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INTEGRATING PHYSICS AND MATH THROUGH MICROCOMPUTER-BASED LABORATORIES (MBL): EFFECTS ON DISCOURSE TYPE, QUALITY, AND MATHEMATIZATION

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ABSTRACT. The purposes of this study were to understand the nature of discourse in terms of knowledge types and cognitive process, source of utterances (student or teacher), and time use in microcomputer-based labs (MBL) and verification type labs (VTL) and to gain an understanding of the role of MBL in promoting mathematization. The study was conducted in 2 grade 11 classes in which students studied Hooke's law and Newton's second law of motion using MBL during 1 year while a different group of students studied the same topics with the same physics teacher using a VTL approach. All sessions were videotaped, transcribed and coded using a taxonomy developed by DeVito & Grotzer (2005). In addition, evidence to support each of the 5 steps of mathematization was sought from the actions of the teachers and their discourse with the students. Results showed that conceptual knowledge type utterances were significantly more frequent in MBL sessions, cognitive processes of remembering and understanding were significantly more frequent in the MBL sessions, students spent most of their time analyzing the graphs in the MBL sessions, and MBL has a potential to promote mathematization in favorable instructional environments in physics laboratory classes.

KEY WORDS: discourse quality, discourse type, mathematization, microcomputer-based laboratories, physics laboratories

Preparing technologically literate and competent citizens has become a central goal of many educational systems worldwide because of the alleged causal relationship between the use of technology and the attainment of important and valued educational goals, such as encouraging students to use higher order thinking and problem solving skills in science, maths, and other subject areas. The emphasis on this goal has resulted in serious attempts by stakeholders in the educational process to encourage the use of digital technologies, especially computers, in the teaching/learning process, concurrent with an emphasis on the development of a variety of technological tools that have the potential to reap the assumed benefits of using technology in the classroom. One of these tools is microcomputer-based laboratories (MBLs). This tool functions as a "data grabber" and consists of two types of hardware: sensors or probes to collect physical data (such as temperature, humidity, distance, force, etc.) in real time and another device connected to the sensor that digitizes and stores the collected data. When students use these tools in science

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laboratories, they have an opportunity to collect and work on first-hand experimental data. Collecting, representing, and interpreting data collected from experiments using the sensors may provide students with opportunities to work in authentic scientific settings similar to those in which scientists work and attempt to generate generalizations and idealizations reflected in mathematical models or real phenomena (Gillies, Sinclair & Swithenby, 1996). This paper focuses on understanding the role that a MBL plays in learning physics and in promoting mathematical modeling in the laboratory.

The use of digital technologies may help alleviate problems associated with the current practices used in science laboratories that overemphasize procedure and do not encourage students to think about the purpose and results of their investigations (Hofstein & Lunetta, 2004). The advantages of using MBLs, over more traditional laboratory approaches, such as verification type laboratories (VTLs), have been attributed to their capacity to provide instantaneous information on the value of variables to display graphs concurrently with the observed phenomenon, record, replay, and export representations for multimedia editing and presentation, store data for further analysis (Scheker, 1998), and link theory to experiments (Bisdikian & Psillos, 2002). MBLs allow the production of visual displays thus opening possibilities for students and teachers to interact while discussing these displays.

According to Krusberg (2007), MBLs were designed to relieve students of the time-consuming “busy work” of collecting and graphing data and to help them focus on more conceptual matters related to content. The time saved from this process can be used to help students analyze and discuss data and results and to examine a larger number of physical phenomena in each laboratory period without having to master the use of complicated tools. Krusberg suggests that MBLs help student construct in-depth understandings of physics concepts, understand the empirical nature of science, appreciate the nature of scientific research, and become familiar with error analysis. However, using MBLs may not be as effective in helping students to master the use of simple and sophisticated tools and experience the use of different measurement tools.

Thomas (2001), however, warns that the hypothesized causal relationship between the use of technology and improved science learning has not been scrutinized thoroughly and accordingly such conclusions should not be used to support the use of computer technology, whatever its assumed potential, without further study. Thomas continues that “despite such potential, much of the past research in relation to the learning outcomes resulting from high school science students’ use of computers, may be considered generally ambivalent, providing little firm justification for implementing the innovation" (p. 31). Specifically, Thomas highlights the relative lack of research on students' and teachers' interactions and discourse in traditional high school laboratories, as well as in laboratories that use innovations such as MBLs and other computer-based applications. More importantly, there is lack of research on the effect of these technologies on student learning. Furthermore, Thomas suggests that research on the use of technology be based on sound theoretical frameworks, consider the importance of the use of models and modeling, attempt to investigate the role of metacognition in instruction, and study the role teachers' and students' beliefs and epistemologies play in change related to implementation of new computer technologies.

Consequently, the purposes of this study were to understand the nature of discourse in terms of knowledge types and cognitive process, source of utterances (student or teacher), and time use in MBL and VTL laboratories and to gain an understanding of the role of MBLs in promoting mathematization. Consequently, the study addressed the following questions: (1) What is the nature of the types of knowledge and cognitive processes that take place between grade 11 students and the physics teacher during a VTL versus MBL lesson? (2) How is time used during VTL versus MBL laboratories? (3) How do MBLs features, as compared to those of VTL, enhance mathematization in physics laboratory classes? It is worth noting that several research studies have investigated the relationships between the use of MBLs and performance in science or between the teaching of science, scientific discourse, and mathematization. However, the researchers could not identify studies that investigated the integration of math and physics, through an MBL as it relates to classroom discourse and mathematization.

Review of the Relevant Literature

To understand how MBL activities support or constrain students' construction of profound understanding of chemistry concepts, McRobbie & Thomas (2000) investigated the effect of students' and teachers' beliefs on their use of technology in chemistry. In addition, they were interested in the extent to which students learnt and developed thinking skills and how their learning and thinking were used in the MBL classroom. Results indicated that the use of MBLs was influenced by teacher's objectivist epistemology of chemistry and by the teachers' and students' traditional views of teaching, learning, and the role of practical work, which meant the MBLs were used to confirm scientific laws and classroom practices rather than being structured to help students to reflect on the data acquired from the MBL experiments. This deprived students of the opportunity to develop a deep understanding of chemical concepts and to change their well-ingrained misconceptions about gas laws. McRobbie and Thomas proposed that, for the potential of MBLs to be realized, there is a need to seriously consider teachers' beliefs and epistemologies regarding teaching and learning

Russell, Lucas & McRobbie (2004) focused their research on a specific component of MBLs, namely the displays, and aimed to investigate the role MBL displays play in secondary level physics students' construction of knowledge about thermal physics. Results showed that students used the MBL graphical display as a working document and were engaged in in-depth discussions of this display. During this process, students were able to confirm predictions, reconcile divergent views, analyze the graphs thoroughly, and predict future developments, thus experiencing a process of conceptual change. Additionally, results indicated that the length of the data collection stage of the experiment along with the enduring nature of the display resulted in high-quality interactions and discussions. Furthermore, results showed that the probing nature of the teacher's questions was instrumental in helping students understand the concepts and construct well thought-out responses to questions and inquiries by the teachers and members of other dyads. However, teachers can also benefit from using MBLs, as according to Espinoza (2006–2007), when science teachers employ MBLs in inquiry-based activities, their use of science process skills needed for inquiry increased and concurrently their performance on content-related tasks improved significantly.

In another area of inquiry, integrating math teaching and computers has been shown to produce positive effects on student achievement and attitudes. Funkhouser (2002), for example, showed that students who received constructivist instruction in geometry using computer-augmented activities achieved more highly in geometry and developed more positive attitudes toward maths. Dynamic computerized environments could be looked at as virtual laboratories in which students can play, investigate, and learn maths, provided that the laboratories are accompanied by suitable curriculum materials and classroom teaching practices (Arcavi & Hadas, 2000).

Mastering mathematical skills and concepts is often viewed by curriculum developers and teachers as a prerequisite for understanding physics in secondary schools. Consequently, it is left to students to transfer and apply mathematical concepts and skills in new physics contexts. However, this conception of the pedagogical relationship between maths and physics is severely constrained by the domain specificity of maths learning in the sense that maths learning is specific to the context in which learning takes place (Niss, 1999).

To improve the quality of learning in maths, Freudenthal (1991) called for having students start by exploring phenomena that require organization by using maths, a process that he labeled as mathematization. Physics offers a rich variety of such situations that are amenable to being structured by mathematization that encompasses interdisciplinary activities like modeling and representation. According to Michelsen (2005), mathematization requires that “situations from physics are embedded in the contexts to be mathematized—a horizontal linking of maths and physics. Also the vertical mathematization must include a vertical structuring, that is the conceptual anchoring of the general model in the systematic and framework of math and physics respectively” (p. 206).

The use of mathematization in traditional physics laboratories is constrained by instructional management factors, particularly data collection and mathematical calculations that consume most of the instructional time. On the other hand, because it provides the capability of real-time collection of data and a menu of mathematical models that may fit the situation, MBLs are hypothesized to enhance mathematization in physics laboratories.

Mathematization refers to a process used by students to solve real-life problems. According to the Programme for International Student Assessment (PISA, 2003)

> Mathematization consists of five steps: 1)starting with a problem situated in reality; 2) organizing it according to mathematical concepts and identifying the relevant math; 3) gradually trimming away the reality through processes such as making assumptions, generalizing and formalizing which promote the mathematical features of the situation and transform the real world problem into a mathematical problem that faithfully represents the situation; 4) solving the mathematical problem; and 5) making sense of the mathematical solution in terms of the real situation, including identifying the limitations of the solution. (p. 37).

According to the above steps, students acquire the ability to identify or apply a suitable mathematical model to a real-life problem by looking for regularities and patterns, generalizing and formalizing information through developing useful ways of representing the real-life problem, understanding the relationships between the language of the problem and the symbolic language needed to understand it mathematically and then linking it with known problems or other familiar mathematical formulations. The final step involves the translation of the mathematical result into a solution that works for the original problem context, allowing the learner to reflect on the applicability of the solution.

Horizontal and Vertical Mathematization

In mathematization, learners conceptualize perceived reality through translating the real world into the mathematical world. This is referred to as horizontal mathematization (de Lange, 1987). Then, they work on the problem within the mathematical world and use mathematical tools in order to solve the problem. This is referred to as vertical mathematization (de Lange, 1987). Horizontal mathematization includes distinguishing the specific maths in a given context, schematizing, formulating and visualizing a problem, discerning relationships and regularities, and recognizing similarities between different problems (de Lange, 1987). Alternatively, vertical mathematization includes representing relationships with formulas, verifying regularities, creating models, and generalizing (de Lange, 1987). The two phases underlying the process of mathematization, horizontal and vertical, are represented in Figure 1.

Figure 2 shows a schematic diagram of the mapping of mathematization as it applies to MBL physics lab situations. Depending on the physics teacher's epistemological framework and pedagogical content knowledge, the features of an MBL seem to provide an environment that has the potential to facilitate or impede some aspects of mathematization. First, as a didactical tool, the MBL provides students with the opportunity to collect and work on real-world experimental data in real time. Whether

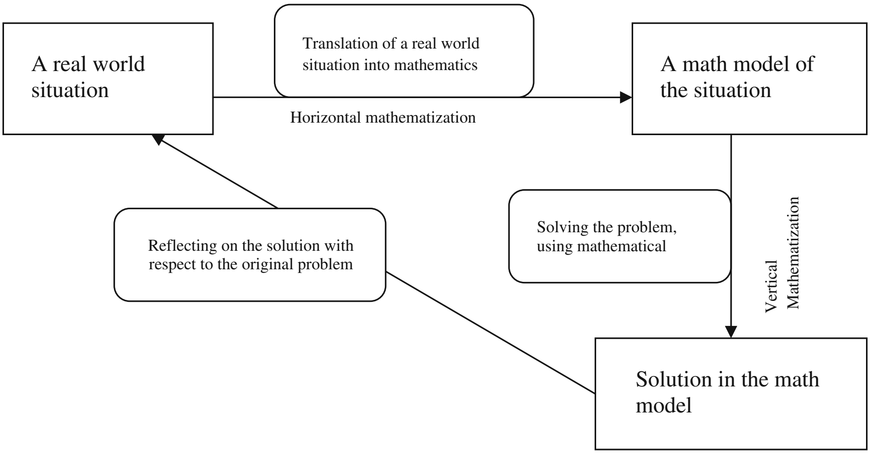

Figure 1. Horizontal and vertical mathematization according to de Lange (1987)

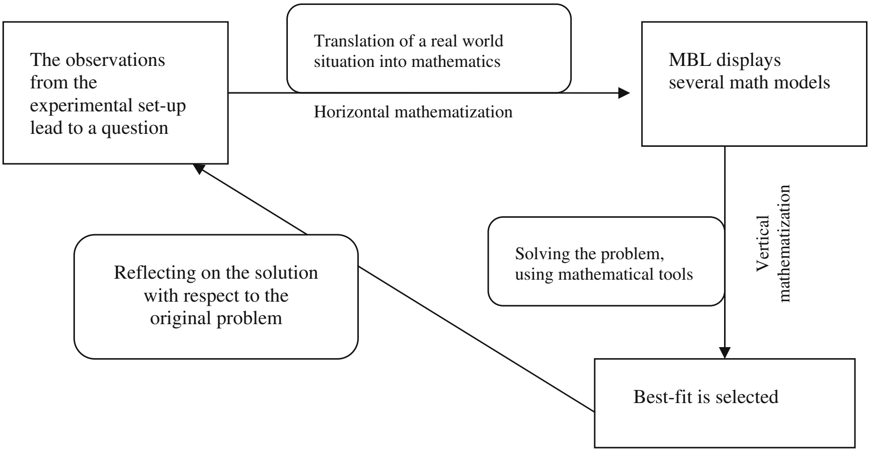

Figure 2. Mathematization as applied in MBL physics lab situations

the teacher uses this aspect to pose a question about hypothetical relations between variables or simply to use the MBL as a data grabber depends on the teacher's instructional design. Second, the MBL provides a menu of mathematical models in the form of function formulas, graphs, and numerical tables that may serve, if supported by an appropriate instructional design, as a context for engaging students in thinking about mathematical models that can describe a set of data derived from a real-world situation. Third, an MBL provides data (mean square error in the model) that may engage the students in evaluating the adequacy and accuracy of a particular mathematical model. Fourth, the real-time data collection and processing provide time saving that may be used efficiently in exploring and assessing the adequacy of a particular mathematical model. Fifth, the MBL, if accompanied by an appropriate instructional design, may be a powerful tool to engage students in validating in the real world (experimental setup), the predictions that the mathematical model may provide.

Some features of an MBL provide more of a challenge than an opportunity for engaging students in some aspects of mathematization. One major disadvantage of the MBL is the fact that it does not provide opportunities for students to engage in model construction, by trimming away reality through processes such as making assumptions, generalizing, and formalizing, which promote the mathematical features of the situation and transform the real-world problem into a mathematical problem that faithfully represents the situation. Furthermore, it would be a challenge to the physics teacher and learners as well to make sense of the processes in horizontal mathematization, without the learners' active participation in constructing the mathematical model. This provides a serious challenge to the students on the cognitive as well as motivational levels.

METHOD

Data Collection

The study was conducted in two different grade 11 classrooms in a private co-educational school in a suburb of the city of Beirut in Lebanon, in which English is the medium of instruction of science and maths. Students in the grade 11 classes came from middle to upper socioeconomic families and were following the International Baccalaureate program, a rigorous pre-university course of studies. Both teachers who participated in the study were pursuing graduate degrees in education and were known to be active in implementing innovations in the teaching of physics and maths in their schools. Moreover, both teachers were regular participants in workshops that aimed to improve the teaching and learning of physics and maths, especially in the areas of inquiry, assessment, and integrating technology in teaching science and maths.

Prior to conducting the study, the two teachers who participated in the study were involved in a 3-day workshop whose purpose was to introduce them to designing experiments and collecting and analyzing data by using computers. Specifically, the workshop aimed to help participants to design an experiment, collect data using computer sensors, analyze data collected by computer sensors, select an appropriate mathematical model to fit the data, and draw conclusions. The two participating teachers were enthused by the workshop activities and decided to start using MBL in their classrooms. Consequently, they facilitated a secure entry into the school for the researchers.

The study was conducted over the two academic years 2004–2005 and 2005–2006. During the first academic year, Hooke's law and Newton's second law of motion were taught to grade 11 students using MBL. The two MBL lessons involved students in formulating a question, designing an experiment in cooperation with the teacher, collecting data using the MBL setups, fitting the collected data into a mathematical model, discussing the modeling process, and drawing conclusions based on the experimental data, plus data manipulation, and modeling. These two sessions were taught jointly by the maths and physics teachers and were videotaped.

The following year, Hooke's law and Newton's second law of motion were again taught to grade 11 students by the same physics teacher, yet in the absence of the maths teacher. The laboratory sessions in this case were of the verification type. The two verification type laboratory sessions addressed the same topics as that of MBL sessions but involved students in collecting and analyzing data to verify content matter taught in class, discussing the results, and drawing a number of conclusions based on the results. Again, these two sessions were videotaped for the purpose of the study.

Hooke's law and Newton's second law of motion constituted a part of the school physics curriculum and were taught according to the teachers' yearly plans. In preparation for the MBL laboratory sessions, the teachers prepared lesson plans that were discussed in a group meeting with the researchers. Then, the teachers implemented the lessons in the school physics laboratory. The physics teacher typically started the lesson and did the experiment in collaboration with the students. Then, the maths teacher took over as soon as the graph was displayed to select and discuss with the students the mathematical functional relationship best described by the graph. Two of the researchers attended the MBL sessions without any interference in the lesson proceedings. The VTL sessions were also conducted in the physics laboratory. However, the physics teacher used the lesson plans he typically uses in such laboratories.

Data Analysis

While other videotape data analysis methods exist in the literature, such as the category-based analysis of videotapes (Niedderer, von Aufschnaiter, Tiberghien, Buty, Haller, Hucke, et al. 2002), the decision was taken to carefully transcribe and analyze the videotapes (Niedderer et al. 2002) to get a detailed characterization of classroom discourse. Thus, the videotapes were transcribed verbatim, and time was recorded every 2 min on the transcriptions. To answer the research questions related to types of knowledge and cognitive processes (question 1) and time use (questions 2), the transcriptions were divided into units that represented complete ideas which were labeled as "utterances". Each utterance was coded using DeVito & Grotzer's (2005) taxonomy which included knowledge types and cognitive processes and which was based on a revised Bloom's taxonomy (Anderson & Krathwohl, 2001; Krathwohl, 2002). Categories of knowledge types included factual, procedural, conceptual, and metacognitive knowledge, while cognitive processes include seven categories: perceiving, remembering, understanding, applying, analyzing, evaluating, and creating (Table 1). This analysis was based on a social constructivist orientation that emphasizes the social nature of knowledge construction and the role played by meaningful interactions in this process.

Following the analysis, data were coded using SPSS, and descriptive statistics were calculated for types of knowledge, cognitive processes and time use. Additionally, chi-square tests were used to investigate the differences between MBL and VTL sessions regarding the types of knowledge and cognitive processes. Time analysis for each transcribed lesson was performed to examine the patterns of time use during the four sessions. Each 2 min was analyzed to identify actions taking place and their duration during this period. Then, the total time for similar actions was computed for each session. The transcriptions, videotapes, and codes constituted the "audit trail", which could be examined to identify

TABLE 1

Definitions of knowledge types and cognitive processes [adapted from Krathwohl (2002), p. 214 and p. 215]

Knowledge types	
Factual knowledge	The basic elements that students must know to be acquainted with a discipline or solve a problem in it
Conceptual knowledge	The interrelationships among the elements, within a larger structure that enable them to function together
Procedural knowledge	How to do something, methods of inquiry, and criteria for using skills, algorithms, techniques, and methods
Metacognitive knowledge	Knowledge of cognition in general, as well as awareness and knowledge of one's own cognition
Cognitive processes	
Perceive[a]	Becoming aware of something directly through any of the senses, especially sight or hearing
Remember	Retrieving relevant knowledge from long-term memory.
Understand	Determining the meaning of instructional messages, including oral, written, and graphic
Apply	Carrying out or using a procedure in a given situation
Analyze	Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose
Evaluate	Making judgments based on criteria and standards (checking and critiquing)
Create	Putting elements together to form a novel, coherent whole or make an original product

[a] This process was added to cognitive processes provided in Krathwohl (2002)

methodological strengths and weaknesses and the means for establishing validity. Moreover, to ensure reliability, data analysis involved several stages. In the first stage, the two authors, an external researcher, together with a trained assistant discussed the coding scheme to make sure that there was a common understanding of its details and then they coded 10 min of the transcripts together. In the second stage, the external researcher and the trained assistant coded another 10 min of a different transcript independently, then met to discuss the coding. The interrater reliability was approximately 70%. Two more stages of coding and discussion between the external researcher and the trained assistant were needed to reach almost complete concurrence. Consequently, the rest of the data were analyzed by the external researcher. It is worth noting that, while the researchers were aware of the source of the transcripts (MBL or VTL), the assistant was not made aware of these sources to ensure reliability of the coding. "Appendix" presents examples of the coding that was used in the study.

Finally, evidence to support each of the five steps of mathematization was sought from teachers' actions and their discourse with the students. The mathematization lens was used to look at and interpret the data. Two issues were of concern to the researchers. The first one relates to whether mathematization was actually taking place in MBL versus VTL sessions. The second issue related to the type of mathematization, if any, that took place in each case. The transcription of each of the two lessons was examined for evidence of mathematization by looking at the discourse that occurred in each of the five steps of mathematization. In many cases, the video was used to supplement the discourse by examining the teachers' actions. For each step, typical episodes were selected from the discourse to be included in the results section to support the assertion about the presence or absence of mathematization.

Results

The following sections present the frequencies and percentages of utterances during the MBL and VTL sessions on Hooke's law and Newton's second law of motion analyzed by knowledge type and cognitive process. These are followed by results of data analysis by time, spent on different activities during the four lessons. Finally, the extent to which the elements of mathematization as well as the type of mathematization (horizontal and vertical) were present in the laboratory sessions is presented.

Knowledge Types

Results of categorizing utterances by their source (teacher or student) presented in Table 2 showed that teachers controlled classroom talk in all the sessions: 74% (750 [440 + 310] utterances) of the total utterances came from the teachers while only 26% (260 [166 + 94] utterances) came from students. Moreover, Table 2 shows that, in the MBL sessions, teachers and students' utterances were mostly of the conceptual knowledge type, followed by factual, procedural, and then metacognitive. In the VTL sessions, teachers' utterances were mostly procedural, followed by factual, metacognitive, and conceptual. For students in the VTL sessions, utterances were distributed between factual, conceptual, and procedural knowledge types, with very few of the metacognitive knowledge type.

Table 2 shows that 54% of the total utterances of both teachers and students were of the conceptual type in the MBL sessions as compared to 14% in the VTL sessions. Moreover, Table 2 shows that 43% of the utterances in the VTL sessions were of the procedural type as compared to 19% in the MBL sessions and 32% of the utterances in the VTL sessions were of the factual type as compared to 20% in the MBL sessions. A chi-square showed significant differences in the distribution of knowledge types in the MBL and VTL sessions ($\chi^2 = 167.5$, $p = 0.0$). Inspection of the standardized residuals with values greater than 2 showed

TABLE 2

Frequency and percentage of knowledge types in utterances in MBL and VTL sessions

	Knowledge type									
	Factual		*Conceptual*		*Procedural*		*Metacognitive*		*Total*	
	#	%	#	%	#	%	#	%	#	%
Teacher and students										
MBL	120	20	327	54[a]	113	19	46	7	606	100
VTL	128	32[a]	58	14	174	43[a]	44	11	404	100
Teacher										
MBL	89	20	230	52[a]	88	20	33	8	440	
VTL	91	29	33	11	147	47[a]	33	13	310	
Students										
MBL	31	19	97	58[a]	25	15	15	8	166	
VTL	37	39[a]	25	27	27	29	5	5	94	

[a] Standardized residual <2

that the percentage of conceptual knowledge type was significantly higher for the MBL sessions and the percentage of factual and procedural knowledge types was higher for the VTL sessions.

A chi-square on the data categorized by teachers and students showed significant differences between the utterances of teachers ($\chi^2 = 144.4$, $p = 0.0$). Inspection of the standardized residuals with values greater than 2 showed that the percentage of conceptual knowledge type in teachers' utterances was significantly higher for the MBL sessions and the percentage of procedural knowledge type was higher for the VTL sessions.

Furthermore, a chi-square on the same data showed significant differences between the utterances of students ($\chi^2 = 28.9$, $p = 0.0$). Inspection of the standardized residuals with values greater than 2 showed that the percentage of conceptual knowledge type in students' utterances was significantly higher for the MBL sessions and the percentage of factual knowledge type was significantly higher for the VTL sessions.

Cognitive Processes

Table 3 presents the frequencies and percentages of cognitive processes used in the MBL and VTL sessions. Results show that the most frequently used cognitive process in the MBL sessions was understanding, followed by remembering, perceiving, analyzing, applying, creating, and evaluating. Conversely, the most frequently used cognitive process in the VTL sessions was perceiving, followed by remembering, understanding, applying, evaluating, analyzing, and creating. A chi-square showed significant differences in the distribution of percentages of cognitive processes in the MBL and VTL sessions on Hooke's law and Newton's second law of motion ($\chi^2 = 77.2$, $p = 0.0$). Inspection of the standardized residuals with values greater than 2 showed that the processes of remembering and understanding were significantly more frequent for the MBL sessions and the processes of applying and evaluating were significantly more frequent for the VTL sessions.

Time Analysis

Time analysis of the sessions on Newton's second law of motion showed that time was mostly spent on two activities in the MBL sessions: introductory discussions and analysis of the graph that resulted from the experimental data with a relatively shorter period spent on doing the

TABLE 3

Frequencies and percentages of cognitive processes in the utterances in the MBL and VTL sessions

	Cognitive process															
	Perceive		*Remember*		*Understand*		*Apply*		*Analyze*		*Evaluate*		*Create*		*Total*	
	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
MBL	88	14	168	28[a]	202	33[a]	40	7	47	8	21	4	40	7	606	100
VTL	85	21	79	20	78	19	64	16[a]	28	7	49	12[a]	21	5	404	100

[a] Standardized residual < 2

experiment and performing calculations. Alternatively, time was divided, almost equally, among three activities in the VTL session: introductory discussions, doing the experiment and performing mathematical calculations with no time spent on graphical analysis because there was no time to draw the graph (Table 4).

Table 5 shows that the pattern of time use during the MBL and VTL sessions on Hooke's law was similar to that of the sessions on Newton's second law, with two exceptions: The teacher spent 10% of the time discussing sources of error in the data collected in the MBL experiment, while no time was spent on the applications in everyday life. Conversely, the teacher spent 20% of the time discussing applications in everyday life during the VTL session.

TABLE 4

Duration (seconds) and percentage of time spent on different activities during the sessions on Newton's second law of motion

	Time use[a] (Newton's second law)							
	Introductory discussions		*Group work (calculations)*		*Experiment*		*Graphical analysis*	
	Time	*%*	*Time*	*%*	*Time*	*%*	*Time*	*%*
MBL	1,323	50	132	5	58	2	1,140	43
VTL	658	31	830	38	678	31	–	–

[a] Time use was measured by the number of seconds for each activity

TABLE 5

Duration (seconds) and percentage of time spent on different activities during the sessions on Hooke's law

	Time use[a] (Hooke's law)									
	Introductory discussions		*Experiment*		*Graphical analysis*		*Sources of error*		*Relation to daily life*	
	Time	*%*	*Time*	*%*	*Time*	*%*	*Time*	*%*	*Time*	*%*
MBL	505	29	102	6	965	55	168	10	–	–
VTL	245	13	873	46	392	21	–	–	378	20

[a] Time use was measured by the number of seconds for each activity

Mathematization

According to PISA (2003), mathematization consists of five steps: (1) starting with a problem situated in reality, (2) organizing the problem according to mathematical concepts, (3) transforming the real-world problem into a mathematical problem, (4) working within the mathematical mode, and (5) making sense of the mathematical solution in the real world. The following paragraphs describe the process of mathematization in the MBL and VTL sessions.

Step 1: Starting with a problem situated in reality

In the two MBL sessions, the physics teacher (PT) always started with questions that encouraged the students to make conjectures about relationships between the physical variables under consideration in that particular laboratory session. For example, the PT showed the traditional experimental setup for Hook's law and started the session on Hooke's law saying:

> Look at the apparatus in front of you: read question two and try to think of a certain design. All right, I want to give you some data here: This hook, with no masses on it has a mass of 10 g and each one of these washers, of these bodies here, is also 10 grams. Copy that table that you see on the board over there. Please, in the first column put the letter m which stands for mass; in the second column l, and it stands for length. The third column, put x and that stands for extension, and then the last column, we are doing a little division here of F/X

The questions raised in each of these MBL sessions were intended to engage students in thinking about the physical relationships to be demonstrated through experimentation in that particular laboratory session. They do not exactly define a problem in a mathematical sense because the questions do not constitute a situation that can be transformed into a mathematical problem. In fact, the situation that is to be modeled mathematically is the experiment itself.

On the other hand, the following excerpt represents the way the PT introduced the session on Hooke's law in the case of VTL:

PT: What is the title of this experiment?

Student: Hooke's Law

PT: Ok, what is the purpose of this experiment?

Student: Proving Hooke's Law

PT: Excellent ...what is the purpose of Hooke's Law?

Student: Measuring elongation

Another student: Discover the stiffness of the spring

PT: Ok, we need to discover the stiffness of the spring

The PT continued by saying:

> ...What I would like you to do is to open your textbooks on page 105 ...open your book to page 105 and look at the protocol given to experiment 8.1 a little bit ...OK ...compare this to the setting you have in front of you and basically I would like you to tell me what this experiment is all about ... and what it is basically, that we're trying to do.

The first phase of the mathematization seems to be almost missing in the first VTL session as the PT reminds students of content and asks them to recall the laws they have studied in class. Soon after, the teacher reviews all the content that relates to Hooke's law covered earlier. He seemed to discourage students from providing any relational suppositions regarding variables under consideration in that particular laboratory session. In other words, the starting point is memory work and not a real-world situation.

Step 2: Organizing the problem according to mathematical concepts

The mathematical concepts that were used in the two MBL sessions were limited to the concepts of variables and relations between them. This is understandable since the objectives of each of the two lessons (Hooke's law and Newton's second law of motion) were to have students acquire concepts, principles and laws in physics. For example, the PT expressed the variables in symbols and even suggested a mathematical formulation of the relationship between the force (F) and the extension in the string (x) in the session on Hooke's law. In the session on Newton's second law, the PT identified the variables only in words. However, VTL sessions did not seem to provide similar opportunities for students simply because the concepts had been acquired in class before students attempted to conduct any experiments. Because there was little room for students to organize the problem according to mathematical concepts, they resorted to formulas they had memorized, as evidenced in the following excerpt from a VTL session on Newton's second law of motion:

PT: So what is the purpose of the experiment?

Student: To test Newton's second Law which is F = ma ...

In another situation in the same lesson, the following exchange takes place:

PT: How do you think we're gonna calculate the 'T' [the tension]?

Student: T = Kx

In a third instance in the Hooke's law VTL session, one of the students directly spelled out $F = K \times \Delta L$ when the teacher mentioned the name of the law. It is evident from the discussion above that MBL sessions provided opportunities for students to organize given problems according to mathematical concepts, whereas VTL sessions do not.

Step 3: Transforming the real-world problem into a mathematical problem

The features of MBL are critical in this phase of the mathematization process in the sense that they present constraints and opportunities. Using MBL did not seem to provide the opportunity for students to engage in "gradually trimming away the reality through processes ... which promote the mathematical features of the situation" (PISA, 2003, p.37). Rather, MBL presents a menu of mathematical models, in the form of a formula, a graph or a table of values, on the screen without any control from either the student or the teacher, thus making the MBL act as a "black box". The fact that this feature is a constraint in the process of mathematization is best illustrated in the following example. In the laboratory session on Hooke's law, discussions led the students to expect that the relationship between the force applied and the extension it produces would be positive and linear. However, the graph that was displayed on the screen was a straight line in the fourth quadrant. This generated discussion (and confusion) for the maths and physics teachers, as well as the students since they could not rationalize why the software produced a representation that was not consistent with their initial expectations. On the other hand, the MBL presented an opportunity for mathematization by providing a menu of functional relations (with the mean square error of each) for the student to choose from, based on the concept of best fit of data. This feature is unique to MBL because it provided students with an efficient method to explore the optimal mathematical model that best fits the data. VTL sessions did not provide evidence of any transformation of a real-world problem into a mathematical problem. The fact that there had been no real-world problem initially made it impossible to observe this feature. Students seemed to start with mathematical representation almost exclusively by recalling already taught formulas.

Step 4: Working within the mathematical model

In the two MBL sessions, once the graph was displayed on the screen, the maths teacher (MT) took over the lesson. The general pattern followed by the MT consisted of the following activities: Through a whole-class instructional format, the MT started a series of questions to enable students to choose from the menu, the appropriate mathematical model (functional relationship) and to rationalize their choice. The MT seized the opportunity to consolidate the students' understanding of the mathematical concepts involved (linear function, inverse function). The MT shied away from explicitly linking the mathematical concepts to the physical concepts. The display of the mathematical model on the screen provided a context for a lively classroom discourse about the best-fit model. In many cases, the discourse was triggered by discrepancies that resulted in cognitive tension between the teacher and students and among the students themselves. An example is the discrepancy between the standard (criterion) for best fit in MBL and that of the teacher. The following excerpts illustrate each of the discrepancies.

MT: What's the mean square error for the proportional fit?

MT: 0.021, right? And for the linear fit?

Student: 4.87x10−4

MT: OK, if you move a little bit here ...can you see the lower part of the yellow line? Do you see where it continues?

Student: Through the origin

MT: Regardless of the square mean error, what should it be?

MT: What's the y-intercept if the line passes through the origin?

Student: Zero

MT: So, it becomes $y = mx$, proportional fit. Does it make sense now with your physical result? Can you link it to the physical result?

A second discrepancy was between the model expected by the students and the one displayed by the MBL. This is illustrated by an episode from the laboratory session on Hooke's law. The students were led to believe that the relationship between the force and the extension in the string was positive and hence the graph would be in the first quadrant. The MBL displayed the graph in the fourth quadrant. The MT tried to rationalize the discrepancy in terms of the definitions of the variables by saying:

> Is x the difference between the initial length and extended length or the extended length itself?

On the other hand, the PT tried to rationalize the situation in terms of experimental error.

> You see the computer was recording measurements every 0.5 cm but I wasn't sure if Mario was really seeing a displacement equal to 0.5 cm ...And apparently there is a slight difference between what the computer is set to record and what actually has been happening at the cart. So there is a small error that the x here did not correspond to the x the computer program was set to have. I'm not sure if the pull by Joe all the time was constant because our nervous system sometimes does not allow us over a long period of time, to be able to hold something for a long time exactly the same way.

Both interpretations did not convince the students and left them confused.

The third discrepancy was between the PT and the MT in choosing the model and occurred in the laboratory session on Newton's second law of motion. The experiment consisted of keeping the weight (F, pulling force) constant while varying the mass (m) of the cart by adding mass to it. The PT selected the line representing $v = at$ (v, a, t represent velocity, acceleration, and time, respectively), whereas the MT tried to rationalize the choice of the model $a = F/m$ (where F is kept constant). Though both models are tenable, the second one is more appropriate and powerful. Anyway, this discrepancy led to some confusion among students.

The VTL sessions seemed to provide an opportunity for students to practice the use of calculators in an attempt to find the values they needed to fill in the tables they were supposed to complete. Once students finished observing the demonstration presented by their PT, they broke up into groups where they used their calculators to find T values (tension) and ΔL values (elongation/compression) during the Hooke's law VTL session. Similarly, students spent a very long time working in groups on a much more complicated procedure to calculate F values (force) and a values (acceleration) in the case of Newton's second law in the VTL session.

In both VTL sessions, time was not sufficient for students to plot the required graphs. Thus, the PT had to sketch "the expected" graph on the board and try to discuss it with students. Therefore, in this phase, students not only spent most of their time on mathematical calculations that were grounded mainly in conversions related to units of measurement but also they did not even make use of the data due to time constraints.

Step 5: Making sense of the mathematical solution in the real world

In the two MBL sessions, no significant attempt was made to make sense of the mathematical solution in terms of the original real-world situation (experimental setup). Both teachers missed many opportunities to have students see the power of the mathematical modeling in making sense of the physical reality. One such missed opportunity was in the MBL session on Newton's second law, when the MT established that the model representing the force (F) and acceleration (a) was a straight line passing through the origin. However, no suggestion was made to actually weigh the mass of the cart and compare it with the slope of the straight line represented by $F = ma$.

In VTL sessions, the PT missed the opportunity to relate the mathematical model to real-world aspects in the case of the Newton's second law session as time ran out while students were carrying out their basic mathematical calculations. However, this was not the case with the Hooke's law session. In this VTL session, though the PT did not relate the model to an initial real-world situation, he related it to some other aspects of real life, specifically measurement of forces by using a spring balance. This is manifested in the following excerpt from the PT:

> Since we said that each spring, depending on its nature, has its own curve, so now......... dealing with scientific technical springs that we buy for the lab, in their catalogue they

show you a curve like this (straight line) for each one ...which is standard and it shows here ΔL , 1, 2, 3, 4 ....and it shows you here forces 10, 20, 30 Newton and they tell you, you can use it to measure forces like the dynamometer ...the dynamometer is nothing but a spring put in a cylinder that has graduation ...so what this tells you is the following: Exert a force ... If you want to know the force you are exerting ..., if you succeed in letting it extend by 2 cm, then the force you have put is 20 N and this is how I'm using this spring to measure forces. The forces are very hard to measure , so that's why we use springs that have been studied ...Then, you read the elongation and then you go to the table and you should know what the force is that you have put on it. And this is to come to the idea; we use Hooke's Law to be able to measure quantitatively, values of forces ...

Student: Like the spring balance

PT: Yes ...now I wish we could get a spring balance

The PT at this stage gets a spring balance and shows the applicability of Hooke's law in a real-world situation in an effective manner.

The last step of the mathematization, which recommends relating the mathematical solution to the initial real-life situation, was missing in the MBL sessions. This was also the case in one of the VTL sessions. While the nature of MBL or VTL does not prevent the teacher from focusing on this relationship, the PT decided to emphasize it only in one out of four possible situations where it could have been done. This highlights the possible effect of a teachers' belief system about teaching on instructional decisions, regardless of the instructional technology used.

Discussion

Results of this study were interpreted in light of the special features of the instructional setups used during the laboratory sessions. In particular, the lesson plans for the MBL and VTL sessions were prepared in collaboration with the researchers. However, the MBL sessions were co-taught by the physics and maths teachers, whereas the VTL sessions were taught by the physics teacher alone.

Results showed that the conceptual knowledge type utterances were significantly more frequent in the MBL sessions than in the VTL sessions while factual and procedural knowledge type utterances were more frequent in the VTL than in the MBL sessions for both teachers and students. Moreover, results indicated that the cognitive processes of remembering and understanding were significantly more frequent in the MBL sessions, while the processes of applying and evaluating were significantly more frequent in the VTL sessions. Additionally, time analyses showed that students spent most of their time analyzing the graphs in the MBL sessions, while students in the VTL sessions spent most of their time on calculations or conducting the experiment.

Furthermore, results showed that physics experiments conducted in an MBL environment provided the kind of real-world situations that are amenable to mathematization. Thus, mathematization, suggested by Freudenthal (1991) as a pedagogical theory for the meaningful learning of math, may apply to the meaningful learning of physics as well. Finally, using MBL seems to promote effective mathematization both vertically and horizontally by virtue of its powerful mathematical tools that can be manipulated instantaneously. In contrast, when using VTL, students come to the laboratory already "knowing" what they are expected to "investigate". Thus, they are engaged in performing mathematical calculations, a situation that inhibits any horizontal mathematization and decreases opportunities for vertical mathematization.

Based on the results of the study, three assertions can be made. These are (1) MBLs provide more opportunities than VTLs for meaningful discourse about physics content, (2) MBLs provide opportunities for engagement in inquiry type activities, and (3) MBLs provide real-world situations that are amenable to mathematization and that promote model identification and assessment. These three assertions are discussed below:

Assertion 1: MBLs provide more opportunities than VTLs for meaningful discourse about physics content

It appears that the MBL tools provided students with opportunities to interact with each other and with the teacher by using higher-level knowledge type utterances. This increase in conceptual talk could be attributed to a variety of factors including availability of time for students and the teacher to interact regarding academic content and accessibility to visual displays.

Time analysis showed that 93% of the time was spent on introductory discussions and graphical analysis in the Newton's second law MBL session, while 31% of the time was spent on introductory discussions in the VTL session and 69% on calculations and conducting the experiment. Almost the same pattern can be seen in the Hooke's law session: 94% of the time was spent on introductory discussions, graphical analysis and discussing sources of error in the MBL session, while 46% of the time was spent on doing the experiment and 54% on introductory discussions, graphical analysis and applications in everyday life. Seemingly, by reducing the amount of time spent on procedural type activities, MBL sessions provided more opportunities for teachers and students to engage in higher-level cognitive processes and conceptual-type discourse. The opportunities to interact with others regarding academic content in the MBL sessions might have allowed students to activate their prior knowledge and to determine the meaning of the instructional messages more frequently than in the VTL sessions. Students in the VTL sessions, however, were mostly involved in procedural activities and in carrying out and checking calculations.

Results of this study support the hypothesis made by Rochelle, Kaput & Stroup (2000) regarding the mediation role of MBL. The computer visual displays of mathematical models represented by graphs played a mediation role by allowing students and teachers to discuss and analyze academic content and, in the process, develop shared meanings about the results of the activities. Because they can be used repeatedly and on demand, graphs produced by the MBL tools provide learners with opportunities to interact with representations of scientific events for extended periods of time, during which they can process information more deeply in collaboration with other students and the teacher (Rochelle et al. 2000). Conversely, the interactions regarding data, their visual representation, and content matter were not possible during the VTL sessions because time constraints did not allow students to draw the graph or to spend an extended period discussing this graph. Rather, time was spent on doing the experiment and on performing repetitive calculations.

To put it briefly, the tools available to students and teachers using MBLs provided them with the opportunity to shift the emphasis in laboratories from lower knowledge types and cognitive processes to higher-level ones. Thus, rather than spending time discussing experimental setups, doing repetitive calculations and manually plotting graphs, teachers and students could be involved in conceptual meaning, having discussions and mathematical modeling processes.

One significant finding of this study was that teachers controlled classroom talk in both the MBL and VTL sessions, as evidenced by the large difference in the number of teacher's and students' utterances. It appears that teachers in this study were not totally convinced of the benefits of creating an environment in which students freely express their ideas and views regarding academic content.

However, the fact that teachers controlled classroom talk does not necessarily mean that students were passive receivers of information during the laboratory sessions. Results showed that the ratio of teacher utterances to total utterances was 77% for VTL and 73% for MBL sessions (Table 2). However, there were more utterances in MBL than in

VTL sessions (606 for MBL and 404 for VTL). This may be accounted for by fact that the graphs that were produced in MBL sessions provided a context for discussion, whereas the time was spent on discussing experimental procedures in the VTL sessions. Moreover, Table 4 indicates that 678 seconds were spent on discussing the experiment in VTL compared to 58 s in the MBL sessions. Also 1,140 s was spent on graphical analysis in the MBL sessions, while no time was spent on the analysis of graphs in the VTL sessions.

The increased time spent on graphical analysis in the MBL sessions—because of the presence of the graph—seemed to have resulted in more conceptual utterances in the MBL than in the VTL sessions, whereas group work calculations and discussions of the experimental setup in the VTL sessions seemed to account for the more procedural utterances in VTL than MBL sessions. Similarly, results indicated that significantly more conceptual utterances were made by students in the MBL as compared to the VTL sessions (58% for vs. 27%). In summary, analysis of teachers' and students' utterances and time analysis support the claim that more conceptual learning took place in the MBL than VTL sessions.

Assertion 2: MBLs provide opportunities for engagement in inquiry-type activities

The nature of the MBL activities might have allowed students to be involved in a more complete inquiry process as suggested by Orfanos & Dimitracopoulou (2003). Time analysis of the MBL sessions showed that students had the time to conduct the experiments, collect data, observe the graphs generated by the MBL tools and discuss and analyze the graphs. On the contrary, time analysis of the VTL sessions showed that time was mostly spent on procedural hands-on activities and on calculations, not allowing students to reach the stage of drawing the graphs, let alone discussing and analyzing them. Students in the MBL sessions spent a relatively short time on procedural activities in a process analogous to authentic inquiry, suggesting that MBL tools could be used as inquiry empowering tools (Hofstein & Lunetta, 2004).

Assertion 3: MBLs provide real-world situations that are amenable to mathematization and that promote model identification and assessment

The results of this study support the hypothesis that physics experiments conducted in an MBL environment provide the kind of real-world situations that are amenable to mathematization. Thus, mathematization, suggested by Freudenthal (1991) as a pedagogical theory for the meaningful learning of maths, may apply for the meaningful learning of physics as well.

The results indicate that the potential of MBL in the mathematization steps for which MBL had a potential to contribute to mathematization was partially realized because of the physics and math teachers' epistemologies as reflected in their instructional designs and practices. The first two steps in mathematization (starting with a problem situated in reality and organizing it according to mathematical concepts and identifying the relevant maths) were realized more in MBL than VTL not because of MBL itself but because of the instructional designs used in each. In MBL, the inquiry instructional design called for posing a problem situation and organizing it according to mathematical relationships, whereas the VTL instructional design assumed that the lab activity was intended to verify an already known physical law.

In step 3 of mathematization (trimming away reality to construct a mathematical model), MBL had little to offer in terms of model construction. However, two potentials of MBL were reasonably realized. First, students were engaged in assessing the mathematical models that may best fit the data, by looking at the mean square error, and as evidenced by the results, this generated lively discussion and argumentation regarding the best-fit model. Second, the time saving in MBL and its utilization in exploring and assessing the adequacy of a particular model were substantiated. Time analysis of data from MBL sessions showed that most of the time (55% for Hooke's law and 43% for Newton's second law of motion) was devoted to analyzing and discussing the graph that resulted from plotting the data, while most of the time (46% for Hooke's law and 31% for Newton's second law of motion) was devoted to performing the experiment in the VTL sessions. In contrast to model identification and assessment in MBL, VTL students spent most of their time performing procedural tasks with no or very little thinking—a constraint which weakened vertical mathematization (working within a mathematical model) in VTL.

The potential of MBL in steps processing the mathematical model (step 4 of mathematization) was only partially realized because of the conflicting epistemologies and instructional designs of the maths and physics teachers. First, the maths and physics teachers conceived of their roles as providing a context to "teach their subject". For example, the maths teacher used the model as a context to teach functions and graphs without much reference to the situation they represented. Second, processing the mathematical model was also riddled with discrepancies that were due to a lack of coordination between the maths and science teachers and a deficiency in internalizing the power and limitations of the technology, as well as their surface understanding of mathematical modeling.

The MBL has potential in promoting the last step in mathematization (making sense of the mathematical solution in terms of the real situation, including identifying the limitations of the solution), in that it allows the learner to test the model in reality. For example, the learner could check the model by measuring the mass of the body and comparing it with the slope of $F = ma$ (Newton's second law of motion), or identify the limitation of a mathematical model (limiting the range of values may produce a model which is different from the theoretical one). However, the instructional design of both teachers did not make use of this potential of MBL. A replication of this study, which avoids the pitfalls of the instructional design, may better support the claims regarding the potential of MBL in promoting mathematization.

CONCLUDING REMARKS

There are always tradeoffs when technology is used in science classrooms and laboratories. In this study, there was a tradeoff between emphasizing conceptual understanding of physics or mastering the use of simple and sophisticated tools and experiencing the use of different measurement tools. Similarly, in mathematization, the tradeoff was between model construction and model evaluation. In this study, we decided to focus on conceptual understanding and on model evaluation because these are valued in the science and maths education communities.

Additionally, it is important to emphasize that the use of technology in and by itself does not guarantee that this technology is used as a cognitive tool rather than a digital resource (refer to Songer, 2007), and much of this depends on teachers' epistemologies. In this study, many of the drawbacks of using MBL can be attributed to the maths and physics teachers' epistemologies, as indicted in assertion 3. Thus, there is a need for equipping teachers with appropriate theoretical frameworks and helping them to align their epistemologies with the cognitive demands and opportunities provided by MBL.

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APPENDIX

Examples of the Coding Used in the Study

	Teacher		**Student**		**KT**	**CP**
Utterance	**P**	**M**	**P**	**M**		
OK Guys. I would like you to look a little with your physics eyes and	√				A	0
I would like you to observe the variation of velocity put on the y-axis and you have on the x-axis the time…	√				A	0
and my first questions to you is: what type of motion are we talking about?	√				B	2
uniformly accelerated rectilinear motion			√		B	1
You are saying it is uniformly accelerated rectilinear motion	√				D	1
How did you use that	√				C	2
it is a straight line passing through the origin			√		B	1
and it is constant what?			√		B	1
the acceleration is constant					B	1
where is the acceleration, can I see the acceleration immediately?	√				C	1
Yes, the slope			√		B	1
and the slope, is it constant here?	√				B	1
yes, it is constant			√		D	1
Why is it constant?	√				B	2
because it is accelerated			√		B	2
because the slope of the line is always constant			√		B	1
OK. I would like us to look now comparatively at two lines …Are the two lines indicating that the motion .. ?	√				A	2
OK what type of motion do I have here on the second one here?	√				B	2
What type of motion do I have here?	√				B	2
uniformly accelerated rectilinear motion			√		B	1
Again it is uniformly accelerated rectilinear motion	√				B	1
Where I had a light body I had uniformly accelerated rectilinear motion	√				A	1
When I had a heavy body placed, I also had uniformly accelerated rectilinear motion	√				A	1
In both cases I had V versus t is a straight line	√				B	2
In other words, in both cases what can I say about the acceleration?	√				B	2
It is uniformly accelerated			√		B	1

P: Physics, **M:** Maths

	Teacher		**Student**		**KT**	**CP**
Utterance	**P**	**M**	**P**	**M**		
What can you say about the slopes of those two lines, the one that is in yellow and the one that is in green?		√			B	2
The one with the yellow line has a larger slope				√	A	2
It is steeper				√	A	2
Exactly, steeper		√			A	2
It is a larger slope than that		√			A	2
We all know what a slope is … what is a slope?		√			B	1
Y over X				√	B	1
That is the change in Y over the change in X		√			B	1
We are still talking about math here… we didn't say anything about physics		√			A	0
What is the difference between these 2 experiments, physically speaking?		√			B	2
What happened .. what did you take from the first experiment what did you take from the second one?		√			A	2
The one in yellow moves faster than the one in green				√	A	2

P: Physics, **M:** Math

Legend:

Knowledge Types (KT)			
Factual knowledge	**Conceptual knowledge**	**Procedural knowledge**	**Metacognitive knowledge**
A	B	C	D

Cognitive Processes (CP)						
Perceive	**Remember**	**Understand**	**Apply**	**Analyze**	**Evaluate**	**Create**
0	1	2	3	4	5	6

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