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Developing Cognition with Collaborative Robotic Activities

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ABSTRACT

Cognition, faculty related to perception, imagination, memory, and problem solving, refers to internal mental processes through which sensorial input is acquired, elaborated, used, and stored. One of its importances relies on the fact that it affects in a direct way the learning potential. It has been shown that, even thou cognitive processes develop side by side with biological maturity, this cognitive development can be enhanced by means of mediated learning as signaled by Feuerstein's Mediated Learning theory. Based on this theory is that we propose an intervention model that addresses school academic issues using technologically assisted small group collaboration, pursuing a dual academic objective: to thrive students' cognitive processes while addressing school curriculum topics. The purpose, therefore, is to balance the students' cognitive differences by means of in-school content-filled classroom activities. Our aim is to make use of peer mediation in a real world setting with a virtual construction of it. In this paper, we describe this novel intervention model along with an in-school usage experience. For this, we present an activity designed for high school students, specifically aimed to assist the learning of kinematics, graph interpretation, and graph plotting. In this activity the students work in groups of three, using a robot and wirelessly interconnected Personal Digital Assistants (PDA). By means of a controlled experiment, we show how technologically-supported peer mediation promotes the students' enrichment of their cognitive processes in each of the different stages of the mental act (input–elaboration–output), favoring communication skills, insight, and reasoning, while also restraining impulsive conduct and trial-and-error answers.

Keywords

Cognition development, Robotic assisted teaching, Interactive learning environments, Face-to-face computer supported collaborative learning, Intelligent tutoring systems

Introduction

Cognitive processes are the organizing mental structures which control the subject's interpretation and storage of information (Neisser, 1967). This establishes, among others, the conduct toward stimuli, affecting in a direct way the capability of learning.

According to Piaget (1966), cognitive processes develop as a result of the interaction between stimuli and the organism. In this perspective, where cognitive development goes side by side with biological maturity, the organism is treated as a receptor of stimuli that, by means of these, builds up and matures its cognitive processes. Feuerstein expands on this idea indicating that human beings are cognitively modifiable (Feuerstein, 1970; Feuerstein et. al, 1980). He proposes that the cognitive development of an individual can be enhanced by means of a mediator who selects, organizes, and structures stimuli in order to attain a specific goal. The results of the mediation are the acquisition, by the mediated subject, of appropriate behaviors, sets of knowledge, and operational structures which modify his cognitive structure, thus allowing the enrichment of his cognitive processes.

The aim of peer mediation is to develop mediation teaching styles and cognitive modifiability. Peer mediation is mainly based on Vygotsky's sociocultural and Feuerstein's mediated learning experience theories (Vigotsky, 1930/1978; Feuerstein, 1986). Experimental research has shown that peer mediation improves analogies capabilities (Tzuriel & Shamir, 2007), thrives inventive thinking skills (Sokola et al. 2008), and increases scores in math (Shamir et al. 2006) and Science (Cattle & Howie 2008). There is also work performed in adults, where it has been used with organizational groups that need to be flexible enough to lead initiatives for change (Dawes, 2006).

Feuerstein's Instrumental Enrichment Program (FIE) (Feuerstein et al. 1979) intends to modify the cognitive structure of disadvantaged students, or persons with special educational needs. This program, based on the Mediated Learning Experience (MLE) theory (Feuerstein, 1986), consists of a battery of activities, tests, situations, and problems, constructed to modify the students' cognitive deficiencies. Nevertheless, since the aim of the program is to correct cognitive functions, no specific academic issues are addressed.

In this paper we propose, based on Feuerstein's theories but not on his instruments, an intervention model that addresses school academic issues using technologically assisted small group collaboration. We focus on a dual academic objective; to thrive students' cognitive processes while addressing school curriculum topics. The purpose, therefore, is to balance the students' cognitive differences by means of in-school content-filled classroom activities. Our aim is to make use of peer mediation in a real world setting with a virtual construction of it. We show our approach with high school children working in groups of three, using a robot, and each with a wirelessly interconnected Personal Digital Assistant (PDA). By taking advantage of the robot's autonomy and accurate navigation systems, and the mobility of PDAs, we designed an activity designed to assist the learning of kinematics concepts, graph interpretation, and graph plotting. By means of a controlled experiment, we show how cognitive functions can be enhanced with technologically supported peer mediation.

This paper is structured as follows: Section 2 introduces the cognitive functions addressed; Section 3 illustrates the pedagogical model; Section 4 details the technological system; and section 5 describes the implemented activity and results. Finally, Section 6 presents the conclusions of this work.

Table 1. Feursteins defined cognitive functions

Cognitive Function	Mental Stage	Ability to:
Clear perception	Input	Accurately distinguish stimuli information
Precise information gathering	Input	Perceive information thoroughly, selecting relevant data in a careful and organized way
Systematic exploration of a learning situation	Input	Organize and store the received information
Spatial organization	Input	Establish relations between events and objects located in space
Temporal orientation	Input	Establish relations between past and future events
Object conservation	Input	Preserve an object as invariant even though some of its attributes change
Organization of information	Input	Use different information sources, basic for establishing relations events and objects.
Perception and definition of a problem	Elaboration	Determine what is asked by the problem, what data must be found, and how to find it
Selection of relevant knowledge	Elaboration	Choose relevant knowledge needed to solve the problem
Internal mental representation	Elaboration	Use abstract symbols and concepts to represent and generalize reality
Perceptual organization and structure	Elaboration	Direct, establish and project relations
Conduct planning	Elaboration	Develop a strategy which includes every step towards the goal or solution. Steps must have an order and a temporal sequence.
Hypothetical thinking	Elaboration	Construct and validate hypotheses
Logic evidence	Elaboration	Prove answers by means of logic reasoning. Ability to justify a solution.
Explicit communication	Output	Use a clear and precise language to communicate an answer to another individual.
Uninhibited answer communication	Output	Express the answer in a fast, correct and systematic way
Answer Control	Output	Reason and consider before giving off an answer. Restraint trial and error kind of answers.
Accurate and precise answer	Output	Accurately identify and use different dimensions, such us size, distance and time, as well as relations among them

Cognitive Functions

Feuerstein' approach works at a metacognitive level. It is grounded in a cognitive map which identifies the cognitive functions in their input, elaboration and output phases (Dawes, 2006). For the correct execution of each of these phases, the individuals require to employ diverse mechanisms and mental processes, defined as cognitive processes. Therefore, these processes may be understood as the set of internal, organized, and coordinated mental actions through which an individual processes received information, builds answers and conclusions, and communicates them. The cognitive functions of each of the three stages, as defined by Feuerstein (Feuerstein et. al, 1980), are shown in Table 1.

The input functions refer to the amount and quality of the data gathered by the individual before facing the solving process. After, the elaboration functions concern with the resolution process itself. Finally, the output functions relate with the correct and precise communication of the constructed solution.

During the first stage (i.e., input) the individual understands the problem, determines the ways to address it, and gathers relevant data, storing it in an organized and structured form. In this stage, the employed cognitive functions relate to perception, comparative conduct, language use, analysis of different information sources, use of spatial-temporal relationships, and impulsivity restraint.

Throughout the second stage (i.e., elaboration) the individual solves the problem by constructing an appropriate answer. For this, he analyzes and relates the previously acquired information, develops abstract representations, proposes hypothesis, validates them, and justifies his solution. Depending on the problem addressed, the solution may be not unique, what favors divergent reasoning.

In the last stage (i.e., output) the individual communicates the constructed solution. In this stage the individual must use clear and precise language in order to express the answer in a fast and correct way. In this stage the individual is expected to reason and consider before answering, overcoming random and trial-and-error type of responses.

Intervention Model

Feuerstein's Instrumental Enrichment Program (FIE) focuses on the cognitive functions shown in Table 1. Supported by a battery of specifically designed instruments, its aim is to modify the cognitive structure of individuals, correcting deficient cognitive functions and improving the development of their operational abilities. The intervention we propose, while not based on FIE, it's based on its underlying theoretical base.

The intervention model we propose is based on three main aspects. First, it exploits peer mediation through face-to-face collaboration (Zurita & Nussbaum, 2004; Zurita & Nussbaum, 2007), being the activities designed to be solved not individually, but collaboratively by a small group of students; second, it exploits the real world in which the students are immersed; and third, it combines this real world dimension with an abstract dimension. The underlying technological system that supports these requirements will be described in the next subsection. Following, we will describe the pedagogic model of the interventional activities.

Technological Model

The technological system used consists of an autonomous mobile robot and a set of wirelessly interconnected handheld devices; at the beginning of the activities, each student is supplied with one of these handhelds (Figure 1). As seen in the figure, the students and the robot share a common physical space.

This system allows exploiting the real dimension by means of a mobile robot able to interact with the physical world in two ways, sensing it and moving through it. Because mobility is fundamental for real-world interactions, the robot must be supplied with accurate navigation systems to allow it to precisely fulfill the educational activities. In relation to the students, the inherent mobility of the wirelessly interconnected handheld devices allows them to explore, measure, and analyze the physical environment.

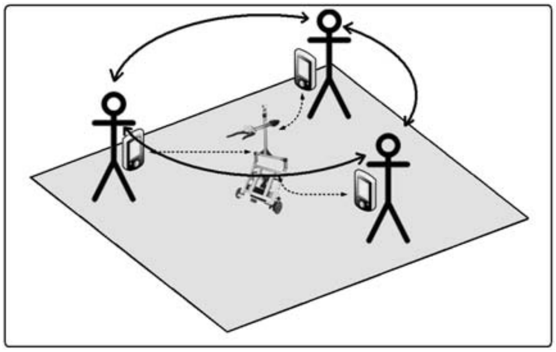


Figure 1. Collaborative Robotic System diagram

The abstract dimension is provided by the handheld devices, where the students are requested to solve the problems. In this way, while a part of the problem is displayed physically, students model this reality to be able to provide abstract answers based on relevant physical information. Therefore, the handhelds graphical interfaces are the main mean through which each student interacts with the technological system.

Regarding face-to-face communication, for it to happen effectively among the students they must be allowed to keep a constant visual contact among them. In this sense, because of the reduced size and mobility of the wirelessly interconnected handheld devices, these become transparent tools during the activities, providing neither physical nor visual barriers among the students, allowing constant visual contact and face-to-face interactions to occur in a natural way.

Technological Requirement	Description
Interaction with students	The system must provide an interface to allow its interaction with each student.
Communication among devices	Seamless communication must be provided among all system's devices, which is accomplished through wireless communication.
Interaction with real world	The system must be able to interact with the physical world, perceiving it and acting on it.
Autonomous Mobile Device	The system must provide a mobile device capable of traveling precisely and autonomously in its surrounding environment.
Face to face interaction	The system must not obstruct visual contact between the students. It must also provide the students of a shared physical space in which they can undertake effective face to face interactions, even when interacting with the technological system.
Student mobility	Students must be able to freely move around their surroundings to explore, measure, or analyze the interaction between the system and the environment, as well as to favor student's face to face interaction.

Table 2. Requirements of the technological system

Finally, collaboration is supported based on the wireless interconnection among the handheld devices and the robot. Based on it, the systems is able to determine tasks, roles, and interaction rules among the students. Therefore, the system is capable of guiding collaboration, for example, by forcing every student to agree with group's answer before continuing, or by distributing complementing roles among the students, generating a need in them to work together.

The summary of the previously addressed system requisites is shown in Table 2.

Pedagogical Model

The pedagogical model proposed is shown in Figure 2. First, the system presents the problem to be solved by the students, distributing relevant information among a set of handheld devices; each handheld device is assigned to a specific student. After the question has been proposed, the robot physically executes a set of movements that complement the problem's information. After the robotic motion ends, the students are required to construct a common answer in their handheld devices. This answer must be constructed in a collaborative way, either by constructing an only answer in a shared and common process, or else by allowing each student to propose an individual answer, after what the group selects the one that better addresses the proposed problem.

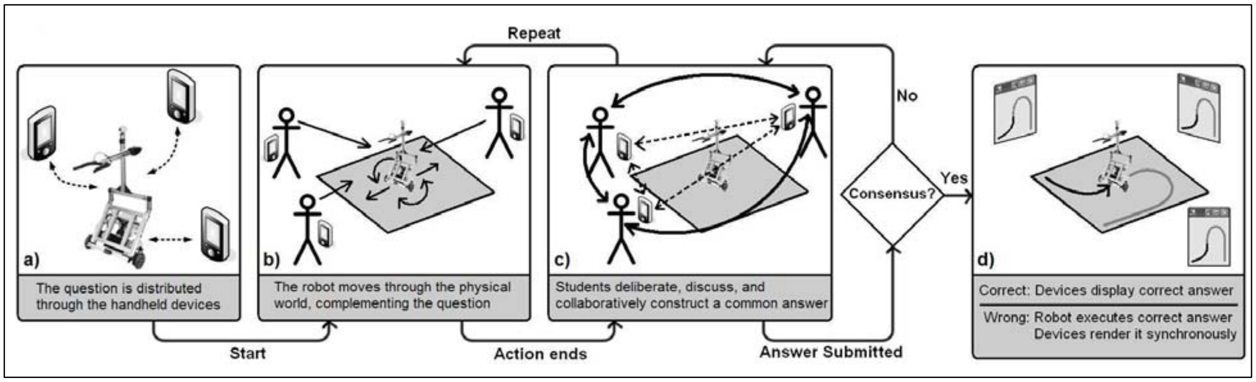


Figure 2. Pedagogical model for interventional activities

Once a common answer has been constructed the systems prompts the students to confirm their consent with the constructed answer. In case agreement is not met, the students are impelled to propose a new set of answers, or else to collaboratively construct a new one. Once consensus has been achieved, the system evaluates the answer. According to its correctness, the system is able to provide feedback by displaying the correct answer in two forms, abstractly through the handheld devices, and physically by means of the robot. Finally (not shown in the figure), a theoretical reinforcement question is presented to the group. By means of it, the system helps the students to transfer, generalize, and abstract the concrete concepts just learned.

Regarding cognitive aspects, the real dimension, which takes advantage of the physical-world, requires the students to immerse, measure, and explore their surroundings in order to gather relevant information. This dimension fosters functions related to the input mental stage such as: *Clear Perception* and *Precise information gathering* since the students must distinguish relevant information from irrelevant stimuli and/or sensorial noise; *Systematic exploration of a learning situation* since they are required to extract and store appropriate parameters out from the relevant stimuli and information; and *Spatial organization* because of the inherent spatiality of the real-world dimension of the model.

Complementary, the abstract dimension and face-to-face collaboration stimulate functions relating to the elaboration and output mental stages. The abstract dimension takes advantage of graphical interfaces. Supported by these, it requires the students to transform information obtained from the physical-world into abstract models of reality, and/or to solve the physically shown problems in a virtual environment. This abstract dimension favors the development of *Internal mental representations* based on the need to represent reality using symbols and rules, as well as *Visual transport* when required to shift from the abstract to the real dimension and vice-versa.

Face-to-face collaboration relates mainly with output cognitive functions. Based on a collaborative problem-solving approach, face-to-face interactions give the students the chance to explain and verbalize their ideas, obtaining a clearer perspective of the learned subjects (Gillies, 2006). Moreover, since the constructed answer must be approved by every group member, students are encouraged to propose and defend their ideas while asking their peers to explain and justify whatever ideas that they do not consent to or understand. In this respect, it has been shown that students working collaboratively increase their participation in group discussions, develop a higher level of discourse, interrupt less, and provide more valuable contributions to discussions (Shachar & Sharan, 1994). Hence, face-to-face collaboration promotes the development of *Explicit communication*, *Uninhibited answer communication*, and *Answer Control*. Furthermore, since the resolution is collaborative, students are encouraged to take roles and divide the problems into different complementing tasks, behaviors directly related to the *Conduct planning* cognitive function.

Finally, while the purpose and structure of any particular activity may vary according to the specific academic subjects addressed, in order to take advantage of the pedagogical model proposed, every activity must always maintain the collaborative scheme as well as the physical-abstract dimensional requirement.

Implementation

Based on the proposed intervention model, we situated our study in high school physics, specifically in graph plotting. We designed an activity named *Graph Plotter* whose academic purpose is to develop and enhance graphical skills among the students, such as constructing kinematics graphs of velocity and distance, and its reading and interpretation. To achieve this, the robot executes a set of movements to be plotted by the students. This activity, along with the cognitive processes addressed by it, is detailed in the next subsections.

Graph Plotter Activity

The educational activity consists of a group of three students that have to graph different linear movements performed by a mobile robot in a collaborative way. For this, each student is given a WiFi enabled PDA which establishes a wireless network with the robot and with the rest of the PDA devices. The tools provided to the students are a set of on-screen blank virtual axes and a set of on-screen synchronized chronometers, along with a measuring tape for them to measure real distances.

The motions of the robot are one-dimensional (i.e., the robot moves along through a straight line), varying its speed, acceleration, and direction. The types of graphs which the students are requested to plot are either position versus time or velocity versus time. On group demand, the robot can repeat the performed motion for the students to be able to gather all the required data and validate their plots.

To build the graphs the students are given measuring tapes to calculate, as precisely as possible, the relevant distances traveled by the robot. In addition, an on-screen chronometer, synchronized with the starting of the robot's movement is displayed which allows them to determine the time of occurrence of each of the different movement events. Concerning the virtual dimension, where the solution must be developed, along with the chronometer a synchronous color sweep graphically shows the movement's current time (Figure 4b).

Figure 3 shows a diagram of the activity flow. Upon starting the activity, and after the exercise's objective has been explained (Figure 4a), the robot performs a set of linear movements on the floor (Figure 5) which the students have to plot using the stylus on their PDA screens (Figure 4b–4c). The group may ask the robot to repeat the movement as many times as necessary. When all the group members finish their plot, the group is presented every individual member's solution, so as for the group to select their final collective answer (Figure 4d), what favors discussion, consideration and reasoning (Zurita & Nussbaum, 2004); if different answers are chosen, the system requires them to come to an agreement (Cortez et al. 2005). Independent of the number of times the students fail to achieve a consensus, the system will keep demanding consent before continuing with the activity.

When the collective answer has been chosen, the system autonomously determines whether the proposed answer was correct or not, informing the students. How an answer is evaluated will be described in the next paragraphs. In case the answer was correct, the system shows in each PDA screen the exact solution superposed over the students' answer (Figure 4e); otherwise the system displays the students' plot alone on the PDA screens. After this, the robot repeats once again the movement, while the system synchronously renders the correct graph on each student's PDA (Figure 4f). This allows the students to observe the relationship between the movement in the physical dimension and its abstract representation on the PDA's screen.

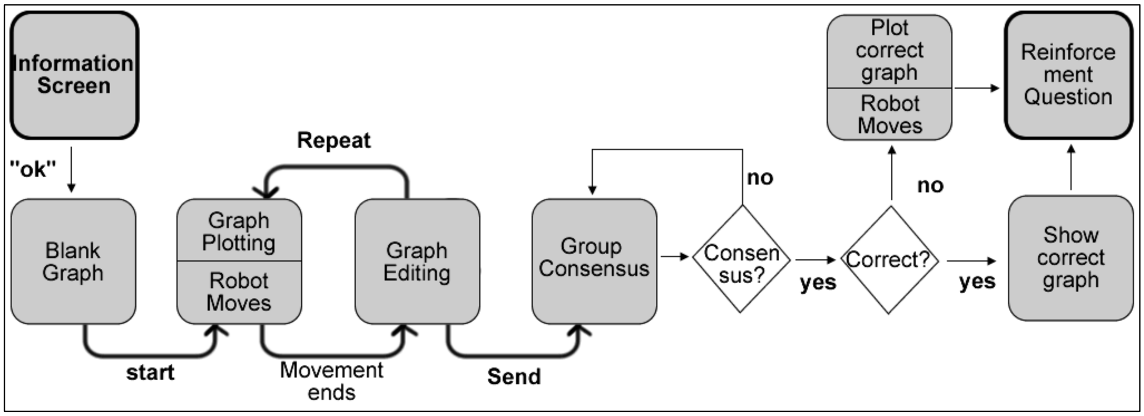
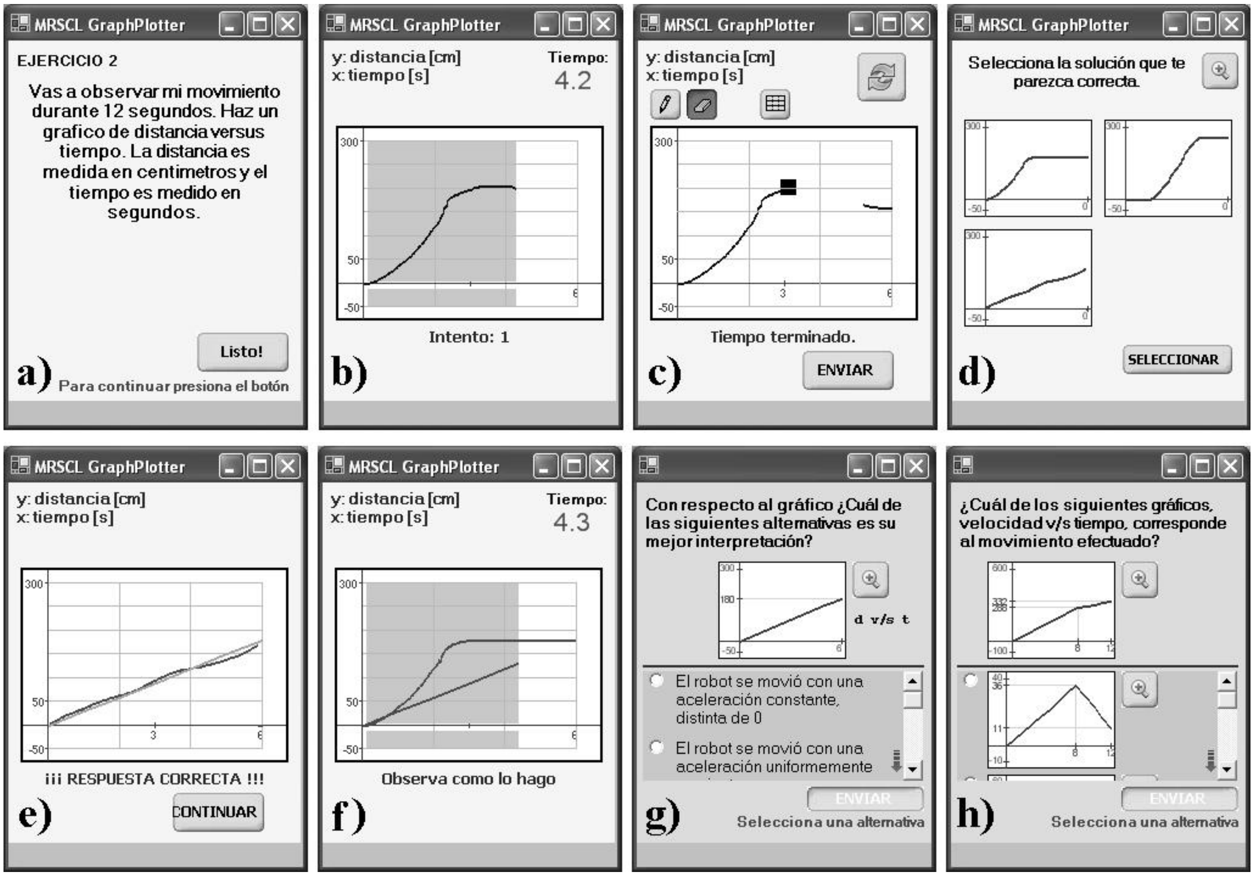


Figure 3. Diagram of *Graph Plotter* Activity flow (Mitnik et al. 2009)



EJERCICIO 2

Vas a observar mi movimiento durante 12 segundos. Haz un grafico de distancia versus tiempo. La distancia es medida en centimetros y el tiempo es medido en segundos.

Para continuar presiona el botón

y: distancia [cm]
x: tiempo [s]

Intento: 1

Tiempo terminado.

Selecciona la solución que te parezca correcta.

¡¡¡ RESPUESTA CORRECTA !!!

Observa como lo hago

Con respecto al gráfico ¿Cuál de las siguientes alternativas es su mejor interpretación?

○ El robot se movió con una aceleración constante, distinta de 0

○ El robot se movió con una aceleración uniformemente

¿Cuál de los siguientes gráficos, velocidad v/s tiempo, corresponde al movimiento efectuado?

Selecciona una alternativa

Figure 4. Screenshots of *Graph Plotter*. a) Exercise goal. b) Graph plotting while the robot moves. c) Graph editing. d) Selection of the group answer. e) Exact answer superposed to the correct group answer. f) Correct answer is rendered in each PDA. g) Symbolic-Textual reinforcement question. h) Symbolic-Symbolic reinforcement question.

Finally, independent of whether the graph was correct or wrong, a reinforcement question is asked to the students for them to infer knowledge from the previous experience. While in the plotting stage the students are asked to transform reality into an abstract model, in this final stage the plot is used to extract and analyze information. All reinforcement questions are multiple choice questions which refer to the last motion performed by the robot, addressing issues such as: displacement in a time interval, instant and average velocities, instant accelerations, textual descriptions of the motion (Figure 4g), maximum/minimum variable values, and transformation into other kinematics graph (Figure 4h), among others. This is how, while the question has always a symbolic component (i.e., the graph), the required answer may be either textual (Figure 4g), numerical or symbolical (Figure 4h). Once again, for the group to respond every individual member must agree with this collective answer.

The whole activity ends after the students have answered all the exercises planned for that activity session. These previously planned exercises are supplied to the system using an exercise file.

Regarding technological issues, all the software used in the activity was designed and developed specifically for it, including user interfaces, inter-device synchronization, collaboration schemes, and the activity logic. The physical robot used was a commercially available one.

In order to evaluate whether the proposed graph is correct, the system compares it with the exact solution performing a point-by-point error calculation. Since plotting a perfect graph is extremely difficult, the system determines that a proposed graph is correct if the sum of the point-by-point error falls below a predefined threshold.

In relation to inter-device clock-synchronization, inaccurate time synchronization between the PDAs and the robot would translate into erroneous or delayed student measurements. Hence, an accurate clock-synchronization algorithm was developed to overcome the variable latency-time and communication delays inherent to wireless network connections. Details of the algorithms used may be found in (Mitnik et al. 2008).

Graph Plotter Experimental Design

This activity was tested with 10th grade students that had been taught kinematics during the same year. The activity was used by 24 16-year-old students. Throughout the two weeks of the experiment, the students completed five working sessions of 60 minutes each. Each session consisted of a set of at most seven difficulty-increasing exercises. Throughout the activity sessions the exercises continually increased in complexity. At the beginning of each session students were randomly assigned into groups of three members. Since many of these students came from different classrooms, many of them had never interacted before with their group mates. All through the activity, video recording and in-site observations were performed. The data collected by these two methods was analyzed based on the cognitive functions described in Table 1.

During each session, exercises of position and velocity graphs were combined. Teacher assistance was provided throughout the whole experiment, yet only when required by the students themselves. Other than this, during the study the students received no other form of kinematics instruction.

Since academic learning is an important issue in the intervention, accurately determining the learning accomplished by the students is prior. In order to assess this learning, a pretest-posttest design was used, administering the pretest the day before the intervention began, and administering the posttest the day after the intervention concluded. The instrument used in both tests was the *Test of Understanding Graphs in Kinematics* (TUG-K) (Beichner, 1994), a 21 multiple choice test designed specifically to measure graph interpretation skills; its reliability and internal consistency have been validated (Beichner, 1994). A relevant issue of this test is the fact that it focuses on the seven more difficult aspects of graph understanding, aspects commonly not understood by the students after traditional kinematics classes. Hence, this test is a very difficult one and scores are expected to be low.

Finally, motivation was also measured based on the results of a post activity motivational survey. Each of the survey's questions had five possible answers: --, -, 0, +, and ++; "--" meaning "very little" while "++" meant "very much". The questions of the post-activity survey were the following:

- Did you like this activity?
- How motivated did you felt during the activity?
- How entertaining was the activity?
- How challenging was the activity?

Results

After the intervention ended, we observed that the students spent 10 to 15 minutes solving each exercise. This solving time was consistent through all the intervention sessions even thou the exercises continually increased in complexity. As mentioned before, learning outcomes were tested based on a specific graph understanding test. Cognitive aspects, on the other hand, were analyzed based on qualitative in-site and video recording observations.

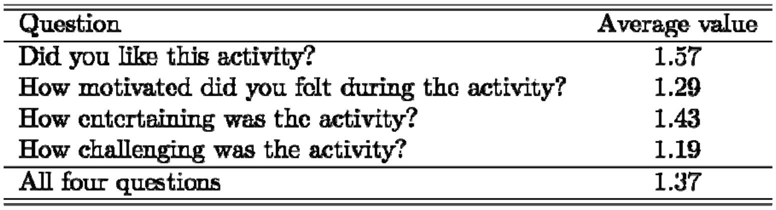
Learning results

To determine how this activity achieved learning and graph understanding throughout the students, a pretest and a posttest were administered. Even thou the activities were designed to be solved in groups, these test were answered individually by each student in order to identify the independent learning outcomes. The average pretest score was of 5.11 correct answers. This mean score increased after the intervention to a score of 7.11 correct answers. By performing paired samples T-test we could determine that this increment of two correct answers, corresponding to a 39% increase, was statistically significant ($p<=0.01$), presenting a *medium* effect size (Cohen’s d = 0.785) (Mitnik et al. 2009).

Motivational results

Regarding motivation, students were observed to be motivated when participating in the activities and during all the resolution process. In relation to the elements that promoted motivation, it was observed that motivation was supported by the students’ need and possibility to immerse into the activity. Supported by this immersion, the students were not just spectators, but became relevant actors of the activity, developing a great commitment to their team and toward the activity resolution process. This motivation was seen to prolong all-throughout the intervention. This is how during the last session many of the students expressed their wish to continue working with this kind of activities.

These observations were consistent with the results of the post activity survey. As mentioned before, each of the four questions had five possible answers: --, -, 0, +, and ++. In order to quantify these results we assigned these answers the scores -2, -1, 0, 1, and 2. The mean score of each of the survey questions is shown in Table 3. As seen, the global mean value was found to be 1.37, signaling that in average the students found the activity almost amid “motivating” and “very motivating”.



Question	Average value
Did you like this activity?	1.57
How motivated did you felt during the activity?	1.29
How entertaining was the activity?	1.43
How challenging was the activity?	1.19
All four questions	1.37

Table 3. Mean values of the motivational survey. The questions had five possible answers: -2, -1, 0, 1, and 2

Graph Plotter Observed Cognitive Processes

From the qualitative observations obtained for the previously described activity, and following the cognitive functions of each of the three stages, Input, Elaboration and Output, as defined by Feuerstein (Feuerstein et. al, 1980) we reached to the following results.

Input

Clear perception. The failure of this cognitive process would be evidenced by an incomplete or erroneous information gathering. Since the activity and the environment were both, novel and complex for the students, they were forced to learn how to observe and extract relevant data from the problem. Even though most students were unable to determine useful information on the first session, all of them were seen to develop this observance ability throughout the study. Students learned to differentiate relevant from irrelevant data. For example, after the first session students started focusing on the instants when speed or direction changed, rather than on the intervals during which the robot moved in a steady way. Based on this, they learned that in order to gather the information required in a correct and complete way, they did not needed to be measuring distances constantly, but required just a few specific measurements.

Precise information gathering. Initially, the groups presented extremely uncoordinated processes when gathering information. Even when the whole group knew what information was needed, lack of coordination appeared, shown when two students gathered the same information, also leaving some pieces of information ungathered. This forced the students to observe the robotic motion many times before being able to solve the problem. Nevertheless, throughout the study students were seen to develop collaborative strategies which allowed them to gather information in an organized and efficient way. This is how the students assigned each group member a particular role in the gathering process, showing not only collaboration, but teamwork. In a particular group strategy, for example, one student notified whenever the robot changed speed, another one marked the spot where this happened, and the last one recorded the time of this occurrence.

Systematic exploration of a learning situation. While the strategies developed proved to be effective, these would have been useless unless the students developed a way to organize and store the gathered information. Since relevant information consisted of two parts, the time and the position of the robot when its speed changed, students were seen to store information as pairs of data. Nevertheless, because of the strategies used, one student possessed the timing data while another stored the corresponding distances. Hence, each student stored his/her information in chronological order to pair it with his/her teammate's data.

Spatial organization. Students learned how to position themselves in order to fulfill each role requirement in their collaborative work. In the first sessions the physical arrangement of the groups offered little help concerning the data gathering process (Figure 5a), nevertheless this arrangement evolved to the one seen in Figure 5b, where each student is placed according to his/her role. For example in Figure 5b the rightmost student is placed far from her group to observe when the robot executes its speed changes.

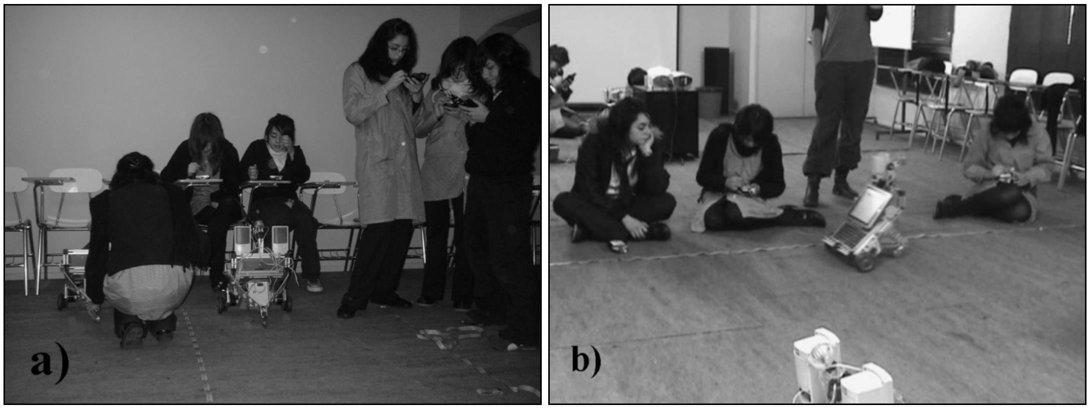


Figure 5. Students working with *Graph Plotter* Activity. a) During first sessions, the physical arrangement of the group offers little help to the data gathering process. b) Physical arrangement after strategies were developed and roles were assigned. The rightmost girl is placed where the robot changes its speed. The middle girl focuses on her PDA's virtual chronometer, while the leftmost girl, in charge of notifying speed changes, maintains her attention on the robot

Temporal orientation. In combination with *Spatial Organization*, this ability was fostered based on the nature of the problems, where it was essential to relate events such as speed changes, distances, and times. For example, students understood that velocity depends not only on distance or time, but on the relation between these.

Object conservation. This ability is supported by the invariant attributes of the kinematical concepts. For example, students could observe that the distance traveled is independent of the velocity at which it was traveled, or the time spent traveling it.

Organization of information. The use of different information sources is attained twofold. On the one hand, students obtained information presented by the robot itself, measuring it by means of measuring tapes and a chronometer. On the other hand, each teammate acted as a new information source, not only because of his/her adopted role, but because of his personal thoughts and ideas regarding the resolution of the problem.

Elaboration

Perception and definition of a problem. Throughout the activity, the types of requested graphs were randomly assigned to be either position or velocity vs. time. Therefore, students learned to discriminate what type of graph was being asked, what information was required, and how was this data represented in each case.

Selection of relevant knowledge. Position and velocity graphs have different meanings regarding slope, area under the curve, and height. After the study, we observed that the students became able to correctly analyze graphs which represented very different movements, even when their plots looked very similar. This was accomplished because the students developed the ability to switch between the two kinematics models learned, according to the proposed problem.

Internal mental representation. Expanding on the previous paragraph, because kinematic models and graphic representations are abstract representations of reality, the correct use of internal mental representations was crucial for the correct resolution of the activity. Without the ability to use abstract symbols and concepts to represent reality, the problems simply could not have been solved.

Perceptual organization and structure. During the activities, independent of the type of graph, the scale of the axis changed from problem to problem. Therefore, the students learned not only to plot their data, but also how to scale and represent it according to the set of axis posed in the problem.

Conduct planning. The collaborative strategies developed by the students, mentioned in the previous section, focused not only on the data gathering process, but on the resolution process as a whole. It was seen that, initially, the students watched the robot's movements in order to identify the positions and number of speed changes. After this they distributed roles among them, each student placing himself at his corresponding location (Figure 5b). Then they asked the robot to repeat the movement. During this first repetition the students collected and measured relevant data. Once this was accomplished, they gathered together to assemble every member's data and plot their own graphs. In case one or more members were uncertain of the plotted answer, they asked the robot to perform again, time when the students checked the correctness of their response.

Hypothetical thinking and *Logic evidence*. The development of these cognitive functions was observed throughout the discussions of the students, time when each member presented his hypotheses or ways of thinking. Based on the fact that the students were able to observe as many times as necessary the robotic movement, they were able to validate or reject the proposed graphs. Moreover, since every group member was required to agree with the group solution, the students developed the ability to justify their solutions in order to convince the other members of the correctness of the defended graph.

Output

The output-stage cognitive functions are mostly developed due to the collaborative structure of the activity. Because consensus was demanded, plenty of dialogue aroused among the students.

Explicit communication. This cognitive function was fostered each time a group member needed to defend or present his ideas to a teammate. In these common discussions it was seen how the students learned to adapt their explanations according to their listener needs. An example of these were dialogues where one student explained to another using knowledge previously acquired by both of them, using phrases such as "*remember when the robot moved slowly, the plot was like this… well, now it also moved slowly, so the plot must be similar*".

Uninhibited answer communication. Initially, the students were quite shy when the time came to explain their points of view. However, as sessions passed, students were seen to become more confident on their reasoning. Based on the constant dialogues, the students developed the ability to construct better and more precise explanations.

Answer control. Random and trial-and-error answers, as well as student impulsiveness, were completely inhibited thanks to the consensus requirement. Since each group member was required to agree with the proposed solution, and each member was seen to demand explanations before agreeing on an answer, each student was forced to reason and fundament their answers before proposing them. This reasoned proposals resulted in the construction of better explanations and faster consensus reaching.

Accurate and precise answer. Finally, this cognitive function was seen to develop by means of the answers themselves. When comparing the answers of a student in the first, middle and final sessions, we could observe that the exactitude of the plots improved significantly.

Conclusions

The technologically-based pedagogical model presented opens new perspectives regarding the use and potential of computer assisted instruction. In particular, this novel activity model has shown to accomplish a dual academic purpose: it allows the students to correct and enhance their cognitive processes while also addressing school curriculum topics, such as physics in the presented case.

From the qualitative analysis we can conclude that in order for the students to achieve cognitive development throughout all the three stages of the mental process, each of the constructs of our model is required, these are: a real dimension, a virtual dimension, and a collaborative design.

First, the real dimension provided by the physical robot focused mainly on the development of the *input* cognitive functions. Based on this real-world exploring capability the students were able to train their abilities to precisely gather information from their environment, to differentiate relevant from irrelevant data, to develop strategies, to coordinate the group members all through this gathering process, and to organize and store this collected information in a useful manner. All these are examples of *clear perception*, *precise information gathering*, s*ystematic exploration of a learning situation*, and *organization of information*, among others. This cognitive training showed visible as the students progressed from an uncoordinated data gathering process in which relevant data was commonly lost, to a distributed role scheme were each student contributed with a complementing part of the required data.

Second, the virtual dimension provided by the PDAs focused mainly on the development of the *elaboration* cognitive functions; this virtual dimension provided the activity with the ability to exploit the use of real-abstract relations. By requiring the students to develop mental representations of their physical reality, to model it using abstract symbols and concepts, and to determine the appropriate model to use in each problem (e.g., either position or velocity representations), students trained cognitive functions such as *selection of relevant knowledge, internal mental representation*, *perception and definition of a problem*, and *perceptual organization and structure*. On the other hand, based on the collaborative nature of the activity, its pedagogical design, and because the robot can act as an endless tutor, students were given the opportunity to propose as many hypothesis and ways of thinking as they want, being able to validate or reject them through the repeated observation of the robot's movements. These allowed the students to develop *conduct planning*, *hypothetical thinking*, and *logic evidence*.

Finally, the face-to-face collaborative design of the activity promoted the development of the *output* cognitive functions. Because consensus was demanded, plenty of dialogue aroused among the students. Students learned not only to verbalize their ideas, but also to adapt their explanations according to their listeners' knowledge and needs. Since each student needed to defend and logically validate his answer in front of his teammates, students were encouraged to reason before delivering an answer; this allowed impulsivity to be inhibited while insight among the students was intensified. All these are examples of how *explicit communication*, *uninhibited answer communication*, *answer control*, and *accurate and precise answer* were enhanced.

Regarding the cognitive enhancement as a whole, this approach differs from Feuerstein's Instrumental Enrichment Program (FIE) in two ways. On the one hand, while FIE's sole purpose is to correct cognitive deficiencies, not addressing any curriculum objectives, the intervention model here presented allows the teaching of specific academic issues, as for example, kinematics. Because cognitive modification is accomplished in parallel with curriculum learning, this cognitive training needs no extra classroom time, making it feasible to be inserted into the school curriculum. On the other hand, FIE requires the child to consciously dedicate time and effort in the program. Our intervention model, on the contrary, allows cognitive training to be unnoticed by the students since they are focused on solving the activities rather than on cognition training. Hence, our model achieves cognitive modification as a natural result of the activity.

Concerning curriculum issues, graph understanding showed a significant increase after the intervention. Since the measuring instrument was a rather difficult test, the 39% increase in the students' scores sustains the claim that not only cognitive modification was accomplished, but also curriculum learning.

Finally, students were seen to learn in a rather stimulating environment, as confirmed by their will to continue participating in this kind of activities. This finding was also supported by the results of the motivational survey which showed that in average the students found the activity to be either "motivating" or "very motivating". It is important to say that, while motivation may be attributed to the newness of the technologies used, we believe this to be relevant, but not a key issue. Based on the observations made, and on the fact that motivation remained constant all-through the intervention, we believe that the key issue that promoted motivation among the students was the fact that the students' needed to immerse into the activity setting, becoming relevant actors of the activity, and developing a great commitment toward their team and toward the activity resolution process.

To conclude, regarding the future work of this research, it focuses on the design and development of new educational activities which take advantage of the pedagogic and technologic model here proposed. Examples of activity subjects can be found in the field of mathematics, where the robot may be used to illustrate concepts of geometry, vectorial calculus, and path planning, among others. In relation to the measurement of cognitive functions, part of the future work focuses on the development or modification of measuring instruments in order to be able to obtain quantitative measures of the cognitive progress of the students.

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