Teaching and Learning in the Science Laboratory

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A Laboratory-Based Teaching Learning Sequence on Fluids: Developing Primary Student Teachers' Conceptual and Procedural Knowledge

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Abstract

This work is part of a long-term research programme concerning the design, development, application and evaluation of a laboratory-based teaching learning sequence (TLS) dealing with fluids. We have developed and discuss here an approach to the teaching of the conceptually demanding topic of fluids, which focuses on promoting student teachers' conceptual and procedural development towards a suggested scientific model and experimental method. In this study we focus on the design aspects of the TLS as well as on selected results concerning students' conceptual and, mainly, procedural knowledge.

Introduction

During the last two decades a huge amount of work has been published concerning students' understanding and conceptual difficulties regarding scientific concepts and phenomena (Gabel 1994). Less research has been devoted to pupils'/ students' views on the nature of science and their scientific practices (Driver, Leach, Millar & Scott 1996). Recently, there has been growing research interest in the study of several different aspects of students' procedural knowledge and their learning during labwork (Wellington 1998; Leach & Paulsen 1999). However, if we look at instruction, teaching approaches often treat such aspects of scientific knowledge in a rather isolated manner. Recently, more holistic teaching /learning approaches concerning the various aspects of scientific knowledge have been attempted through the development of didactical structures (Lijnse 1995) or teaching learning sequences (Psillos & Kariotoglou 1999). Teaching learning sequences (TLS) are considered as medium-scale curriculum development, as well as a product of developmental research (Lijnse 1995). Important factors affecting the design of TLS are pupils' /students' views, content transformation (Duit 1999), educational constraints and the choice of experimental field. The last factor refers to the choice of phenomena / experiments which are appropriate to facilitate learning procedures.

In this context we have been involved in a long-term research and development programme in the area of fluids concerning the teaching and understanding of aspects of conceptual knowledge and scientific inquiry. The programme involves the development and study of medium-term laboratory-based teaching sequences at different levels of education. In the present study, we present design features of a 12-hour TLS (Kariotoglou 1998), as well as results concerning aspects of conceptual learning and, mainly, aspects of learning of scientific inquiry by prospective primary teachers.

Designing a laboratory-based teaching sequence

Research results on students' domain-specific conceptions and reasoning, on the one hand, and content analysis on the other are brought into play in order to develop the

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fluids model to be taught and define the intellectual demands on students. We hold that the models accepted by the scientific community need to be transformed in order to be intelligible to students. As a result we reconstructed the scientific model to be appropriate for teaching, a research product influenced heavily by investigations on students' domain specific knowledge. Details on the content transformation are reported in previous work (Kariotoglou, Koumaras, & Psillos 1993), while basic elements of the content to be taught are included in the left column of Table I.

From previous studies (Engel-Clough & Driver 1985; Kariotoglou & Psillos 1993) and our own data, it emerges that on the one hand some elements of students' conceptions do succumb to learning opportunities. On the other hand, other conceptions may act as deep-level conceptual obstacles with regard to understanding scientific models about the macroscopic treatment of fluids. With regard to the states of matter, for some pupils fluids are considered to be a fourth state of matter between solids and liquids while a few of them identify fluids with liquids (Kariotoglou & Koumaras 1997). For most students, important intuitive conceptions containing the germ of scientific concept development are that pressure is related to the depth and the nature of the liquid, although many of them consider pressure to be influenced by the amount of the liquid in the container. This emerges from our own and others' research and indicates the non-differentiation between the two concepts, thus lending the characteristics of force to the concept of pressure (Kariotoglou & Psillos 1993; Engel-Clough & Driver 1985). So, it seems that the most important conceptual obstacle towards scientific modelling derives from the meanings that pupils attribute to the concept of pressure, which is usually confused with the pressing force. It is worth noting that most pupils do not recognise the transmission of pressure through liquids, while those who understand the transmission of actions are not sure if the pressure or the force or even the volume of liquid is transmitted. At the level of tertiary education, results from a questionnaire addressed to 80 of our students in the context of the present study showed that they do not hold significantly different views from pupils. However, the students' replies were richer in the terminology used and the range of justifications provided. Based on the above thoughts, the interplay between the scientific model to be taught and students' views led us to the construction of a conceptual change strategy dealing with the conceptual differentiation of force and pressure (Smith, Carey & Wiser 1985; Kariotoglou & Psillos 1993).

The basic objective of our approach is to interlace content and methodology in a unified corpus of knowledge overcoming any gap that may exist between theory and practice (Howe & Smith 1998). For this reason, we developed qualitative and quantitative experiments concerning empirical laws in order to engage the students in data-processing activities (Howe & Smith 1998). With the qualitative experiments, we aim mainly at the students' familiarisation with the phenomena, concepts and experiments under study. With the quantitative ones, we aim mainly at promoting students' learning of scientific inquiry. We focus on four aspects of scientific inquiry: performance of experiments, distinction and control of variables, taking and processing measurements and making inferences (Millar 1998). We expect that our students, as prospective primary teachers, recognise the value of testing their conceptions. So their engagement in such work would reveal the role of experimental work during science instruction. On the other hand, the negotiation of experimentation, e.g., data processing or making inferences, involves students in using concepts scientifically, while leading also to the development of principles and laws such as Pascal's principle (Germann & Aram 1996). So the two levels of negotiation of knowledge, i.e., the conceptual and procedural, are not separated but interlaced, so that students are led to the knowledge of one level by making use of the knowledge of the other, and vice versa (Millar 1998).

The familiarisation and practice of our students in the process of scientific inquiry is based on a "usually used approach" to scientific methods. In this context, we consider a cyclical procedure functioning on two levels: a level of representation and the level of the material world. The questions to be answered, the hypothesis formed from both prediction and interpretation, and the design of the experiment are included in the first level of the procedure. The performance of the experiment, the gathering and processing of data and the results of the experiments are included in the second level of the procedure. Our TLS exploits aspects of scientific inquiry, attempting on the one hand to verify/falsify the students' conceptions as learners (distinction and control of variables) and, on the other hand, to familiarise them, as prospective teachers, with aspects of experimental methodology (performance of experiments, taking and processing of measurements, making inferences).

Teaching approach

The TLS consists of four units, each of them lasting approximately three hours. The successive steps of our teaching approach with regard to conceptual and procedural development may be seen in Table I. The conceptual goals and content (left column) are interlaced with the designed procedural aims and content to promote students' conceptual and methodological understanding (right column). The objective of the 1st unit is the students' familiarisation with the phenomena / concepts and experiments under study. It is also the unification by the students of the experimental fields of liquids and gases into the unified category of fluids (Kariotoglou, Koumaras & Psillos 1995, Psillos & Kariotoglou 1999). With the term experimental field we mean the choice of experiments/phenomena, which are appropriate to facilitate students' learning. At the start of this unit, the students had to hypothesise the outcomes of three experiments and interpret them. The 1st experiment involved the flow of water out of a pierced bottle containing water. The 2nd experiment involved the piercing of an inflated balloon and the 3rd experiment concerns the compression/extension of air or water in a syringe. After the realisation of these experiments they had to discuss the results and compare them with their predictions.

The familiarisation phase is very important for two reasons. First, because it contributes to the creation of a broad conceptual and methodological framework of thinking and intervening for our students who are not familiar with such scientific procedures. Second, because it helps the students to familiarise themselves with the first steps of experimental/scientific inquiry (performance of experiments, distinction and control of variables, taking and processing measurements and making inferences) and their discussion at group level. This phase helps students to feel more prepared for the next step of the TLS application, which involves the negotiation of the quantitative experiments.

The objective of the second unit are both the enhancement of the students' intuitive views about pressure, e.g., the relation of pressure to depth and their introduction to quantitative experimentation focusing on the distinction and control of variables, taking and processing of measurements and making inferences. These objectives are pursued by engaging the students in experimental work, e.g., to control the variables affecting hydrostatic pressure: i.e., depth, type of liquid, vessel shape, amount of the liquid.

Table 1: The steps of the teaching approach and units of the TLS

	Conceptual Aim & Content	Procedural Aim & Content
UNIT 1 1st STEP	*Familiarisation with phenomena and concepts* Prediction and interpretation of three experiments Unification of experimental fields	*Familiarisation with qualitative experiments and inquiry* Making hypothesis on the three experiments Performance of the three experiments
UNIT 2 2nd STEP	*Enhancement of intuitive conceptions* Basic law of hydrostatics Hydrostatic pressure as an intensive quantity	*Introduction to quantitative experimentation* Distinction and control of variables Experimental verification of the empirical law for hydrostatic pressure
UNIT 3 3rd STEP	Creation of a cognitive conflict Distinction between pressure and force Introduction of the relation between pressure and force	*Comparison application in order to verify/ falsify hypothesis* Pressure's comparison in a wide / narrow vessel; Force's comparison to detach two suckers
UNIT 4 4th STEP	*Application of the knew knowledge to investigate principles and laws* Discovery of Pascal's principle and Boyle's / Mariotte's law	*Application of quantitative experiments to investigate relations between variables* Measurement of pressure in different points of a bottle, after increasing the pressure by air-pump

The objective of the 3rd unit is the distinction by the students between pressure and pressing force. We introduce the new knowledge about pressure, force and their relationship, taking advantage of the students' dissatisfaction with their initial, undifferentiated conception of pressure – force. In this unit there is no significant experimental work from the point of view of procedural knowledge. The two experiments carried out in this unit are quite simple: a) measurement of the pressure at the same depth in a large and a narrow vessel; b) comparison of the forces required to detach two suckers of different size. The role of these experiments was to facilitate cognitive conflict rather than promote procedural knowledge.

The 4th unit is an application of the results of the 3rd one and it concerns the investigation by the students of Pascal's principle and Boyle's/Mariotte's law. As regards procedural knowledge, the 4th unit aims at the application of the experimental methodology introduced in the 2nd unit, targeting the development of the students' skills with respect to the performance of an experiment and making inferences. We used a specially developed experimental apparatus, which consisted of three digital manometers connected at three different points in a closed vessel containing water. In the top of the vessel there is an air pump in order to create an increase in pressure, which is transmitted to every point of the water. The students were asked to take measurements with the manometers after the creation of a new pressure difference. Then the students were asked to process these data, i.e., to make abstractions of the values of the pressure at each level before and after the creation of the pressure change. We wanted our students to recognise that the differences are equal and then to infer that pressure is transmitted invariantly to any point of the liquid.

During all units the students predict, interpret and carry out experiments and discuss in groups and in front of the class the results of the experiments. In this way, the students feel at ease to express their views and to try experimental approaches at the peer-to-peer level. Later on, having acquired experience and feeling more confident, they participate in class discussions in order to improve their understanding and verify their skills. During group experimentation, the teacher offers only technical help to the students, while during whole class work, the teacher has a double role. On the one hand (s)he demonstrates some basic experiments, beyond those carried out by the students. On the other hand (s)he co-ordinates the discussion, helping the students to clarify the concepts of the scientific model and the steps of experimental inquiry.

Research questions and research methods

The basic research questions of this work are derived from a need to assess our students' development and our basic teaching-learning assumptions underlined above. These are the following:

- What are the learning pathways of the students' attending TLS on the topic of fluids, following laboratory-based teaching strategies?
- What are the students' constructions on experimental inquiry during labwork?
- What is the influence of the students' existing theoretical knowledge on both procedural and conceptual development?

In the first phase, data were collected during autumn 1996, from a pilot application with a small group of 10 students. The majority of our students were non-science majors and were selected after a written test and an individual interview in order to secure a group of mixed ability with a variety of alternative conceptions concerning fluids and pressure. The final application took place during autumn 1997, after some minor changes in the content and the articulation of the sequence, derived from the pilot application. The sample of the final application was similar to that of the pilot one.

Video and audio recordings of whole class teaching were used for monitoring aspects of classroom interactions providing evidence of "on-task" student constructions during experimental activities or demonstrations. The conceptual development and the improvement in experimentation of individual students is captured in a stroboscopic manner on selected tasks/experiments, during the whole sequence. With these methods we managed to describe the reactions of each student on the crucial points and experiments, such as, the control of variables affecting hydrostatic pressure (2nd unit), the recognition of cognitive conflict (3rd unit), or the way of understanding the transmission of pressure (4th unit). From the sample of 10 students we selected three (3) students (see conceptual domain, next page) who were representative in recognising the cognitive conflict and consequently in understanding the differentiation between pressure and force. We thus traced the successive steps of 3 students towards the expected learning.

Individual semi-structured interviews were carried out with all students at the beginning and with the three selected at the end of the teaching. Results from these interviews were complemented by a written questionnaire.

From the above descriptions it can be seen that this research is qualitative in that it aims at the description of conceptual and procedural learning rather than at the measurement of success in a quantitative way. We consider that our research and its results are valid and reliable because we use multiple sources of data, we exploit a panel of experts to test both our research materials and our conclusion from the data. We also follow participatory modes of research in the frame of the whole group project and because this research is part of a long-term programme of our group (Kariotoglou 1998).

Research Results and Discussion

The design, development, application and evaluation of this TLS is a long-term research programme (Kariotoglou et al. 1993; Kariotoglou et al. 1995; Psillos & Kariotoglou 1999). In the present study we make reference to the results of our previous work on students' conceptual development and will focus mainly on the description and analysis of students' constructions concerning the aspects of procedural knowledge mentioned previously, during the application of the TLS. We also discuss the relation between the students' prior theoretical knowledge and their achievements.

Conceptual domain

During the familiarisation phase (1st unit) our students display in their explanations evidence of a transitional phase from the phenomenological level to the desired model, although this transition is not always accompanied by scientifically sufficient explanations. With respect to the unification of the experimental field, the majority of our students seem to unify the concepts of liquids and gases as fluids at the conceptual level, in a roughly speaking homogeneous way. Three out of the ten students interpret phenomena at a level complying sufficiently with the desired model. The rest of the students are less successful in using the concept of pressure, but they eventually use it as a concept to describe liquid and gas phenomena in a consistent way. As an example, one student employs pressure to interpret both liquid and gas experiments, besides using the concept of pressure incorrectly ("... *the exerted pressure...*") to classify the phenomena.

With respect to the distinction between pressure and pressing force, the complete discussion of the recognition of cognitive conflict is treated in detail elsewhere (Kariotoglou 1998; Psillos & Kariotoglou 1999). Here we present the main results with regard to the learning pathways (Niedderer 1997) described in our previous studies. Our students approach the distinction between pressure and force at three levels. An example of the first level was when a student with very good initial knowledge distinguished between the two quantities using her knowledge of the relevant theory and formulas. However, in applying her knowledge to the experimental situation, she attributed to pressure the properties of force, i.e., she considered it additive. This suggests that pressure and force may be undifferentiated even by those students who provide correct interpretations to relevant tasks in the initial questionnaire. On the other hand, perhaps, the student's very good knowledge made her seek stronger arguments, such as proving experimentally that pressure is not an additive variable. This led us to the conclusion that the student perceived the proposed cognitive conflict at a different level than the one designed. She required more evidence in order for her cognitive conflict to be resolved.

The 2nd level approach we classify as that of the three students who understood the cognitive conflict as predicted by the design of the TLS. At this point we should note that the conflict revealed to the students by the teacher is disunity between two representational systems, the first being the undifferentiated notion of pressure/force and the second the results of the two experiments referred to in the 3rd unit (see above).

Finally, the 3rd level we classify as that of the three students who realised the difference between pressure and force at a different level than that initially aimed at and, what is more, in contrast to our initial design. According to the latter, the difference that could be shown experimentally and be comprehensible, as indicated by the analysis of content, was the dependence of force, as opposed to pressure, on the quantity of the matter. Despite this, these students appreciated a difference originating in the TLS ("there is pressure", "force is exerted"), that we didn't expect to lead to differentiation.

As regards the remaining three students, two retained their initial knowledge and one student (totally three out of ten) answered using a different way of thinking for each task, so he is difficult to classify.

Concluding the results on the conceptual domain of the TLS, we may claim that it achieved its target conceptual aims (seven out of the ten students), although the teaching design did not predict two of the above three pathways to the conceptual target. Concerning the relation between the students' achievements and their prior knowledge, we can remark that all the students (3 individuals) with initial rich knowledge improved their knowledge to an acceptable level or even higher, whether or not they followed the pathway designed. Some of the students with poorer initial knowledge improved their knowledge, whether or not through the pathway designed (4 individuals). Finally, the others with poor initial knowledge did not improve it (3 individuals).

Procedural domain

We shall describe the students' constructions concerning the four aspects of procedural knowledge: a) performance of experiments b) distinction and control of variable, c) taking and processing of measurements, d) making inferences. For these aspects we study our students' (in)efficiency in understanding or intervening in experimentation.

Performance of Experiments

Our students confronted several difficulties during the performance of experiments due to their lack of practical experience. We provide an example regarding the use of a digital manometer, which consists of a long thin pipe connected to the main measurement unit. When the pipe is inserted into water, pressure is transmitted by the air contained in the pipe, thus resulting in an indication on the manometer's display. In most cases the students' difficulties using the instrument lead them ask for the teacher's help

*S (*student*) 1: what is this? (*pointing at the thin pipe*). Where do we put it?*

Or, even for the simplest instruments, like a ruler for measuring the depth at the point of measurement:

S2: ... this is a ruler ... not an instrument ... err ... oh yes. It is the instrument for the measurement of depth ...

Another example concerns the performance of the experiment to investigate Pascal's principle. In this case, the lab guide provides detailed instructions for the realisation of the experiments. It appeared from the observations that the students did not have significant difficulties in performing this experiment. The problem in this case arose in the representational part of the experimental methodology proposed. For example, initially our students did not find it plausible that by using the air pump they increased the pressure above the water in the closed vessel. Instead they understood it as increasing the air in the vessel:

T (teacher): What did you achieve by using the air pump?
S1: We put (more) air in the vessel.
T: Why? What did we gain by this?
S1: Err ... to increase the air, hum ... the atmospheric pressure. ...
S2: I think (that) normally it is possible to increase the air (he means the pressure).

Putting the above extract in the overall framework of this research we can state that, although our students have understood the concept of pressure at the conceptual level (see the two previous pages), they face difficulties in using this concept, as an entity, to intervene in the experiment.

Concluding this paragraph we can remark that our students face difficulties in realising the experiments, mainly in understanding the role of the instruments or the reason for an intervention.

Distinction and control of variables

It seems that our students did not face particular difficulties, when they had to decide how they should proceed to distinguish and control the variables affecting hydrostatic pressure:

*S1: (*reading the lab guide*) ... what are the factors affecting hydrostatic pressure? ...*
S2: ... the depth ... eeeer ... the kind of liquid....
S3: ... the shape of the vessel.... hum... or the quantity of liquid? ...
S1: ... let's try to check (test) them...

Or for the control of variables

S1: ... how should we check the variation of pressure with depth? ...
S2: ... err ... we measure pressure at different depths, hmm ... with the manometer....
S3: ...Yes, but we also need to know the depth...err.... Have we got a ruler?

Or for the next variable:

S1: ... now we should check the other variable (that means) ... the cross section of the vessel...
S2: ... err ... we shall take two vessels, one large and one narrow and we shall pour water into them, ... eeeer ... up to the same level ...
S3: ... the same level ... err ... or the same quantity?

S2: ... if we do that we will not know what caused the effect.... I mean the shape of the vessel or the level of the water?

S1: .... You are right ... err ... when you check a variable ... all the others must be constant ... so let's use the same level ...

We consider that the distinction and control of variables consist of two parts: a representational, where students choose the variable and decide how they will proceed the test and an interventional one when they realise the experimentation. Taking this remark into account, we can note here that the distinction and control of variables are easy tasks for our students, concerning the representational part of these procedures. But as pointed out in the previous section, the interventional part of the procedure is not so easy, given the difficulty in choosing and using the instruments.

Taking and processing measurements

The greatest difficulty is created when our students are about to process the measurement data coming from the measurements of pressure at various depths. The three groups of students found small differences in the pressure values at the same level, e.g., at 10 cm, the 1st group found 30 (arbitrary) pressure units, the 2nd 32 and the 3rd 31 units. The students discussed these "discrepancies" and the choice of the "best" value at length:

S1: I wonder... we didn't find the same values (all the groups). Why? ... err ... we used identical instruments (manometers) with the others ... also (identical) vessels...

S2: ... it is reasonable... they are similar (instruments), but not the same... it also depends on who measures ... the precision with which one observes ... the (digital) manometer is more reliable, while when using the ruler ... it is possible to have some error ...

T (teacher): Are these pressure values plausible? ...

S3: .... yes... they may deviate a little ... but...

S4 (2nd group): ... why do the others measure zero pressure units, while we measure 1 unit? (when they measure pressure at 0-cm depth)

S5: ...umm, it must be some uncontrolled effect... an error.

S4: ... Oh yes ... that's why our values are systematically higher than those of the other teams...

Then the discussion focussed on the values 30, 32 and 31 units that were found by the three teams for pressure at the level of 10 cm. The students argued at length about what should be reported as a result, namely "31", "31 ± 1" or "30 to 32". Regarding the last format, it was noticed that the students with a good knowledge of theory did not accept the use of the interval "30 - 32" to express their result. We infer that for these students, theory dominates the experiment with which they are not familiar, thus leading them to prefer more precise expressions of a measurement result. In contrast, the students with a poor knowledge of theory considered the interval expression as plausible, possibly because it incorporates the "errors of measurement". Our observations on the influence of students' views about the representation of measurements on the preferred format for reporting experimental results are similar to those encountered in the literature (see e.g. Evangelinos et al., Chapter 4 *of this volume*).

Another important aspect regarding measurements and errors was revealed when the students investigated the influence of density/type of fluid on pressure. It was observed that the students with good theoretical knowledge measured pressure in pure and salt water at only one depth (10 cm), finding a result of 30 and 35 units of pressure respectively. In contrast, the students with a limited knowledge of theory decided to take measurements at five different depths, justifying their choice as follows:

> *S: Since there are errors (in measurements), how can we tell if 31 is different from 33? ... If in all cases (at all depths) we measure a difference ... which is repeated ... this is more convincing... We just want to make sure...*

From such results we may suggest that the students with poor theoretical knowledge understand more easily the implications of experimental errors, as compared to those with a better knowledge. It seems that the imbalance in the presentation of the theoretical and experimental aspects of scientific inquiry in textbooks may create obstacles in assimilating methodological aspects of measurements and data treatment.

Making inferences

Our students have difficulties in making inferences from the processed data and they need the teacher's help in most cases. In the following extract we have an indication about how the students understand the transmission of pressure (Pascal's principle), in accordance with the properties of pressure (2^{nd} unit), as well as how the teacher scaffolds students' understanding:

> *T: ...What can you conclude from this data... (There is a table that contains the pressure' values in every manometer. After the creation of every single pressure difference, we have performed a set of measurements)*
> *S1: ...The pressure increases with the depth...*
> *T: ...Did the increase (in pressure) transmit to all the points (of the water)?*
> *S2: ...Yes, but normally it should be the same at all points...*
> *T: ...What do you mean? How did you note it?*
> *S2: ...We observed it, the reading increases in all manometers...*
> *T: ...Is this related to any property of pressure we have learned about in a previous lesson?*
> *S3: ...Yes, hum... that it is not exerted at a specific point, err ... it just exists everywhere..."*
> *S4: ... err ... it also has no direction...*

This last comment was made by a student with a poor knowledge of theory, while the "better" students had more difficulty in understanding the scalar nature of pressure. Again, it seems that the students with a poorer knowledge of theory more readily assimilated the new knowledge presented to them through the experimental procedures used in the TLS than did those with a good knowledge.

Conclusions

In this work, we have described aspects of the design and theoretical assumptions for the development of an innovative, laboratory-based, teaching learning sequence, dealing with both the procedural and the conceptual knowledge concerning fluids and pressure. The results of this sequence application revealed significant conceptual rather than procedural student constructions. Most of our students achieved the conceptual target though they followed three (3) different pathways, two of which were not predicted by the design of the sequence. The students' constructions corresponded to their initial poor or good theoretical knowledge. Students with good initial knowledge improved their knowledge to an acceptable level or even higher. Students with poorer knowledge did not show the same evolution as the others, though many of them achieved the conceptual target.

It seems that this type of TLS may be able to help students achieve only some of all the possible aspects of procedural knowledge. These include, for example, the distinction and control of variables. Our students perhaps confronted severe difficulties in the performance of experiments due to their lack of experience. In the case of the representational part of the experimental approach, the problems are more complicated. Our students with good conceptual knowledge do not easily accept the experimental errors or other "discrepancies" of the experimentation. That is possibly why the students are led astray from their solid theoretical basis. In contrast, the students with less knowledge accept some of these problems more easily. It seems that adequate theoretical knowledge leads students to more difficulties regarding the understanding of experimental procedures than their lack of experience in handling apparatus and instruments, probably because theory is influencing and leading their observations.

Our attempt to overcome any gap that may exist between theory and practice by interlacing the content with methodology had significant conceptual results, such as the differentiation of pressure and force. The results were not so clear with respect to the procedural knowledge. In this case our students had difficulties in the interventional part of experimentation, e.g., performance of the experiments, using concepts as entities, although they did not have problems with the representational part of the experimentation. The constructions concerning errors depended on the initial level of theoretical knowledge; students with poor initial knowledge easily assimilated the knew knowledge about errors.

Recommendations

These results provide significant implications concerning the design of such a TLS and the teaching of fluids and pressure. The designer of a TLS should take into account students' initial level of knowledge, providing appropriate tasks and materials to scaffold the constructions of the students in each of the three groups. The three different levels in the understanding of the differentiation of pressure and force revealed in this work could offer useful insights into the learning of pressure and force.

The interlacing of theory and practice will be facilitated if conceptual achievements are associated with easy procedural tasks and vice versa. So the cognitive conflict approach is mediated by qualitative or semi-quantitative tasks, while the procedures of data treatment and measurements should enhance the students' conceptions, which are close to the scientific ones.

The interventional part of experimentation is more difficult for the students than the representational one. A familiarisation phase should give the students' the opportunity to handle the experiments and apparatus, applying the relevant scientific concepts and procedures and not just putting things to work.

The acceptance of experimental errors or "discrepancies" by students with a good theoretical knowledge but poor experimental practice could be facilitated by an epistemological discussion aimed at revealing aspects of the nature of Science.

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