent SNAC

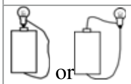
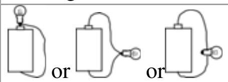
Category of conceptions	Example of sub-category of conceptions	SAC	Most prevalent SNAC
Behavior of electric circuits	Complete/closed single-bulb electric circuit	A complete single-bulb electric circuit is a circular, closed route arrangement of a bulb, a battery, and a wire, in which each of the two terminals of the bulb is connected with a different terminal of the battery (see the figures below). In this case, current is passing through all circuit elements and the bulb lights	A complete single-bulb electric circuit is a circular, closed route arrangement of a bulb, a battery, and a wire, in which one of the terminals of the bulb is connected with both of the battery's terminals (see the figures below). In this case, current is passing through all circuit elements and the bulb lights
			

Table 12.3 The mean frequencies and standard deviations of SACs and SNACs on the study's test in the three conditions

	PM&VM		VM		PM	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
Conception type	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
SAC[a]	0.3 (0.3)	3.8 (0.6)	0.4 (0.2)	3.5 (0.5)	0.4 (0.4)	3.2 (0.7)
SNAC[b]	6.7 (0.8)	3.3 (0.9)	6.7 (0.6)	4.1 (0.7)	6.5 (0.6)	4.5 (0.9)

[a]SAC denotes scientifically acceptable conception
[b]SNAC denotes scientifically not acceptable conception

example of such subcategory, see Table 12.2), each of which included one SAC and a number of SNACs that students could hold.

Furthermore, the qualitative analysis on students' conceptions revealed that the PM alone and VM alone conditions shared about the same conceptions across the electric circuits concepts studied, as either SAC or SNAC, both before and after the study's test was administered. The PM&VM condition was found to share the same SAC and SNAC with the PM alone and VM alone conditions only before the study. After the study, the blended combination PM&VM condition had the highest prevalence for each SAC and the least for each SNAC. Table 12.3 shows the overall picture by means of mean frequencies of SACs and SNACs on the study's pre- and posttest in the three conditions. Overall, the results of the qualitative analysis confirm what was found in the quantitative analysis. On the pretest, very few students already possessed correct conceptions of the domain, and they displayed a variety of conceptions that were not scientifically acceptable. On the posttest, a higher number of correct conceptions could be seen than on the corresponding pretests, and in all cases, the number of SNACs found in the answers of the students went down. However, it is apparent that students in the PM&VM condition shifted from SNACs to the SACS to a greater extent than did those in the PM and VM alone conditions. This again is a result that is very much in line with what was found in the quantitative analysis.

12.5.2 Differences in the Experimentation Processes Followed across the Study's Conditions

For understanding the reasons, students' conceptual understanding was found to develop differentially between the PM&VM condition and the PM and VM alone conditions, we examined whether students differed in terms of the processes they followed during experimentation by studying our participants actions and discourse. In so doing, we used the video data.

Our analysis revealed a number of differences, which most of them were found to be VM dependent. First, VM students were found to set-up a circuit on the computer faster than PM students did on the lab bench. The VM affordance of receiving immediate feedback about errors (and thus offering to the students the opportunity to fix the experimental set up immediately) helped students in this respect. Second, VM students were found to repeat experiments easier and more frequently than PM students. We associated this with the VM affordance of faster manipulation, which allowed VM students to experience more examples. Third, VM students spend most of their discourse time more productively than PM. In particular, VM students were discussing more about the circuit at task and much less about process-related problems/issues (i.e., concerning the feedback received from the manipulatives used, particularly from PM [e.g., PM did not provide observable feedback in some circuits] and the problems faced when constructing complex circuits), as opposed to the PM students. The latter relates to the "messy" nature of science, which only PM students experienced. Despite the fact that experiencing the "messy" aspect of PM is vital for students to understand the true nature of science, in this case it affected negatively students work because the process-related problems distracted them from focusing on the conceptual aspects of the experiments. The affordance of providing always observable outcomes in VM environments, no matter what, have contributed in eliminating this problem among VM students.

The only difference found in favour of the students using PM was the fact that these students acquired and developed the psychomotor skills needed for setting-up a circuit in real life. This finding was also confirmed by the two practical questions of the test, which required from students to build circuits. The students of the VM alone condition were found to face problems in setting-up circuits in real life, because throughout the intervention, they did not get a chance to build physical circuits. On the other hand, besides the PM condition, the students of the blended combination did not face such problems because they also experienced building physical circuits through PM.

12.6 Discussion and Implications

In this study it was found that the use of a blended combination of PM&VM, according to the Olympiou and Zacharia [15] framework, was more conducive to sixth graders conceptual understanding of the electric circuits concepts than the use of PM and VM alone. This complies with the findings of the studies that made use of the Olympiou and Zacharia [15] framework at the university level for enhancing undergraduate students' conceptual understanding in Physics. Hence, it appears that the Olympiou and Zacharia [15] framework could successfully be used at the primary school level, at least with students similar to our participants and in the subject domain of electric circuits.

This study also points to the fact that blending PM and VM is better than using PM or VM alone, because this is the only way the unique affordances, which were found to be conducive to student learning, could co-exist in a learning environment. In this study, we have seen (a) the PM affordance of acquiring and developing psychomotor skills needed for setting-up a circuit in real life, to enable students learn how to set-up a physical electric circuit; (b) the VM affordance of receiving immediate feedback about errors during the construction of electric circuit, to support students in setting-up a circuit on the computer faster than PM students did on the lab bench, and thus increase their chances for more productive discussions (focusing on conceptual issues rather than on procedural issues); (c) the VM affordance of faster manipulation to provide students with opportunities for repeating an experiment easier and faster; and (d) the VM affordance of providing always observable feedback, which again enabled students to have more productive discussions, with the focus being on the conceptual aspects of an experiment rather than on the procedural ones. Interestingly, the same affordances were found to affect undergraduate students' conceptual understanding in physics, including in the subject domain of electric circuits [5, 29, 30, 34].

Needless to say, these findings also challenge the already established norms of teaching and learning through experimentation in the science classroom. Specifically, it challenges the laboratory experimentation as we experienced it through PM or VM alone, in a way that calls for its redefinition and restructuring [32], in order to include blended combinations of VM and PM [15]. For instance, one practical implication coming out from this study is that primary school students, who study electric circuits and the improvement of their conceptual understanding is at task, should be offered not only the use of VM, which allow better access to observations and less time for setting-up an experiment, but also the use of PM for acquiring and developing the necessary psychomotor skills for building electric circuits in real life. Restricting students to either the use of PM or VM is like stripping them from benefiting from the advantageous affordances of both modes of experimentation.

On the other hand, this call for reform creates the need for further research [5, 10, 25, 28, 32–34]. In particular, the Olympiou and Zacharia [15] framework or other similar frameworks need to be tested across different ages and subject domains, as well as wider sample sizes and different types of manipulatives. Given the increasing presence of computer technology in science classrooms, conducting research concerning VM and their relationship with PM is becoming an imperative need.

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