PHYSICAL MEETS VIRTUAL: BLENDING PHYSICAL AND VIRTUAL MANIPULATIVES TO IMPROVE UNDERSTANDING IN THE DOMAIN OF LIGHT AND SHADOWS

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ABSTRACT
The purpose of this study was to compare the effect of experimenting with Physical Manipulatives (PM), Virtual Manipulatives (VM), and a blended combination of PM and VM, on undergraduate students' understanding of scientific concepts in the domain of Light and Shadows. A pre-post comparison study design was used for the purposes of this study that involved 70 undergraduate students, enrolled in an introductory physics course that was based upon the *Physics by Inquiry* curriculum (McDermott and The Physics Education Group, 1996). The participants were randomly separated into three groups, each corresponding to a condition that involves the use of one of the three modes of experimentation (VM alone, PM alone, and PM and VM in combination). The first group (Control Group or CG) consisted of 23 students that used PM, the second group (Experimental Group 1, EG1) consisted of 23 students that used VM, and the third group (Experimental Group 2 or EG2) consisted of 24 students that used the blended combination of PM and VM. In the case of the blended combination, the use of VM or PM was selected based on whether it provides an advantage/affordance that the other mode of experimentation cannot provide. These affordances of either VM or PM were identified through a literature review of the domain. None of the participants had taken college physics prior to the study. Conceptual tests were administered to assess students' understanding before and after instruction. The data collected through the tests were analyzed both qualitatively and quantitatively. Findings revealed that the use of a blended combination of PM and VM enhanced students' conceptual understanding in Light and Shadows more than the use of PM or VM alone.

KEYWORDS
Physical Manipulatives, Virtual Manipulatives, blended combination, conceptual understanding.

INTRODUCTION

Over the last three decades several research studies have attempted to investigate and document the value of using Physical Manipulatives (real world physical/concrete material and apparatus) and Virtual Manipulatives (virtual apparatus and material that exist in virtual environments, such as computer-based simulations) in laboratory science experimentation. Comparative studies have been undertaken in order to identify which of these two modes of experimentation is the most preferable across several science subject domains (Zacharia & Constantinou, 2008; Zacharia, Olympiou & Papaevripidou, 2008). Findings of these studies, revealed instances where the use of VM would appear to be more beneficial to learning than the use of PM (Finkelstein *et al*., 2005; Zacharia, 2007) and vice versa (Marshall and Young, 2006).

A question that is raised at this point is why the findings of these studies appear to be discrepant to each other. A comparison across the material and methods used in these studies revealed that the differences in outcomes were caused, primarily, by the different affordances that the PM and VM of these studies carried. Given this, a number of more questions are raised concerning the use of PM or VM within science experimentation. For instance, when is the use of PM in science experimentation preferable to

VM and vice versa? Is it better to combine PM and VM or use them alone? A number of researchers advocate in favor of combining the use of PM and VM. In this case, part of an experiment or a series of experiments is conducted with PM and the rest with VM. The reasoning behind this mode of experimentation is the reaping of the benefits of both PM and VM (Winn, Stahr, Sarason, Fruland, Oppenheimer, & Lee, 2006; Zacharia *et al.*, 2008). In other words, since PM and VM have unique affordances that could not be carried by both manipulatives, the only way to bring these affordances in a learning environment is to use both PM and VM. However, how such combination should look like? Research in this domain involves combinations that are sequential (Winn *et al.*, 2006; Zacharia, 2007, Zacharia *et al.*, 2008), parallel (Jaakkola & Nurmi, 2008; Jaakkola, Nurmi & Veermans, in press) or blended (Toth, Morrow, & Ludvico, 2009; Yueh & Sheen, 2009) in nature.

Sequential combinations involve the use of PM before the use of VM and vice versa, as well as in different patterns (e.g., PM-VM-PM, VM-PM-VM). In each case, the use of PM or VM corresponds to the conduction of different experiments. Such combinations were used primarily for methodological purposes. For instance, the Zacharia & Olympiou (2010) study investigated, among others, whether switching means of experimentation, in a sequential pattern, has a different effect on students' conceptual understanding (from PM to VM and vice versa), given that the nature of motor skills involved in PM and VM is different. In addition, studies of this domain showed when PM should precede VM and vice versa. For example, Winn *et al.* (2006) showed that PM should precede VM when there is need to contextualize learning for students with little prior experience of the phenomenon or system under study (e.g. the study of ocean currents; see for more details Winn *et al.*, 2006). On the other hand, it was found by Zacharia and Anderson (2003) that VM should precede PM when the PM experimentation concerns a rather complex phenomenon or system. In such a case, a VM of low fidelity is used, as they leave out the details found in PM and focus only on the to-be-learned structural features. Nonetheless, none of these researchers argued that this is the most effective way of combining PM and VM.

Parallel combinations are also sequential in nature. However, they involve the conduction of the same experiment or series of experiments with both PM and VM. Findings in this domain revealed that the repetition of experiments with both PM and VM enhances students' learning more than when using VM or PM alone. The idea behind this repetition is that students have a second chance to experience and understand something that they missed during the first round of experimentation. A major drawback of these studies is that the time-on-task factor is not controlled, which means that someone could argue that the gains in learning are caused by the time-on-task factor and not by the combination of PM and VM.

Blended combinations involve a targeted use of both PM and VM for the creation of an optimum blend of PM and VM affordances that best serve the learning goals set per learning experiment/activity. In order to do so, a coherent framework that outlines the criteria to be considered for the PM or VM selection, in accordance to each learning goal, is needed. However, no research in this domain has presented such a framework so far. Any blending of PM and VM appears to have been based on researchers intuition, rather on a framework that includes specific criteria for PM and VM selection. In addition to this, research in the domain of blending PM and VM is quite scarce.

The purpose of this study was to contribute towards the development of such a framework. More specifically, we aimed at developing a framework that portrays how to blend PM and VM according to specific criteria, creating such blends for a number of experiments, and comparing them to the use of PM and VM alone across the same experiments. In the case of the framework, we decided to ground it upon the literature that presents the affordances that each manipulative carries and that were found to be unique (carried only by PM or VM), as well as, conducive to learning. Our learning goal throughout this research study was to improve students' understanding concepts related to the domain of light and shadows.

THEORETICAL BACKGROUND

A close look to the research that involved blended combinations of PM and VM for science experimentation purposes (Toth *et al.*, 2009; Yueh & Sheen, 2009) revealed that these combinations were not based on a coherent and justifiable framework. Despite the fact that these studies showed that their blended combinations were found to be conducive to student learning, there is no indication as far as how much more students learning could be enhanced through a well targeted and optimum blend of PM and VM. Given that the development of such a framework becomes an imperative need, if we do not want to miss the great potential that PM and VM could bring into a learning environment through an optimized blending, research in this domain should focus on the development and validation of such a framework.

Zacharia *et al.* (2008) suggested that the best way to develop such a framework is to take the learning objectives and activities and carefully analyze them in terms of what the student should be exposed to (e.g., experiencing an authentic real experience; experiencing reified objects, such as, atoms), and based on this analysis, a synthesis of PM and VM should be designed in such a way that will best serve what has been identified as important for the student to experience. In other words, the use of PM in science experimentation should be preferred over VM when its affordances influence student learning, as specified by the learning objectives, more than VM (e.g., when the acquisition of specific perceptual-motor skills are involved) and vice versa (e.g., when very large or very small temporal dimensions are involved). Off course, the development of such a framework presupposes knowledge of what PM and VM could offer, particularly, in terms of unique affordances. For the purposes of this study we have reviewed recent literature on PM and VM experimentation and identified a number of such unique affordances (see table 1) that were found to promote conceptual understanding. We focused only on conceptual understanding because that was the learning goal we set for this study. Needless to say, such a framework will vary, if the learning goals set are different (e.g., if they focus on aspects of the nature of science).

Table 1. Examples of unique affordances carried by PM and VM.

Learning Objective	Type of manipulative	Affordance	Reference
Observing the real phenomenon	PM	Provision of an authentic-concrete experience	NSTA, 2005
Experiencing certain characteristics of a concrete object	PM	Sensing an objects' roughness, viscosity etc.	Loomis & Lederman, 1986
Experiencing certain motor skills	PM	Use of concrete material and apparatus	Zacharia & Olympiou, 2010
Transferability of real phenomena that involve objects of big or small dimensions in the laboratory or class	VM	Experience of phenomena that involve objects of big or small dimensions (e.g., our solar system)	Hsu & Thomas, 2002
Observing phenomena that cannot be observed in real life	VM	Provision of representations of reified objects (e.g., molecules)	Triona & Klahr, 2003
Observing phenomena	VM	Provision of safety during the	Triona & Klahr,

that cannot be observed in laboratory or class due to safety reasons		conduction of an experiment that involves hazardous material (e.g., radiation)	2003
Making or repeating accurate measurements	VM	No measurement errors (when the experimental set-up is arranged and ran correctly)	Zacharia *et al.*, 2008
Making or repeating measurements quickly	VM	Overcoming time consuming procedures	Zacharia *et al.*, 2008

THIS STUDY

This study was contextualized through the *Physics by Inquiry* curriculum (McDermott *et al.* 1996) aiming to compare the effect of three instructional conditions that differ in the medium (PM or VM) and mode (alone or in combination) of experimentation on undergraduate students' learning in physics, particularly, their conceptual understanding in the domain of light and shadows. The first condition involved the use of PM (Control Group or CG), the second condition involved the use of VM (Experimental Group 1 or EG1) and the third condition involved the use of a blended combination of PM and VM (Experimental Group 2 or EG2; see the *Experimental Design* part below for more details). Blending PM and VM was based on each mediums' unique advantages/affordances (e.g., in the case of VM a student could experience reified objects) that were identified through prior research (see table 1). In other words, PM or VM were selected whenever they had an affordance/advantage over the other medium. Table 2, presents an example of an experiment that involved the investigation of the shadow of a solid iron bar (see figure 1). In this example, the experiments objectives are outlined and matched with unique PM or VM affordances.

Table 2. Example of matching an experiment's learning objectives with PM or VM unique affordances

Learning Objective	Type of manipulative	Affordance	Reference
Observation of the actual physical phenomenon (This objective corresponds to a task, in which students are supposed to make concrete observations on what happens when light is shed on a solid iron bar that is followed by a screen, and what someone sees on the screen).	PM	Provision of an authentic-concrete experience	NSTA, 2005
Representation of the bar's shadow with a scale diagram. (This objective corresponds to a task that requires several accurate measurements. Through this task students are supposed to understand the relationship of the dimensions of the shadow in relation to the distance of the light source between the actual iron bar and the screen, as well as of the dimensions of the actual bar).	VM	Provision of accurate measurements; No measurement errors (when the experimental set-up is arranged and ran correctly)	Zacharia *et al.*, 2008
		Overcoming time consuming procedures	Zacharia *et al.*, 2008

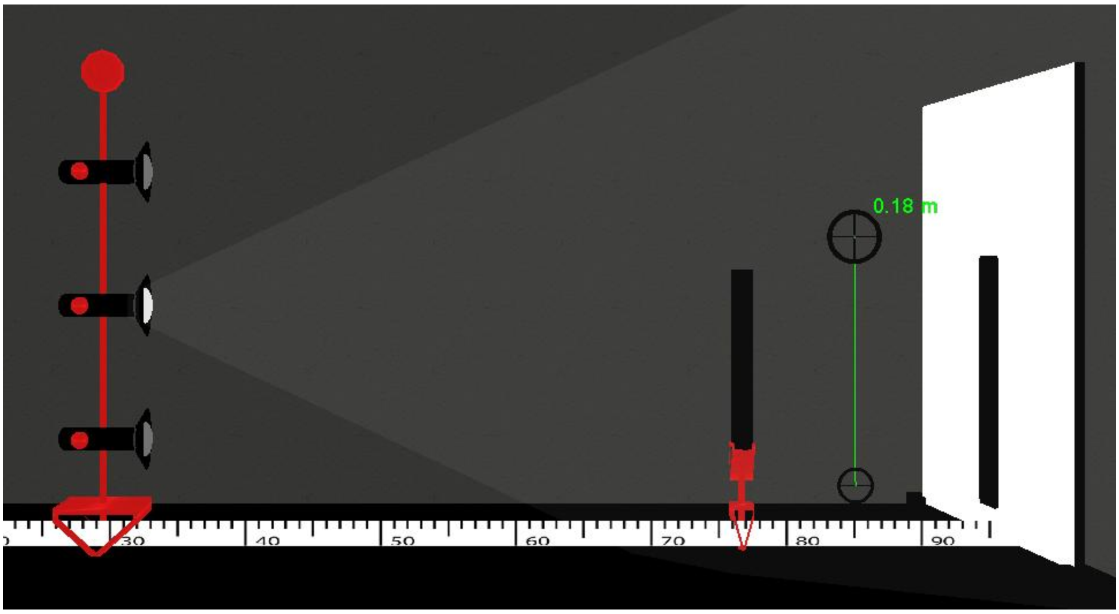

Figure 1. The experimental set-up of the experiment with the solid iron bar. It involves a light source, a solid iron bar and a screen. It also presents the tools used to measure the dimensions of the iron bar, the dimensions of the iron bar's shadow, the distance between the light source and the actual iron bar, and the distance between the light source and the screen.

METHODOLOGY

Sample

The participants of the study were 70 undergraduate students, enrolled in an introductory physics course that was based upon the *Physics by Inquiry* curriculum (McDermott *et al.* 1996), intended for pre-service elementary school teachers. The course took place at a university in Cyprus. The participants were randomly separated into three groups. The CG consisted of 23 students that used PM, the EG1 consisted of 23 students that used VM, and the EG2 consisted of 24 students that used a blended combination of PM and VM. The students in all groups were randomly assigned to subgroups (three persons in each subgroup) as suggested by the curriculum of the study (McDermott *et al.* 1996). This particular curriculum is grounded upon a social constructivist framework that facilitates a constructive, situated and collaborative learning process that assures that the engagement is truly collaborative and helps all students make explicit their ideas. Knowledge and understanding is co-constructed among peers through complementing and building on each others ideas (Damon & Phelps, 1989; Duit, & Treagust, 1998).

Curriculum materials: Physics by Inquiry

The selection of the *Physics by Inquiry* curriculum was based on the fact that through numerous studies it appeared to enhance undergraduate students' conceptual understanding across physics subject domains (McDermott & Shaffer, 1992; Redish & Steinberg, 1999), including the subject domain of light and shadows (that is a part of light and color). This success of the *Physics by Inquiry* curriculum is grounded on three foundational components that were found to support conceptual understanding, namely, inquiry, socio-constructivism and the POE (Predict-Observe-Explain) strategy (see Zacharia *et al.* 2008). For the purposes of this study two parts of the module of light and color were used (McDermott *et al.*, 1996). The two parts that were used focus on an introduction to light, light sources, masks and screens (section 1) and shadows (section 2). The first section involved the investigation of how the light travels and of single and filament lamps using masks and screens. The second section involved the formation of shadows by using several light sources, masks and screens.

Manipulatives

Physical Manipulatives

PM involved the use of physical instruments (e.g., rulers), objects (e.g., metal rings) and materials (e.g., lamps) in a conventional physics laboratory. During PM experimentation feedback was available to the students through the behavior of the actual system (e.g., shape of a shadow on a screen) and through the instruments that were used to monitor the experimental set-up (e.g., rulers).

Virtual Manipulatives

VM involved the use of virtual instruments (e.g., rulers), objects (e.g., metal rings) and materials (e.g., lamps) to conduct the study's experiments on a computer. Most of these experiments were conducted though the Virtual Lab Optilab (Hatzikraniotis *et al.*, 2007). Optilab (see figure 2) was selected because of its fidelity and the fact that it retained the features and interactions of the domain of *Light and Shadows* as PM does. In its open-ended environment, students of the EG1 and EG2 were able to design and conduct the experiments mentioned in the module of *Light and Shadows* by employing the ''same'' material as the ones used by the students using PM. In the *Optilab* environment, students were provided with a virtual work bench on which experiments can be performed, virtual objects to compose the experimental set-up, virtual materials whose properties are to be investigated, and virtual instruments (e.g., rulers) or displays (e.g., screen) as illustrated in Figure 2. Students were able to construct their own virtual experimental arrangements by simple and direct manipulation of objects, materials and virtual instruments. The software offered feedback throughout the conduct of the experiment by presenting information (e.g., distance, color) through the displays of the software. No feedback was provided by the software during the set up of the (virtual) experiment. The level of feedback was analogous to what is routinely available to students through the curriculum material, but there were instances in which varying conversations were made due to the different experimental conditions and the affordances given through each type of manipulative, in each experiment (e.g. dynamically linked representations in a simulated environment).

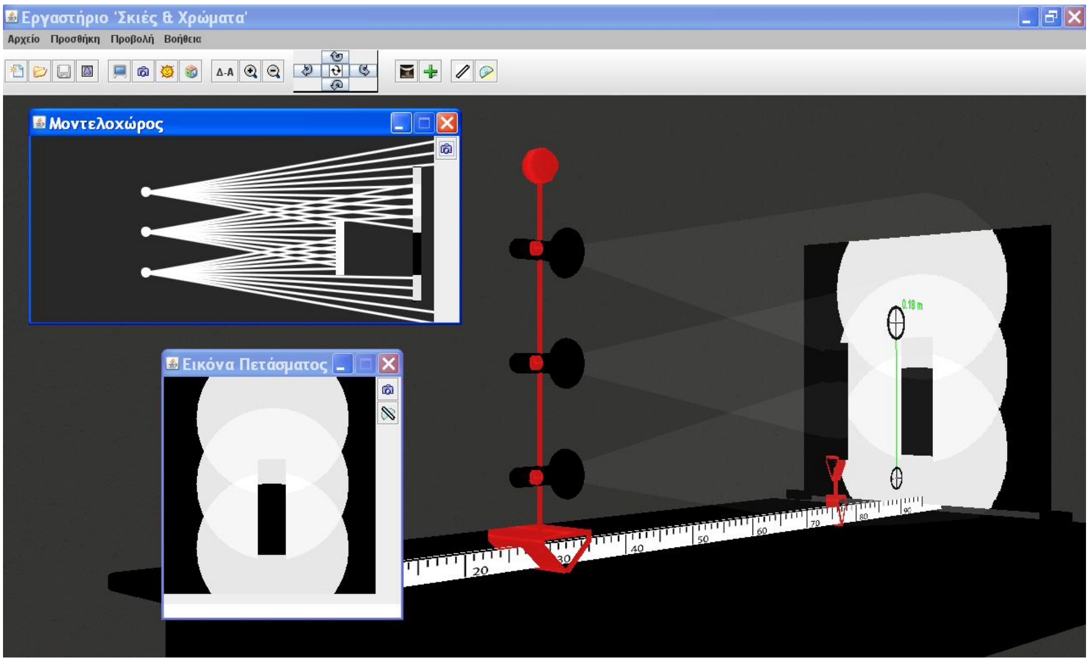

Figure 2. The Optilab environment

Experimental Design

A pre-post comparison study design was used for the purposes of this study that involved three groups, CG, EG1 and EG2, according to Figure 3. All groups worked in the same laboratory environment that hosts both conventional equipment and a computer network arranged at the periphery.

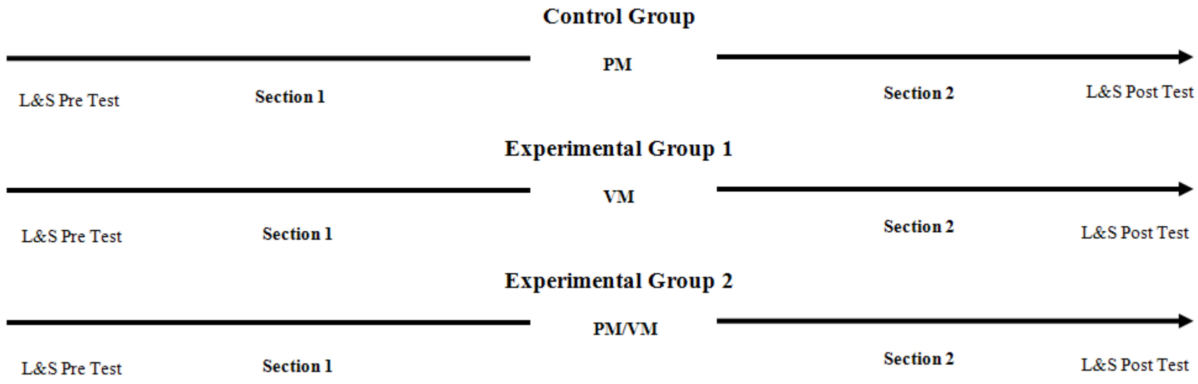

Figure 3. The experimental design of the study

Procedures

After all participants were randomly separated in the study's conditions (CG, EG1 and EG2), within each condition, students were further randomly assigned to subgroups (of three) as suggested by the curriculum of the study. Right before the study, all participants were administered the L&S test before getting engaged in the treatment of the condition they belonged to. At the first meeting, students were introduced to the material they were about to use. The introduction to the routines and procedures of the Physics by Inquiry curriculum was very important because they differ from those involved in the more traditional, passive modes of instruction that students had experienced in physics courses during their K-12 years. For example, the enactment of the Physics by Inquiry curriculum does not involve any lecturing, tutoring, or traditional textbook. Moreover, the role of the instructors in the Physics by Inquiry curriculum is quite different from that in a traditional instruction. It is supportive in nature and requires instructors' engagement in dialogues with the students of a subgroup at particular points of the activity sequence, as specified by the Physics by Inquiry curriculum. For the purposes of this experiment all conditions shared the same instructors. All instructors were previously trained in implementing the Physics by Inquiry curriculum and had experienced its implementation at least for two years. Finally, after all participants completed the study's instructional part (sections 1 & 2), the L&S test was administered one more time (see Figure 3). The duration of the study was 6 weeks. Students met once a week for one and a half hour. The time-on-task was the same for all groups.

Data Collection

The data collection involved only the use of the L&S test, which was developed and used in previous research studies by the Physics Education Group of the University of Washington (McDermott *et al.*, 1996). The specific test contained open-ended items that asked conceptual questions all of which required explanations of reasoning. It was used for the assessment of both sections 1 and 2. Each item of the L&S test was scored separately; however, a total correct score was derived and used in the analysis. The L&S test was scored and coded blind to the condition in which the student was placed. A rubric table was used that specified different criteria for the responses to each item separately. Each response was scored on each criterion. The minimum score on each test was 0 and the total maximum score for all criteria of all items on each test was 100.

Data Analysis

The data analysis involved both quantitative and qualitative methods. The quantitative analysis involved (a) paired-samples t-test for the comparison of the pre-test scores to the post-test scores of the L&S test of each group and (b) ANCOVA for the comparison of the post-test scores of the L&S test across the study's groups. Students' scores in the pre-test were used as the covariate. The aim of the first procedure was to investigate whether the use of the blended combination of PM and VM, and the use of PM and VM alone, within the context of the *Physics by Inquiry* curriculum, improved students' conceptual understanding in each section. The aim of the second procedure was to investigate whether the effect of PM and VM alone on undergraduate students' understanding of concepts in the domain of *Light* & *Shadows*, differed from the effect that the blended combination had on students' conceptual understanding.

The qualitative data analysis focused on identifying and classifying students' scientific (SAC) and scientifically not acceptable conceptions (SNAC) concerning light, light sources, masks and screens, and shadows. The analysis followed the procedures of open coding. In addition, the prevalence for each one of the resulting categories for each test was calculated. The purpose of the latter was to compare if the prevalence of each category of students' conceptions differed prior to and after the study across the three conditions. To ensure objective assessment, the tests were coded and scored anonymously. Internal reliability data were also collected. Two independent coders reviewed 25% of the data. All the reliability measures (Cohen's Kappa for the quantitative part and proportion of agreement for the qualitative part) were above 0.87.

RESULTS

The quantitative analysis showed that the combination of PM and VM and PM and VM alone improved students' conceptual understanding after the study ($p<0.001$ for all comparisons). However, the ANCOVA procedure revealed differences among the study's three groups in the study's curriculum, $F(2, 66) = 5.104$, $p < .05$. Specifically, bonferroni-adjusted pairwise comparisons suggested that EG2 students' post-test scores in the L&S test, were significantly higher than that of students in the CG and EG1. The two p-values were found to be less than the 0.05 level. No differences were found between EG1 and CG. These results indicate that EG2 appeared to better promote the students' conceptual understanding of light and shadows, than the CG and EG1.

The qualitative analysis revealed that all groups shared mostly the same conceptions across the six L&S categories of concepts studied (how light travels, filament bulbs, shadow formation, factors that affect shadow dimensions, calculating shadow dimensions, shadow formation from a long distance) as either scientifically acceptable (SAC) or not scientifically acceptable (SNAC) conceptions, before the study. After the study, the CG and the EG1 were found to share again the same SAC and SNAC (see table 3). On the other hand, the EG2 was found to have higher prevalence for each SAC and lower prevalence for each SNAC than the EG1 and the CG (see table 3). Lastly, all groups were found to share the same most prevalent SNAC across the pre- and post-tests. Overall, these findings indicate that EG2 appeared to better promote students' understanding of concepts in the domain of *Light* & *Shadows*.

DISCUSSION

The purpose of this study was to develop a framework that portrays how to blend PM and VM according to specific criteria, create such blends across the study's experiments, and compare them to the use of PM and VM alone. The findings of this study revealed that the use of blended combinations of PM and VM across the study's experiments enhance students' understanding of *Light & Shadows* concepts more than PM or VM alone. It is important to highlight at this point that all blended combinations were grounded on a framework that we developed so as to match the learning objectives of each experiment with PM or VM affordances that best serve them.

Moreover, our findings imply that the most beneficial way of introducing PM or VM within a science learning environment, when enhancing students' conceptual understanding is at task, is to combine them with VM or PM, respectively. In other words, the use of PM in physics experimentation should be preferred over VM when its affordances influence student learning, as specified by the learning objectives, more than VM (e.g., when the acquisition of specific perceptual-motor skills are involved) and vice versa (e.g., when very large or very small temporal dimensions are involved).

However, the application of a framework, like the one provided in this studied, should be validated through similar research, across K-16 and across science subject domains, before reaching to general conclusions. It is important to investigate whether the same framework works for students of different ages, as well as, for different subject domains.

Finally, it is important to highlight the fact that PM and VM were not found to differ. This finding of this study provide information about the potential and value of the use of PM and VM in inquiry-based experimentation, particularly, of VM which has been disputed as a viable means for experimentation, as opposed to PM. The results of this study indicate that both, the use of PM and VM, when embedded in a context similar to the one of this study, can be equally effective in promoting students' understanding of concepts in the domain of *Light & Shadows*. This finding indicates that the students, in either condition, had about the same observations and experiences, despite any differences in affordances. Off course, in order to reach to more solid conclusions, further research focusing on the learning process, most probably through video data and analysis, is necessary.

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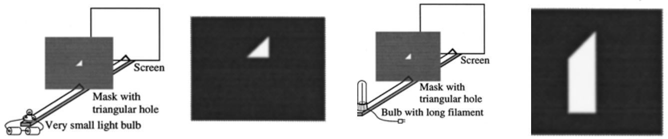
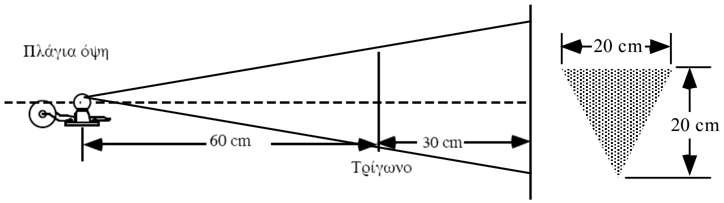
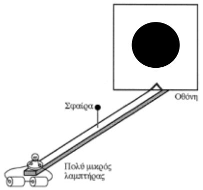
Table 3. A sample of students' conceptions about *Light and Shadows* as they emerged from the qualitative thematic analysis

<table>
<tr><th rowspan="2">Conceptions regarding Light & Shadows</th><th colspan="2">CG (PM)</th><th colspan="2">EG1 (VM)</th><th colspan="2">EG2 (PM&VM)</th></tr>
<tr><th>Pre Tests % (n)</th><th>Post Tests % (n)</th><th>Pre Tests % (n)</th><th>Post Tests % (n)</th><th>Pre Tests % (n)</th><th>Post Tests % (n)</th></tr>
<tr><td>Scientifically accepted conception: When a light bulb is placed in front of a mask with a triangular hole, the image on the screen depends on a) the shape of the hole (e.g. circular, triangular) b) the size of the light bulb and c) the shape of the light bulb. Students who appreciated the role of each of the three factors were able to provide a correct response to both setups as shown below:

</td><td>0% (0)</td><td>78% (18)</td><td>0% (0)</td><td>78% (18)</td><td>0% (0)</td><td>96% (23)</td></tr>
<tr><td>Scientifically accepted conception: The size of an objects' shadow on the screen depends on the distance between the object, the light bulb and the screen. Specifically, the distance between a light bulb and the object is inversely proportional to the size of the shadow on the screen. Additionally the distance between an object and the screen is proportional to the size of the shadow on the screen. Students who appreciated the role of each of the two distances described above, were also able to provide a diagram as shown below:

</td><td>0% (0)</td><td>4% (1)</td><td>0% (0)</td><td>0% (0)</td><td>0% (0)</td><td>38% (9)</td></tr>
</table>

Scientifically accepted conception: Calculation of an object's shadow (size) by a) comparing similar triangles or b) finding the proper scale.	0% (0)	26% (6)	0% (0)	39% (9)	0% (0)	58% (14)
Scientifically accepted conception: The distance between an object and a light bulb is inversely proportional to the size of the object's shadow. During the change of the distance the shape of the shadow remains the same. The object in this case, blocks the light path and consequently the shadow of the object is formed on the screen.	26% (6)	52% (12)	26% (6)	57% (13)	21% (5)	54% (13)
Scientifically not accepted conception: The size of an object's shadow is changing according to the light intensity or its speed. The object's shadow is proportional (or sometimes inversely proportional to the intensity/ or speed of light.	13% (3)	0% (0)	17% (4)	4% (1)	33% (8)	0% (0)
Scientifically not accepted conception: An object's shadow is the reflection of an object on a screen. Shadow is defined as a specific type of light. The majority of students who responded in this way, provided a diagram as shown below: 	17% (4)	4% (1)	17% (4)	4% (1)	13% (3)	0% (0)
Scientifically not accepted conception: When a light bulb is situated in front of a mask with a triangular hole, the result on the screen depends only on the type of the hole (e.g. circular, triangular). The type of the light bulb does not affect the size and the shape of the result on the screen.	35% (8)	13% (3)	74% (17)	4% (1)	58% (14)	4% (1)

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