

Essay

Teaching and Learning Pressure and Fluids

Petros Kariotoglou ^{1,*}  and Dimitris Psillos ²

¹ School of Education, University of Western Macedonia, 53100 Florina, Greece

² School of Education, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; psillos@auth.gr

* Correspondence: kariotog@gmail.com; Tel.: +30-23850-5080

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Abstract: This essay is a synthesis of more than twenty years of research, already published, on teaching and learning fluids and pressure. We examine teaching fluids globally, i.e., the content to be taught and its transformations, students' alternative conceptions and their remediation, the sequence of educational activities, being right for students' understanding, as well as tasks for evaluating their conceptual evolution. Our samples are junior high school students and primary school student-teachers. This long-term study combines research and development concerning teaching and learning fluids and has evolved through iteratively based design application and reflective feedback related to empirical data. The results of our research include several publications.

Keywords: teaching and learning fluids; teaching and learning pressure; alternative conceptions; teaching learning sequences; conceptual change; constructivism

1. Introduction

In the present paper, we describe and discuss a synthesis of several investigations we conducted concerning the teaching and learning of the conceptually demanding topic of fluids. Our aim was to enhance the conceptual evolution of junior high school students and primary school student teachers in the field of science through a proposed Teaching–Learning Sequence (TLS). Our incentive for organizing such a long-term research study was due to a number of factors, namely, the inclusion of fluids in the Greek curriculum as well as in that of several other countries, the variety of everyday phenomena related to fluids, and students' alternative conceptions identified in studies prior to our own [1]. The theoretical framework which our study is based on regarding the teaching and learning of science is individual and emphasizes the importance of learners' prior conceptions and reasoning in facilitating or preventing their understanding of new scientific concepts and models, as well as their active participation in the construction of new knowledge [2–4]. Moreover, it is argued that models that have been accepted by the scientific community may potentially undergo transformations based on research evidence, in order to become knowledge to be taught comprehensibly to target populations [5,6].

In this context, the present synthesis focuses on: the research results on students' domain-specific conceptions and reasoning in the field of fluids; content analysis of the relevant scientific models; the reconstructed research-based scientific model to be taught. In addition, the interactions between the model to be taught and students' conceptions and reasoning led to the development of a pioneering Teaching Learning Sequence (TLS) in fluids, with selected effective tasks. Moreover, we also present selected research results concerning students' and primary school teachers' conceptual evolutions in their various applications of the TLS. At the outset of this paper, we would like to clarify that, despite the presentations essentially having a linear/sequential format, during the numerous studies, there were cycles of research and development concerning students' understanding and iterative development of instructional interventions [7].

2. Students' Domain-Specific Conceptions and Reasoning in the Field of Fluids

Since fluids are included in several curricula worldwide, a number of researchers, as early as the 1980s, have examined students' conceptions related to liquids or gases prior to or after instruction, mainly in compulsory education. Briefly, a considerable number of students, before and after instruction, consider water 'pressure' to be a 'force' or a 'weight' [8], they think that 'pressure' has a preferred downwards direction, increases with depth [1,9] and that the value of 'pressure' increases with the total volume of liquid. Furthermore, other students ignore the incompressibility of liquids or consider them not to have a constant volume.

An essential aspect of these difficulties is students' confusion about pressure and force, an issue that has only slightly, but not explicitly, been approached by researchers. In the present study, we believe that students' conceptions in this domain should be examined systematically in terms of how they relate and/or differentiate the concepts of force and pressure [10]. We, thus, set out to further investigate the vector and scalar features of students' conceptions with regard to liquids in equilibrium using paper and pencil tasks, as well as semi-structured interviews. In order to corroborate the findings, the data were triangulated. For instance, we asked students (13–14 year-olds) before and after instruction, to compare the values of pressure at the same depth in two vessels containing water, for several different situations, e.g., at two different points of the water, at the backs of two divers, in small vessels, in a well, and in the sea, etc. In addition to the descriptive results, we articulated a number of mental models that are possibly used by the students in this domain, named "packed crowd model", "pressing force model" and "liquidness model", as has extensively been presented elsewhere [11].

Briefly, students who adopted the "packed crowd model" consider the density of the water to be variable. This means that the density in the narrow vessel is greater than in the wide one, thus, making the pressure greater in the former than in the latter. These students regard pressure as having no direction, it is considered or calculated on a surface. Students, who adopted the "pressing force" model, consider pressure in the wider vessel to be greater than in the narrower one, as a result of the larger amount of water. They also regard pressure as having a direction, depending on the amount of liquid, is considered or calculated on a surface, divided or shared, and it is expressed as "accepts/exerts pressure".

Students, who adopted the "liquidness model", consider the value of pressure at the same depth of a wide and a narrow vessel to be equal, and the pressure to be the property of the liquid, they calculate it on a point and express it as "has/exists pressure".

The "liquidness model" is relatively close to the scientific one, whereas the "packed crowd" one is primitive. The frequency of evidence in each model varies according to the period of teaching before the test. Usually, after the relevant instruction, approximately 40% of students understand the "pressing force model", 30% the "liquidness model", and 15% the "packed crowd model" [11]. The same models were identified among primary school student-teachers [12], though their wording was richer than that of the junior high school students.

The above-mentioned results show the major difficulties that students face when it comes to understanding this important concept, being a prerequisite for describing and interpreting fluids-related phenomena.

3. Scientific Content: Representations and Transformation

In the context of constructivism, clarification of the gap between students' prior knowledge and the representations of scientific knowledge is of great importance, for elaborating teaching, adapted to students' ideas and reasoning [13]. Taking such a theoretical perspective, we carried out a content analysis of six well-known textbooks on introductory physics, looking at how the concept of pressure is introduced and treated (for more details: [13]). The six textbooks refer to general physics in different

countries at three levels, i.e., junior and senior high school and tertiary education. Briefly, the findings of this investigation show that all of the textbooks introduce pressure via the known formula:

$$P = F/S. \quad (1)$$

(**P** is Pressure, **F** is pressing Force, and **S** is Surface)-half of them also present it through liquids, while the other half through solids. All of the books, with the exception of one, attribute characteristics of a vector to pressure, which is a scalar quantity, and use the expressions “exerted or accepted pressure”. Finally, the calculation of pressure on a surface, accompanied with arrows reinforcing the characteristics of a vector to pressure, appears in all of the six books.

Of course, the textbooks also use elements that attribute features of a scalar quantity to pressure. Such an approach is explicitly followed in four of the six books. It is mainly linked with the equation:

$$P = d \times g \times h, \quad (2)$$

where **P** is Pressure, **d** is density, **g** is gravitational acceleration, and **h** is the depth of the liquid. However, in only two of the six books do the authors use the expressions “... it has pressure...” or “... there is pressure...”, which imply that pressure is a scalar quantity. The content analysis showed that the concept of pressure is articulated and utilized in the textbooks in two distinct ways: as a vector and as a scalar quantity. This leads us to conclude that textbooks often include implicit transformations of the accepted scientific model. The main transformation is the attribution of vector characteristics to pressure, which is close to students’ dominant conception of the “pressing force model”. It would be interesting to investigate the reasons that guided the authors of the textbooks to adopt such transformations for the concept of pressure.

Students who study introductory physics as part of their secondary compulsory education are required to understand the concept of pressure as it is a prerequisite for their conceptual development in the field of fluid mechanics. From the previous description of pressure models in liquids, it is evident that the most significant conceptual obstacle is the non-differentiation of pressure from the resultant pressing force. Therefore, the students who adopted this model could not conceive the meaning of pressure as a scalar magnitude, in comparison to the resultant pressing force, which is a vector. Considered at a point of liquid, the former is expressed as “has or exist pressure”, while the latter as “accepted or exerted force”.

In order to help students comprehend the differentiation between pressure and force in liquids, we have proposed a didactic transformation or educational reconstruction [5,14,15]. Specifically, we propose the introduction of pressure as a primary concept, measured directly, qualitatively and experimentally, rather than introducing it as a derivative magnitude from force with the Equation (1) [13,16,17]. Through this approach, we expect that the concept of pressure will be more comprehensible to students and will subsequently be differentiated from force, which appears to be the dominant concept in students’ minds.

For an integrative approach concerning the teaching of fluids, further didactical transformations, although perhaps not as radical as the introduction of pressure as a primary concept, need to be made. One of these is the unification of liquids and gases in the category of fluids. This is because pressure has a unifying meaning in fluids, i.e., a scalar quantity, which differs from that of solids, where it is considered as stress, i.e., a vector quantity. In this way, we avoid using examples such as the pin of a pin on the board, or the destruction of a wooden floor with a stiletto heel, which are commonly presented in textbooks.

Another conceptual obstacle is the understanding of liquids as non-compressible, meaning that the density of a liquid does not change when it is contained in vessels of a different size, which is essential scientific knowledge. This obstacle may be overcome much more easily than the ones above, with the following experiment: a syringe filled with water is presented to the students, when force

is exerted on the plunger, no compression of the liquid is observed. This, along with the appropriate discussion, can make students understand that liquids are a practical, incompressible substance.

4. An Innovative Teaching–Learning Sequence for the Teaching of Fluid Related Phenomena

A contemporary, widespread strategy for developing innovative teaching approaches based on actively engaging students to change their domain specific ideas using several methods and techniques strategies, such as Predict–Observe–Explain physical phenomena, cognitive conflict, and the use of analogies are Teaching–Learning Sequences (TLS) [18,19]. TLSs are medium-scale (5–15 teaching hours) curriculum packages. According to Psillos and Kariotoglou, “A TLS is often both a research process and a product, which includes research-based structured teaching-learning activities. Frequently, a TLS develops iteratively out of several implementations, in accordance with a cyclical evolutionary process based on research data, which results in its being improved, with empirically validated expected students’ outcomes from the planned activities” [18,20]. Several researchers agree with this outline of a TLS [20,21]. In addition, researchers have argued that grand pedagogical theories are too general in their proposals and that models or frameworks are necessary to design, apply, and evaluate a TLS [21]—one which is most used is “The Model of Educational Reconstruction” [12]. Following this model, we have identified the learning objectives, clarified students’ domain-specific alternative conceptions, carried out a content analysis of textbooks, conceived an appropriate didactic transformation mentioned in the previous sections, as well as developed teaching strategies and activities, which are selectively presented further below. While the proposed TLS for junior high and primary school teachers is in accordance with accepted scientific models in that it focuses on the force–pressure relationship, its structure is based on a sound educational reconstruction of the treatment of these two concepts. Due to time restrictions, the TLS does not include pressure transmission, or the sinking and floating of solids immersed in fluids, although it does set the conceptual basis for studying such principles and phenomena later.

4.1. Basic Teaching–Learning Objectives

4.1.1. Differentiating Pressure from Pressing Force

The main innovative conceptual objective of the TLS is the differentiation of two overlapping concepts, i.e., pressure with the resultant force which is a hard task, demanding thorough instructional design. For this reason, we propose a didactic transposition/transformation for the introduction of pressure as a primary concept to students. Our instructional design is based on the constructivist approach of teaching and learning, and, in particular, creating cognitive conflicts between students’ predictions and the observation of experimental evidence [4]. More specifically, the suggested experiments are: (1) the comparison/measurement of pressure at two points, at the same depth, in a narrow and in a wide vessel, and (2) the comparison of the forces required to detach two different surface sucks (Figure 1).

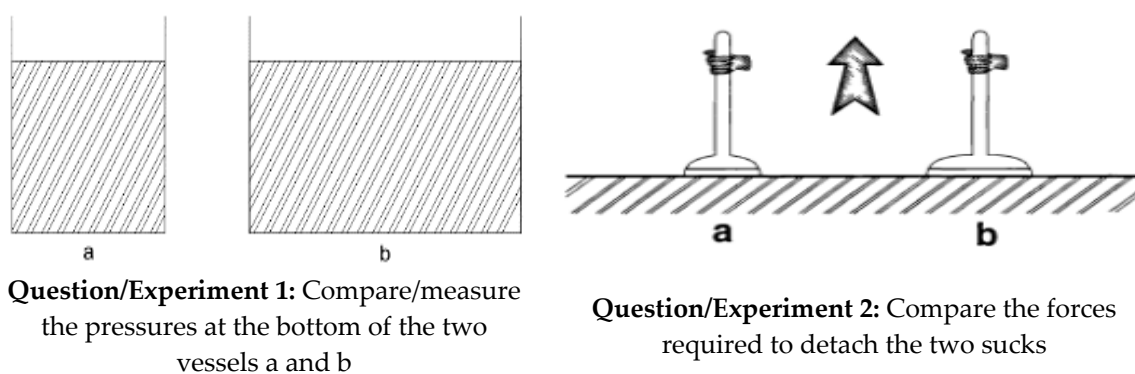


Figure 1. The two tasks/experiments that stimulate cognitive conflict in students [22].

We wish to note that this simple experiment of the comparison/measurement of pressure on the surface of two different vessels is usually not presented in textbooks. We consider this experiment as a significant intervention because it not only elicits students' alternative conceptions (see pressure models), but also helps them to differentiate force from pressure.

4.1.2. Comprehending the Compressibility of Liquids

Another innovative objective in the proposed TLS is to assist students to go beyond their conception of the compressibility of liquids, as some seem to think that, when water is transferred from a wider vessel into a narrower one, it becomes denser, i.e., its density increases. This conceptual obstacle may be overcome much more easily than the others mentioned above with the following experiment: the teacher shows students a syringe filled with water, then when force is exerted on the plunger, students observe that this does not result in compression of the water. Such an experimental result followed by the appropriate discussion can lead students to deduce that liquids are a practical, incompressible substance.

4.1.3. Classifying Both Liquids and Gases as Fluids

A third innovative objective is that of unifying liquids and gases into the category of fluids. Here, we aim to associate pressure (as a scalar quantity) with fluids, in contrast to solids, which are better described through stress, i.e., the force distributed on a surface (a vector quantity). As in several approaches, fluids are used explicitly and not implicitly as a unifying category of liquids and gases, the use of which may foster cognitive economy in students. This objective is attained by excluding all examples/phenomena or experiments where pressure is introduced via solids, for example, an object's impression in the sand or the pin on a wall.

4.1.4. Establishing the Relationship between Pressure and Pressing Force

The TLS also includes more common learning objectives, such as the dependence of hydrostatic pressure on depth: Equation (2). This rule is explained with the relevant experiment and measurements, at the same time, highlighting the experimental methodology, such as the distinction and control of variables.

4.1.5. Enhancing the Dependence of Hydrostatic Pressure on Depth

By the end of the sequence, pressure is related to the resultant pressing force with the following equation, where **F** is the Force, **P** is the Pressure, and **S** is the Surface:

$$\mathbf{F} = \mathbf{P} \times \mathbf{S}. \quad (3)$$

We state that this formula relates the two magnitudes as a linear relation, whereas, in the classical curricula, the formula used is that of Equation (1) in order to introduce pressure as a derivative magnitude via force, which is considered to be a primary concept.

4.2. Selected Features of the Structure and Teaching of the TLS

Using all the above-mentioned elements, we have developed the TLS, which consists of three units each lasting about two teaching hours. A major feature of the TLS is the active involvement of students in the experiments, which were intentionally selected to comprise tasks consisting of liquids or gases but not solids, which are commonly included in standard as well as in some constructivist curricula. Teaching is based on experimentation, group work, and teacher-led discussions. Qualitative and semi-quantitative experiments are conducted, which allow students to focus on different aspects of the conceptual model, providing them with concrete references in order to grasp the meaning, as well as discover the connection between their observations and their deductions. Quantitative experiments are used for students' conceptual growth and familiarization with the design of scientific investigations,

while the effective constructivist teaching strategy Predict, Observe, Explain (POE) is applied in the activities [23]. The experimental activity begins by students predicting what they believe will happen in the two tasks described above. Should they follow the pressure–force model, it means that they identify pressure with force, and thus they would predict that the pressure and the force in the wider vessel is greater than that of the narrower one. A detailed discussion between the teacher and students, as well as among the students themselves, will reveal the inconsistency of their reasoning. The actual case is that the pressure in the two vessels is equal, while the force required to detach the two sucks is not, leading to the existence of two different sizes: pressure (P) and pressing force (F).

In the first unit of the TLS, the aim is to familiarize students with the phenomena being studied and for them to understand that liquids and gases are fluids. To this end, the teacher performs relevant experiments and takes measurements, while the students do some experiments in small groups. The findings are discussed firstly among the group members and then, with the teacher’s coordination, before the whole class. The aim of the second unit is the following: students reinforce the concept of pressure and become familiar with the experimental methodology, focusing on the distinction and control of the variables in the Equation (2), (basic hydrostatic law) [24]. Lastly, in the third unit, students are expected to differentiate pressure from the pressing force by engaging in the process described in Section 4.1.1. In brief, the same procedure is followed as that described above, while the next step is to facilitate students to relate pressure with force and introduce the Equation (3). The content and activities of the TLS are summarized in Table 1.

Table 1. Objectives, structure content and activities of TLS, for teaching fluids and pressure, in junior high school (retrieved with permission from [12], www.tandfonline.com).

Unit/Time Duration	Objectives	Content	Activities
1st unit	Familiarization with phenomena Unification of fields	Experiments in the field of gases and liquids in terms of pressure Measurement of Phyr. and Patm Pressure difference causes the movement of the fluid Pressure has no direction	Discussion/performance in groups and classroom discussion Student experiments
2nd unit	Reinforcement of weak concept (pressure) Familiarization with the experimental methodology	Variables affecting hydrostatic and atmospheric pressure Distinction of variables Experimental verification of the empirical law for hydrostatic pressure	Discussion and performance of experiments before the whole class Demonstration of Experiments
3rd unit	Distinction between pressure and force Theory of pressing forces	Comparison between pressures/forces in a narrow/wide vessel and a small/big sucker Introduction of the relation between pressure and force	Predictions in groups and classroom discussion Demonstration and group experiments

5. Enhancing Students’ Understanding of Fluids: Selected Results

The TLS was developed iteratively and tested on two target samples with some modifications. The first sample consisted of 58 students (13–14 year-olds) from the second year of Junior High School (a.k.a. Gymnasium), which in Greece constitutes one of the compulsory education tiers. The second sample comprises primary school student-teachers studying in the Department of Primary Education, at the Aristotle University of Thessaloniki, Greece. As in numerous other countries, we think that 13–14 year old students, as well as primary school student teachers in Greece have difficulty understanding science. The main presumption for this in terms of the student teachers is that they enter their university studies through studying the Theoretical Orientation in the last two years of senior High school (a.k.a. Lyceum), which comprises arts and humanities subjects, rather than the Applied Orientation, comprising math and science subjects. Furthermore, their tertiary studies to become “one-teacher-to-teach-all subjects” offer a limited number of science courses [25,26]. The data

analysis of applying the TLS on the two sample groups gave satisfactory results [12,27]. In the present paper, due to space constraints, we present only the findings of the TLS intervention on second year junior high school students.

5.1. Qualitative Results

An effective method to facilitate the way pressure is perceived, which is a weak concept, is to have students experimentally validate pressure dependence on depth in a fluid, as well as introducing to them the fundamental law of hydrostatics. By participating in the taking of measurements, students are encouraged to apply their ideas, which is essential for their conceptual evolution. The data analysis of the recorded discussion of students and their teacher during instruction strongly suggests that such activities helped students to consolidate their initial ideas as regards the change of the magnitude of pressure in water with depth. Additionally, taking measurements of pressure enhanced students' notion of the existence of pressure. We believe that taking measurements greatly enhances students' assurance in the validity of the relationship between pressure and depth in different types of fluid. Obviously, the procedure requires further elaboration, because students realize that they need to have two measurements to be able to confirm a relationship; however, they do not seem to realize the need to have more than two in order to enable mathematical treatment. Thus, at this stage, the teacher coordinates the relevant discussion about the experimental measurements and subsequently shows the relationship between pressure and density via Equation (2).

Distinction between Pressure and Pressing Force

Considering questions 1 and 2 after teaching, most of the students answered them correctly (see Figure 1, [22]). As regards question 1, they responded that pressure is the same because the water heights are the same, as explained in the instruction. They also agreed that it is more difficult to detach the larger sucks than the smaller ones because of their difference in size (question 2). There were some students, however, who insisted on their initial conceptions in accordance with the “pressure–force model”. Following their teacher's prompts in order to find a way out of such an impasse, the students proposed to measure the pressure in the two vessels. This shows that they deem experimental measuring as a suitable procedure as a way of checking their own ideas.

It is important to note that students who used the pressure–force model came up against an important discrepancy. By claiming that the pressures in question 1 are equal, and noting that the forces required for question 2 are unequal, in order for these students to be consistent, they would have to have responded that the pressures and forces in both questions are either equal or smaller regarding the smaller area. This discrepancy is not directly perceptible to the students, which is why it is crucial at this stage that the teacher makes it easy for students to understand the discrepancy in their responses. When this contradiction becomes obvious to the students, it leads to disputing their initial ideas. The discussion between students and teacher gradually and slowly leads them to dispel the confusion regarding the two conceptions.

5.2. Quantitative Results

The results of the posttest (just after the instruction) and the post-posttest (eight months later) for both the experimental and control groups are presented in Table 2. Table 2 also includes the percentage of correct answers, as well as the corresponding confidence intervals, to the questions that are required the prediction and interpretation of phenomena involving the concept of pressure. Below are the results for questions 3, 4, 5, 6, and 7 (see Figure 2). These questions are related to pressure comparisons in various situations and are part of a larger questionnaire used in our fluid research study.

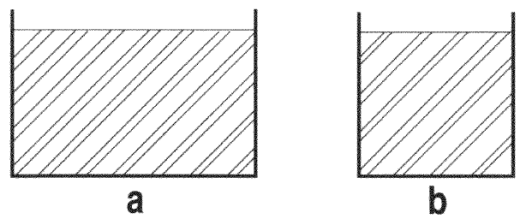
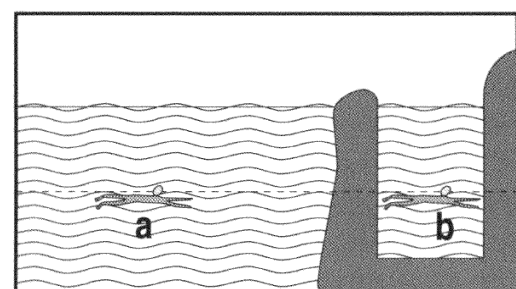
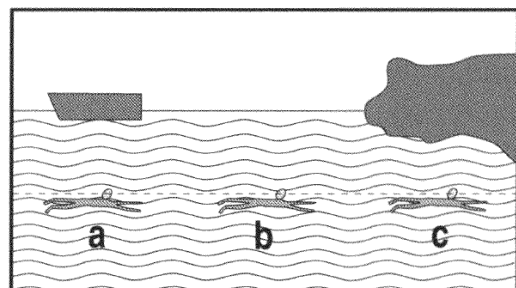
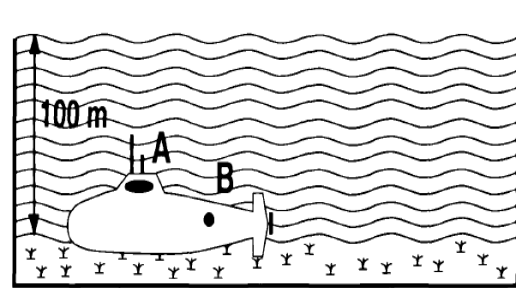
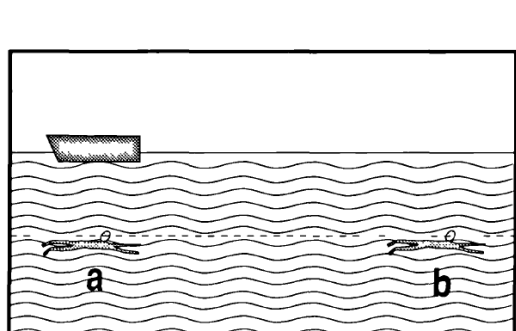
	<p>Question 3 Compare the pressure at a point at the bottom of the vessels (a) and (b) which contain water up to the same level but have different widths.</p>
	<p>Question 4 Compare the pressure at a point on the backs of the divers (a) and (b) swimming at the same level, in the sea (a) and in a well filled with seawater (b).</p>
	<p>Question 5 Compare the pressure at a point on the backs of the three divers (a), (b) and (c) swimming at the same level in the sea.</p>
	<p>Question 6 The submarine rests on the seabed at a depth of 100 m. At point A at the top window, the pressure is 12 atmospheres. What is the pressure at point B of the side window if we consider that points A and B are at the same level?</p>
	<p>Question 7 Compare the pressure at a point on the backs of the two divers (a) and (b).</p>

Figure 2. The five tasks of the quantitative questionnaire [22].

Table 2 shows the percentages of students, who answered the five questions correctly, as well as the confidence intervals corresponding to the significance level $\alpha = 0.05$. The 58 students in the experimental group answered all five questions correctly after the teaching instruction, in a range of 60.5% to 83%, whereas the corresponding percentages for the control group were 20% to 54%. For all of the questions, the difference between the experimental and control groups is statistically significant at the level $\alpha = 0.05$. The findings for the post-posttest show that the percentages of correct answers for the experimental group remained at a similar high level, with only a few regressions eight months

after teaching, whereas, for the control group, these percentages decreased significantly regarding four of the five questions (with the exception of Q 4).

Table 2. Quantitative results [22].

Question	POST TEST		POST-POST TEST	
	Experimental Group (n = 58)	Control Group (n = 214)	Experimental Group (n = 58)	Control Group (n = 214)
3	78.0 ± 10.5	40.0 ± 6.8	65.5 ± 12.0	25.0 ± 5.8
4	80.5 ± 10.5	53.0 ± 6.7	93.0 ± 6.5	43.5 ± 6.9
5	60.5 ± 12.5	20.0 ± 5.4	62.0 ± 12.5	0
6	83.0 ± 9.5	54.0 ± 6.7	84.5 ± 9.5	40.0 ± 6.8
7	71.0 ± 12.5	38.0 ± 6.5	68.0 ± 12.5	15.0 ± 5.0

6. Conclusions

In this paper, we present and analyze a research and development strategy for the teaching and learning of fluids, with an emphasis on the concept of pressure. Our strategy, a result of our research, development, and teaching, was iteratively evolved over a period of twenty years and was applied iteratively and successfully on two target groups: second year junior high school students and primary school student-teachers. The combination of qualitative and quantitative results strongly indicates that our Teaching and Learning Sequence had a significant level of success. The students recognized that pressure is a non-additive magnitude in various contexts and situations, simple or complex. They also learned that pressure has no direction, which is characteristic of pressing force but not of pressure. Moreover, students were able to discriminate between the concepts of pressure and pressing force.

We consider that our strategy is successful on account of the following: firstly, the systematic study, analysis, and understanding of students' reasoning, secondly, the transformation of the content to be taught in order for students to overcome difficulties, and, thirdly, the adoption of a Teaching–Learning Sequence as a research and development framework, which leads to a comprehensive approach of teaching and learning scientific knowledge [18–21]. Moreover, we suggest that the presented Teaching Learning Sequence, as an example of effective good teaching practice, can help physics teachers to elaborate on their teaching and inspire innovative treatment of the topic of fluids and pressure in science curricula for junior high school physics. Finally, the proposed research strategy and educational materials are experimentally validated resources appropriate for teaching in methodology courses addressed to under- and post-graduate primary education teachers.

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