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Engineering education in the development of physical thinking

D Díaz Arenas¹, H J Gallardo Pérez¹, and J P Rojas Suárez¹

¹ Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: henrygallardo@ufps.edu.co

Abstract. The present research project seeks to identify an application of didactic engineering in the teaching and learning processes of mathematics and physics through a pedagogical strategy in a group of 24 ninth grade students from a public educational institution located in the municipality of Tibú, Norte de Santander, Colombia, in order to determine the degree of appropriation of the concepts associated with mathematical physical thinking. Three didactic sequences were designed and applied, based on the theories of didactic situations and semiotic representations, to later determine their effect on the learning process, which showed better results in the communication competence, but the reasoning and problem-solving competences still show difficulties in the students. Therefore, it is concluded that the work in the classroom should be strengthened with the implementation of didactic sequences with clear objectives and that enhance these two processes of mathematics and physics.

1. Introduction

The new approaches that are emerging in the education sciences not only facilitate the appropriation of knowledge itself as an end in itself, but also the need to form an autonomous subject that can successfully face the demands of the citizen. It is no longer a question of students learning, but rather of being able to manage their own learning in an intelligent and autonomous manner, and that the knowledge they acquire be useful in their daily lives (personal, social, and professional) and for solving problems and dilemmas of all kinds, from those of a practical and domestic order to the most profound ethical and social ones [1].

Today's education has a new and greater responsibility: instead of offering information, it must train and enable the learner to seek it, select it critically, understand it and apply it effectively to his or her personal needs and those of society. This leads to a great deal of change, and more, in the way physics is taught at all levels of education, but mainly from the first years of basic education [2]. This has been mainly due to the following two reasons.

The first is the great development of special didactics that has taken place in recent decades, which has revealed that the way in which different knowledge is learned varies according to the content, since it normally involves diverse cognitive processes and involves the exercise of specialized skills. Solving an equation, for example, does not involve the use of the same processes or the development of the same cognitive skills as the literary analysis of a story.

The second reason has to do with the particular attention that has been devoted to the teaching and learning of physics both in terms of its importance in school training and, paradoxically, because of the high rates of averages and failures that students often exhibit.

Learning physics involves hard work, the results of which are often paradoxically disproportionate. In fact, in spite of being a subject in which institutions, teachers and students invest time and effort, the grades that accompany evaluations are not among the highest. The factors involved in these low results



are obviously multidimensional, and include elements such as the socio-affective and cultural context of the student, his or her environmental and economic conditions, the levels of self-motivation and that which he or she receives from his or her school and out-of-class environment, the training and incentives that the teacher possesses, the conditions, means and materials available to educational institutions, the student's attitudes towards the subject, his or her level of commitment to his or her own training, among other aspects, to mention but not limited to [3].

The teacher teaches how to solve typical problems and the student learns that being able to replicate these processes implies the approval of the subject. The most immediate consequence of this way of acting is palpable at first sight: students learn mechanically the way to solve prototypical problems as they have been taught in class, but they are not able to understand the nature of such problems and forms of solution, much less extrapolate their application to real life situations of people [4].

There is, therefore, an almost absolute divorce between physical thinking, mathematical knowledge and the applicability of knowledge to reality. Faced with the difficulty of developing and strengthening specific physical-mathematical thinking, a solution is chosen (replicating processes) that instead of solutions brings even greater problems: misunderstanding of the nature of the discipline, of its usefulness and, on top of that, feelings of frustration, rejection and aversion towards the sciences [5], which continue in many students throughout their academic career and even outside the various scenarios of academic training. In many cases, failure and dropout are caused by the inability of some students to pass these subjects [6,7]; in addition, among the causes of poor student academic performance may be the performance of the teacher [8].

Now, from being the recipient of a wealth of knowledge, the student has become the main subject of attention of the processes, aimed at developing in him/her the ability to obtain and manage autonomously the knowledge necessary for the resolution of the various life situations that he/she goes through in the course of existence [9].

It is therefore necessary to propose alternative solutions for educational practice, among which is the suggestion and exercise of new teaching strategies that facilitate the development of skills and abilities in all areas, particularly those related to physics and mathematics. Strengthening the competencies associated with these areas would have an impact in the medium term on the results of standardized tests for measuring the quality of education and student performance. Therefore, the general purpose of this paper is to propose the use of a set of didactic strategies aimed at improving the physical-mathematical performance of students in basic education.

2. Materials and methods

The research is framed within the quantitative paradigm with both descriptive and inferential approaches [10,11]. The following variables are identified as dependent Variable, level of appropriation and understanding that students in the sample have regarding the standards associated with physical-mathematical thinking. Independent variable, the didactic sequences framed within the methodology called didactic engineering, which are based on the theories of didactic situations and semiotic representations. The research hypothesis suggests that with the implementation of the sequences there are significant improvements in students' academic performance.

Procedure carried out. The research process was based on the methodology called didactic engineering, which defines four stages that were mentioned very briefly.

Preliminary analysis stage. It corresponds to the collection of data that allows to establish the origin of the problem to facilitate its understanding. In it, the epistemological origin of the concept is analyzed, and then the characteristics of the dynamics of teaching the concept in the classroom and the concepts that are derived from such teaching are reviewed. This stage was consolidated with the application of the knowledge test to the students in the sample.

Analysis stage to priori. This phase describes and predicts what the student will do in the experiment. These predictions do not come out of the blue, they are based on some pedagogical current, for example: theory of didactic situations, constructivist theory, theory of semiotic representations, critical mathematical theory, among others; with the purpose of generating didactic sequences associated to the

subject under study, with which it is intended to control the students behaviors and try to solve situations of conceptual or procedural difficulty. This stage is evidenced in the research in the process of design and validation of the three didactic sequences created.

Experimental stage. It is associated with the field work, since it is in this stage of the process where there is contact with the student and his or her conceptions. It is important at this stage that the researcher not only limits himself to the answers provided by the student, but also identifies those aspects that present greater difficulty, the characteristics of the doubts and other aspects that may tend to improve the teaching process. This phase was completed in the course of three weeks, period of time in which the didactic sequences were applied.

Post evaluation and analysis stage. It is based on the set of data collected throughout the experimentation such as observations made of the teaching sequences, student productions inside or outside the classroom, among others; to finally compare the results of the two analyses, the a priori and posteriori. This phase is carried out when the aim is to determine the effect of the implementation of the teaching sequences, which is supported by a descriptive exploration of the results and then to ratify the conclusions through the validation of the hypothesis system.

Instruments used. Two types of instruments were designed and implemented for data collection: knowledge test and didactic sequences.

Knowledge test. This instrument is applied in two moments of research and aims to determine the level of mastery that students have of the skills associated with physical-mathematical thinking. The test is composed of several items, which are mainly focused on the resolution of everyday situations expressed in natural language, which in some cases is supported by a graphic, tabular or bar chart representation, to later answer a series of questions aimed at developing the processes of communication, reasoning and problem solving.

Didactic sequences. To the pedagogical model of the new school [12], which is the one developed at the site where the research was conducted, a modification process was carried out in which three didactic sequences were designed, which were based on Brousseau's theory of didactic situations [13] and on Duval's theory of semiotic representations [14] for the design of the different activities. The dynamics of the application of the sequences incorporates a phase of cooperative work in which the student is expected to formulate all his doubts and initially, these are attended to with his team until he assumes a position as a group, which at the moment of the plenary is agreed upon with the whole class and thus tries to build up the classroom knowledge.

3. Results

Below, for each of the terms of the concepts mentioned, percentages are presented that reflect the difficulty or error in each of the items derived from the diagnosis found in the members of the sample. Once the process of implementing the didactic sequences was completed, the students were given the knowledge test to the next class without being told that there was an evaluation, that is, the students presented the test with the skills they developed during the pedagogical intervention. In each competence, the learning to be achieved and the difficulty found in each of the evidences that constitute it are identified, the two percentages representing the results in the pre-test and post-test, respectively.

Communication competence. Learning: recognizing the concept of measurement as a measure involved in metrology. Perform length measurements. Based on the representation of a set of situations and explain their differences in different distributions: recognize measurements (16%, 0%), explain differences between measurements (60%, 68%). Learning: compare, use and interpret data from real situations and translate between different representations of a set of data: interpret information presented in tables and graphs (52%, 16%), compare different representations of the same set of situations (92%, 44%), compare and interpret data from different sources (96%, 48%). Learning: recognize the possibility or impossibility of an event occurring based on a given piece of information or a phenomenon: identify the possibility or impossibility of an event occurring according to the conditions of the established context (68%, 32%). Learning: recognize relationships between different representations of a data set and analyze the relevance of the representation: identify forms of representation relevant to the situation

from a data set 40%, translate between different forms of data representation (40%, 32%), recognize the appropriate scale to a data set (40%, 56%) select relevant information from different situations (40%, 32%).

Reasoning competency. Learning: establishing conjectures and verifying hypotheses about the results of an experiment applied to physics: verifying hypotheses from the results in a dynamic experiment using basic concepts of physics (88%, 64%) comparing the degree of similarity of two or more events in the same natural space, based on their observation (40%, 12%) Learning: To make assumptions about trends or relationships identified in data sets using approximations or methods of adjustment (56%, 20%) To make assumptions about the behavior of a population according to the results for a sample of the population (88%, 92%). Learning: use different methods and strategies to calculate the probability of a simple event: recognize regularities in physical phenomena and random events (100%, 96%) recognize the appropriate counting technique to determine measurements in a random event (100%, 100%), use different information to assign measurements to simple events (100%, 100%). Learning: use models to discuss the nature of an event: determine and interpret the frequency and probability of physical phenomena empirically or as a result of measurements (100%, 92%) interpret the probability of a simple event from its representation as a ratio or percentage (100%, 96%). Learning: base conclusions using measurement concepts and measuring devices: propose and justify conclusions (100%, 88%) interpret the meaning of measurements according to the context (100%, 92%) recognize relationships and trends between physics and mathematics (100%, 100%).

Problem solving competence. Learning: solve problems that require the use and interpretation of measurements and measuring instruments to analyze the behavior of different situations posed: solve problems that require the calculation and interpretation of measurements (100%, 92%). Learning: solve and formulate problems from a set of data presented in tables, bar charts and pie charts: use information presented in tables and charts to solve problems in everyday contexts or in other areas (36%, 32%), propose questions or problems from the interpretation of the graph or table representing a set of data (84%, 68%). Learning: solving and formulating problems in different contexts, which require making inferences from a set of statistical data from different sources: making simple inferences from statistical information from different sources (76%, 32%), solving social or natural science problems from information analysis (100%, 88%). Learning: pose and solve situations related to other sciences using concepts from physics: solve problems from the social or natural sciences using basic concepts from physics (100%, 60), make and test assumptions about the behavior of simple scientific phenomena (96%, 68%), use appropriate measurement tools to solve problems in physics in natural or social science contexts (96%, 40%).

Based on the results of the initial diagnosis, it is evident that, in the competence of communication as a physical-mathematical process, it could be determined that the evidence of learning to recognize measurement instruments, presented greater strength in students. On the other hand, comparing the degree of applicability of concepts, based on the situations presented, was the evidence of learning within the reasoning competence that presented the lowest percentage of difficulties in the members of the sample. In the problem-solving competence, it was identified that the evidence of learning that intended to use information presented in tables and graphs to solve problems in everyday contexts or in other areas, presented the lowest percentage of difficulty among the members of the sample, when it was intended to solve problems based on information presented in some type of representational record.

Once the process of implementing the teaching sequences was completed, the students were given the knowledge test to the next class without being told that there was an evaluation, that is, the students presented the test with the skills they developed during the teaching intervention. In order to check if there were improvements in the students' learning process, the following analyses were carried out. When comparing the percentage of difficulties in communication competence between the two measurements, it was found that the overall average was reduced by 18% in the post-test. It should be noted that evidence of learning, defined as comparing different representations and comparing and interpreting data from different sources, shows a reduction in errors of 48% simultaneously. In addition, in the evidence of learning called recognizing the appropriate scale for a set of data, after the pedagogical

intervention there was a negative effect reflected in the increase in the percentage of difficulty in students.

When comparing the percentage of difficulties in reasoning competence between the two measurements made, it can be seen that the overall average was reduced by 10% in the post-test. There was a 36% reduction in evidence of learning to make assumptions about trends or relationships identified in everyday situations. It should be noted that evidence aimed at formulating conjectures about the behavior of a phenomenon according to the results of a sample of the same, worsened after the pedagogical intervention.

When comparing the percentage of difficulties in problem-solving skills between the two measurements, it can be seen that the overall average was reduced by 26% in the post-test. There was a 56% reduction in the evidence of learning to use experimental techniques to solve problems in natural science contexts; in contrast to the evidence of learning to use information presented in tables and graphs to solve problems in everyday contexts or in other areas, the percentage difference was 4%. This situation would lead to think that the pedagogical intervention produced a positive effect on the understanding of physical-mathematical thinking. It should be noted that the reasoning competence is the one that leads to the greatest difficulty in students.

In order to collect statistical evidence of what was apparently observed in the classroom and in the results obtained in the measurements, the process of validation of the hypothesis system was carried out under the technique of difference of means for paired samples since two measurements were made at different times to the same sample of students. The inputs for the statistical analysis were the grades obtained by the students in each of the measurements. This information has been tabulated and processed in order to obtain a value for the t statistic, which allows the results of the two tests to be compared by means of a paired difference test. A value for the test statistic $t = 6.56$ is obtained, which leads to a level of significance lower than 1%, it is higher than the critical value that corresponds to $t_{\text{value}} = 1.71$, it is concluded that there is sufficient evidence to reject the null hypothesis, that is, that after the application of the different didactic sequences, it was possible to guarantee better results in the test of knowledge around the concepts of physical-mathematical thinking.

4. Conclusions

In terms of establishing the level of student appropriation of the basic concepts corresponding to physical-mathematical thinking set by the curricular standards, it was possible to identify from the results obtained in the knowledge test that there was a diversity of cognitive difficulties in at least 54% of the students in the sample in the three processes considered, with special emphasis on the use of various methods and strategies for making measurements, the use of models to discuss reality in context, and to base conclusions using the concepts of physics in the reasoning process. With regard to the process of problem solving, difficulties were evident in the resolution and formulation of problems in different contexts that require making inferences from a set of data from various sources, as well as raising and resolving situations related to other sciences using basic concepts of physics and mathematics.

The pedagogical intervention aimed at developing the competences associated to physical-mathematical thinking consisted in the construction of three didactic sequences which were coherently articulated with the processes of physics, mathematics and the concepts of physical-mathematical thinking for this grade. During the construction of these sequences, several representation registers were incorporated with the intention of potentializing data interpretation, and then suggesting a series of questions that demanded from students the application of reasoning, transformations between representation registers, as well as the use of several techniques to obtain results and contextualize them in the light of the proposed situations.

As regards the evaluation of the pedagogical intervention implemented for the development of physical-mathematical competences, it can be observed that the average percentage of difficulty in the post-test was reduced in comparison with the pre-test, mainly in the processes of communication and problem solving. This situation would lead to think that the pedagogical intervention produced a positive

effect in the understanding of some concepts of physical-mathematical thinking. It should be noted that the reasoning competence is the one that causes the greatest difficulty in students, possibly because it demands the understanding of specific concepts in order to formulate conjectures or validate inferences.

Finally, it should be noted that, despite obtaining significantly better results in the post-test compared to the pre-test, difficulties persist in students, especially in the processes of reasoning and problem solving, implying that these processes are developed as they are worked on daily.

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