Forms of Reasoning Used by Prospective Physical Sciences Teachers When Explaining and Predicting Natural Phenomena: The Case of Air Pressure

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Abstract: The co-ordination between theory and evidence is an outstanding characteristic of scientific thinking. Research indicates that students often have difficulty in explaining natural phenomena because they use their own theories to explain phenomena or they are unable to build a bridge between theory and evidence. Science teachers must teach students to collect and select evidence and to use theory to explain it. The objective of this study was to investigate the forms of reasoning used by prospective physical sciences teachers when they build up explanations and make predictions about natural phenomena. Thirty-eight prospective teachers answered a questionnaire structured around three problems focusing on phenomena that can be explained through air-pressure variation. The results seem to indicate a variation in the forms of reasoning used, depending on the problem and the type of request. The number of prospective teachers who consistently use a certain form of reasoning is higher within problems than across problems.

Sommaire exécutif : Lorsqu'ils tentent de trouver des données empiriques pour soutenir de nouveaux modèles ou de nouvelles théories, les scientifiques se servent de leur propre jugement pour séparer ce qui est pertinent de ce qui ne l'est pas. Bien qu'ils utilisent leurs idées pour interpréter les données, ces idées sont également reconstruites ou développées afin de mieux adhérer aux données considérées. L'effet réciproque entre la théorie et les faits n'est pas direct et constitue une caractéristique importante de la pensée et de l'explication scientifique. Ces questions devraient donc faire partie intégrante de tout curriculum scientifique obligatoire visant à contribuer à l'alphabétisation scientifique.

Certaines recherches indiquent que les étudiants éprouvent souvent des difficultés lorsqu'ils doivent expliquer certains phénomènes naturels, parce qu'ils se servent de leurs propres théories pour les expliquer ou encore parce qu'ils sont incapables d'établir un pont de la théorie aux faits. Donc, les enseignants de sciences doivent enseigner à leurs élèves d'une part comment recueillir et sélectionner les données pertinentes, et d'autre part comment se servir de la théorie pour les expliquer. Fournir des explications est généralement accepté comme une partie importante du travail d'un enseignant. Cependant, « on parle beaucoup moins de l'acte et de l'art d'expliquer que des notions scientifiques qu'il faut expliquer [et] l'explication elle-même n'est guère traitée comme un objet susceptible d'être compris, appris ou enseigné » (Ogborn, Kress, Martins, & McGillicuddy, 1997, p. 2). De plus, l'acte d'expliquer requiert un effort intellectuel considérable, car il « implique l'habileté de transmettre des notions scientifiques difficiles sans en altérer le sens ni mentir » (Wellington, 2000). Malheureusement, les enseignants à leurs premières armes sont censés apprendre à expliquer à partir de leur propre expérience de l'enseignement.

L'objectif de cette étude était de se pencher sur les formes de raisonnement utilisées par les futurs enseignants de sciences physiques lorsqu'ils construisent des explications et formulent des prédictions sur les phénomènes naturels. Trente-huit futurs enseignants de sciences physiques ont participé à l'étude. Ils en étaient à la quatrième année d'un programme de premier cycle universitaire d'une durée de cinq ans

visant à former des enseignant de sciences physiques dans une université portugaise. L'année suivante (la cinquième de leur programme d'études), ils allaient effectuer un stage d'enseignement d'un an. Les données ont été recueillies par le biais d'un questionnaire qui se basait sur trois problèmes mettant en jeu des phénomènes susceptibles d'être expliqués par des variations de pression atmosphérique. Mentionnons d'abord deux points importants : premièrement, la pression atmosphérique est un concept théorique qui ne peut être simplement induit à partir de l'expérience ; deuxièmement, il s'agit d'un concept dont les étudiants d'âges différents se font des idées différentes (Driver, Leach, Millar, & Scott, 1997). Les problèmes utilisés dans cette étude sont les suivants : la bouteille et le ballon, la chandelle qui se consume et l'œuf et la bouteille. Dans tous les cas il s'agit de situations en laboratoire qui ont déjà été utilisées par d'autres auteurs, bien que dans des buts de recherche différents. Les versions précédentes ont été adaptées de façon à ce que les questions sur les explications et les prédictions puissent être posées au sujet de chacun des problèmes. La forme même des questions exigeait des étudiants qu'ils se servent de leurs propres théories pour prédire ou expliquer les situations plutôt que de choisir parmi des théories existantes.

Les réponses aux questions ont ensuite été analysées sur le plan des contenus pour déterminer les types de raisonnements dont se servaient les enseignants en formation pour expliquer les faits présentés et étayer les prédictions formulées. Les catégories principales utilisées pour analyser les raisonnements des futurs enseignants sont les mêmes qu'avaient utilisées Driver et al. (1997) lorsqu'ils ont analysé les caractéristiques des représentations épistémologiques chez les étudiants : le raisonnement fondé sur les phénomènes, le raisonnement fondé sur les relations et le raisonnement fondé sur un modèle.

Les résultats montrent des variations d'un problème à l'autre et d'un type de question à l'autre. Ainsi, au moins 50% des participants se sont servis d'un raisonnement fondé un modèle quelle que soit la question posée au sujet de la bouteille et du ballon, alors que le raisonnement fondé sur les relations était prédominant chez les participants lorsqu'il était question des deux autres problèmes. La prédiction sur la possibilité de faire sortir l'œuf de la bouteille (voir tableau 1) s'est avérée particulièrement difficile pour les étudiants, et seuls quelques-uns ont fourni une explication relative à cette situation. Le nombre de futurs enseignants qui utilisent régulièrement un type de raisonnement donné est plus élevé pour un même problème que si l'on considère les trois problèmes dans leur ensemble.

Les résultats suggèrent que les futurs enseignants tendent à expliquer les phénomènes naturels à partir de généralisations empiriques, bien que dans certains cas ils tentent d'utiliser des modèles (le plus souvent de façon incomplète) pour expliquer les phénomènes ou pour expliquer les prédictions qu'ils formulent à leur sujet. Cela pourrait signifier que les connaissances scientifiques des enseignants en formation sont insuffisantes pour qu'ils puissent expliquer les phénomènes scientifiques de façon satisfaisante, et que les didacticiens doivent accorder une plus grande importance à l'explication scientifique. Bien qu'il n'existe aucun consensus sur la meilleure approche pour enseigner à expliquer, il semble qu'une bonne capacité d'expliquer nécessite qu'on apprenne « sur le tas ». Par conséquent, les futurs enseignants doivent avoir, dans le cadre de leur programme d'études, l'occasion de formuler des explications s'ils veulent perfectionner leur capacité d'expliquer, et il en va de même pour les cours de perfectionnement à l'intention des enseignants qui sont déjà en service.

Introduction

One of the arguments for teaching science in schools is that students, as lay people living in a democratic society, need to participate actively in decision-making processes about science-related issues (Kolstø, 2001). To do so, citizens need to have scientific literacy that includes a proper understanding of science and the scientific enterprise, as well as an adequate level of scientific knowledge (Hodson, 1998). This perspective requires that science education move away from the traditional 'teaching science' towards 'teaching about science' (Kolstø, 2001). However, Hodson (1998) points out that the school curriculum often misrepresents science and continues to build an image of science that is locked in the thinking of the 1960s and early 1970s. The view of science conveyed to students is that 'scientific knowledge "exists out there" and scientists carefully, systematically and exhaustively collect information that reveals it' (Hodson, 1998, p. 208). This view is still held by several Portuguese teachers (Costa, Marques, & Kempa, 2000), though it is rejected by most modern philosophers of science (Chalmers, 1982). The latter acknowledge that scientific knowledge is created in people's minds and that scientists look for evidence for or against ideas previously generated rather than prove that they are true or false. As Ryder (2001) points out, '[P]roviding justification for a knowledge claim is different from proving that it is true' (p. 3).

When trying to find empirical support for their new ideas, scientists use their own ideas to separate relevant evidence from irrelevant data (Kolstø, 2001). They use their ideas to interpret evidence but they also rebuild and/or develop them, so that they fit better the evidence selected. The interplay between theory and evidence and the achievement of co-ordination between them is not straightforward (Solomon, 1995), but it is the outstanding characteristic of scientific thinking and scientific explanation. Therefore, consideration of these issues should be included in any compulsory school-science curriculum aiming to contribute to scientific literacy (Ryder, 2001), as 'an understanding of scientific evidence will allow the public to contribute to debates on topical issues that are relevant to their lives' (Gott & Duggan, 1996, p. 799).

Some research studies (e.g., Driver, Leach, Millar, & Scott, 1997; Leach, 1999) indicate that students experience great difficulties when asked to explain natural phenomena. These difficulties may be due to the fact that they do not feel the need for an explanation, they use their own theories to explain phenomena, or they are not able to build a bridge between theory and evidence. Hence, science teachers must teach their students how to collect and select relevant evidence, as well as how to use theory to explain it. However, the serious gap existing between research and practice in science education (Costa, Marques, & Kempa, 2000) may prevent science teachers from becoming aware of this need.

Explaining things is commonly accepted as a major part of the science teacher's job. The point is that 'the act and art of explaining is much less discussed than the scientific ideas to be explained [and] explaining is not treated as something which could be understood, learned or taught' (Ogborn, Kress, Martins, & McGillicuddy, 1997, p. 2). On the other hand, teachers cannot rely on textbooks, as the latter do not relate theory and evidence in a proper way (Ohlsson, 1992; Leite, 2002; Leite & Figueiroa, 2002). Moreover, the act of explaining requires considerable intellectual effort because it 'involves the ability to convey difficult scientific ideas without distorting their meanings or telling lies' (Wellington, 2000, p. 5). Unfortunately, beginning teachers are supposed to learn on their own 'how to explain'; teaching about 'how to explain' is not included in most initial teacher education programs. Thus, beginning teachers' engagement in explaining science to their students is their only 'teacher' on this issue.

In this paper we concentrate on the characteristics of explanations provided by prospective teachers (PTs), as we believe that becoming aware of the features of one's own explanations is a necessary requirement for improving them.

Explaining science phenomena in school: Some research findings

Studies about students' explanations cover a wide range of ages and academic levels and vary from small-scale studies to quite large surveys.

Based on a diversity of data collection techniques, Kuhn (1989) concluded that American subjects, from primary school to adult age, have difficulties in both the differentiation and the co-ordination of theory and evidence. When subjects' theories and the available evidence are compatible, the pieces of evidence are regarded as instances of the theory that serve to illustrate it. The theory, in turn, serves to explain the evidence—that is, to make sense of it. When their theories and the evidence available are discrepant, subjects use a variety of devices to bring them into alignment, either 'adjusting' the theory or 'adjusting' the evidence. The author claims to have support for a developmental framework in which there is a continuum from non-differentiation of theory and evidence to the full differentiation and co-ordination of theory and evidence and to the consciousness of the interaction between the two.

Metz (1991) interviewed 32 three- to nine-year-old children about the working of gears. A sequence of three types of explanation was established: function of the object as explanation, connections as explanation, and mechanistic explanation. In addition, two types of change in explanation were identified: radical substitution (one explanation is supplanted by the next) and transforming incorporation (one explanation forms the basis for the next).

Driver et al. (1997) investigated representations of the nature and status of scientific knowledge held by 9-, 12-, and 16-year-old English students, including ideas about experimentation, the nature of explanation, and the evaluation of theories. Data were collected through semi-structured interviews focusing on six research probes from about 30 pairs of students per age level and research probe. The authors developed a framework for describing major features of students' reasoning that included three main categories: *phenomenon-based reasoning* (where there is lack of distinction between description and explanation), *relation-based reasoning* (where explanations are empirical generalizations tracing relations between observable features), and *model-based reasoning* (where explanations are based on conjectured models that have to be evaluated against empirical evidence). The authors concluded that phenomenon-based reasoning tended to be used most often, but not exclusively, by the 9-year-old group; relation-based reasoning was the most frequent among the 12- and the 16-year-old groups; and model-based reasoning became more frequent with age, although some of its characteristics were very rarely found. The authors pointed out that 'non use' is different from 'not being able to use' and stated that the results of the study did not permit them to conclude that the latter was the case.

Ball (1999) carried out a research study with American, university General Chemistry students, in order to understand the way in which students learn chemical theory and practices and to examine the role of traditional ($n = 21$) and co-operative ($n = 10$) contexts in the learning process. The analysis of the data, collected through several techniques (including class observation, videotapes from lab sessions, field notes, informal interviews, and student-produced documents) led the author to conclude that, whatever the context, students made sophisticated use of theory but little use of evidence and were not able to translate observation into evidence. According to the author, students may see theory use as a natural part of laboratory work but need to be made aware of how observation should be considered as evidence.

Leach (1999) interviewed 95 pairs of English students aged 9 to 16 in order to investigate how they co-ordinated knowledge claims and evidence about four electric circuits. Interviewees had to select observations and explanations from among those given to them to explain the first circuit and to use the explanations selected to predict the behaviour of the other circuits. Afterwards, the actual behaviour of each circuit was shown and students were invited to comment on it in light of their explanations. The results of the study showed that many students selected explanations of the behaviour of electric circuits according to criteria other than a logical, comprehensive evaluation of the relationship between explanation and theory. Besides, when making and evaluating predictions, many students failed to use all the available evidence systematically, contradicted previous arguments, or made ad hoc modifications to explanations. However, a trend for older students to make predictions and evaluate explanations in terms of the evidence presented was also found. According to the author, these results mean that the ability to co-ordinate theory and evidence increases with age.

Afonso and Leite (in press) analysed 9th and 11th grade students' co-ordination of theory and evidence. The authors concluded that, whatever the grade level, the majority of the students are able to distinguish observation from explanation but that they seldom use theoretical entities to explain phenomena. Thus, the majority of the explanations obtained are empirical generalizations that emerge directly from data.

Taken together, the results of these studies seem to indicate that, although the quality of students' explanations increases with age, some students continue to have difficulty in using evidence to support theory and do not use data properly unless they understand that this is a requirement. In addition, there seems to be a tendency to make generalizations directly from data instead of using theoretical entities to explain observations.

Studies involving teachers have focused on several issues: the types of explanation used by science teachers, the enhancement of students' explanatory abilities, and the development of a consensus regarding what processes and practices of science are essential to include in the science curriculum. Thus, Dagher and Cossman (1992) investigated the verbal explanations used by science teachers in junior high school lessons. They observed and audiotaped 40 (seventh and eighth grade) classes taught by 11 physical-sciences and 9 life-sciences teachers. The authors identified 10 different types of explanation: analogical, anthropomorphic, functional, genetic, mechanical, metaphysical, practical, rational, tautological, and teleological. In addition, they found that the type of explanation used by individual teachers varied substantially from teacher to teacher.

Ogborn et al. (1997) reported an ethnographic account of teachers' explanatory practices in the science classroom. They identified four different styles of explanation, which they called the 'teller of tales' (explanations are given in the form of stories), the 'let's think it through together' (explanations are arrived at through collecting and reshaping ideas from the class), the 'say it my way' (explanations as talking—explanatory forms of words are laid out and practised), and the 'see it my way' (students are required to see things in a certain way, sometimes helped by demonstrations to show that the theory is right).

As far as the promotion of students' explanatory abilities is concerned, Meyer and Woodruff (1997) used a teaching methodology based on group inquiry and discourse to explore the advantages of this teaching approach and to document Grade 7 Canadian students' advances in understanding four light and shadow effects. The authors verified that students started by thinking about what they already knew about light, shadows, and other related concepts, trying to generate explanations that made sense to themselves and others. However, by the last two effects, students' explanations had moved towards a problem-centred approach that entailed experimenting and incorporating the results into more functional concepts for all effects. They moved from a referent concept of what a shadow is to a higher order concept of a shadow as the result of how light behaves with objects, showing an increase in the coherence of their explanations.

Lawrence and Pallrand (2000) undertook a research study focusing on the effects of teacher experience on the use of explanation-based assessment. The results indicated that American high school physics students in a class taught by a more experienced teacher using experience-based assessment demonstrated a much greater ability to use knowledge in both the predict–explain and revise–explain phases, when encountering novel situations, than the students of a class taught by a less experienced teacher. To the authors, this meant that teacher experience with explanation-based assessment is a crucial factor in students' success in using knowledge to predict, explain, and revise predictions.

With the purpose of identifying the elements of the processes and practices of science to be included in the 5 to 16 science curriculum, Ratcliffe (2000) carried out a research study involving English scientists, science teachers, historians, philosophers and sociologists of science, science educators, and other people involved in the public understanding of science ($n = 23$). Data were collected through the Delphi method and showed a strong consensus about the inclusion of items such as the insufficiency of data for the construction of knowledge claims, the role of hypothesis and prediction in the development of new knowledge, the possibility of reinterpretation of evidence, and the uncertainty of science knowledge (contrary to what is apparent from school science knowledge). For the author, the results indicated that a consensus is emerging about what basic features and ideas about science should be taught to school students.

The results of studies involving teachers seem to indicate that, as a group, teachers use a wide range of explanation types, although individual teachers may rely on a narrower set of explanations, which may differ substantially from that used by others. In addition, teachers seem to be aware of the fact that data are not sufficient for the construction of knowledge claims and that evidence can sometimes be reinterpreted in the light of new theories. There is also some evidence that it is possible to structure teaching in such a way as to improve students' explanations of science phenomena. As far as can be ascertained from the published literature, no study has focused on how teachers and prospective teachers themselves explain science phenomena, either in terms of the content they use or in terms of the form of the explanation given. However, it would be worthwhile investigating this issue because, to improve the learning of scientific explanation, teachers need to know not only how to explain the accepted scientific explanations to students but also how to explain (from the accepted scientific point of view) the phenomena that they are supposed to teach.

Research questions

After completing the undergraduate program courses, prospective physical sciences teachers are expected to be able to coordinate theory and evidence and to use theoretical models when explaining the science phenomena they are supposed to teach to real students during teaching practice. However, the previous sections indicate that there is some evidence that students of several school levels, including college, have difficulty in using evidence to support theory. As there is a lack of research focusing on prospective teachers' performance on the explanation of science phenomena, this piece of research aims to answer the following questions:

- What forms of reasoning are used by prospective physical sciences teachers when they are asked to explain science phenomena related to air pressure?
- Does the reasoning of prospective physical sciences teachers depend on the type of request (predict or explain) presented to them?
- Do prospective physical sciences teachers use particular forms of reasoning consistently across problems?

Methodology

Thirty-eight prospective physical sciences teachers (PTs) participated in this research study. They were attending the fourth year of a five-year-long undergraduate program for physical sciences teachers in a Portuguese university. The year after (fifth year of the undergraduate program) they would go to school to do one year of practice teaching. As data were collected at the end of the academic year (2000/2001), subjects had completed all the courses in Physics, Chemistry, and Education that are included in their undergraduate program. They had, therefore, completed their preservice education in Physics.

Data were collected by means of a questionnaire prepared for this study. Although a follow-up interview would have provided some deeper information on students' reasoning and have increased the researchers' confidence in their interpretation of students' answers to the questionnaire, it was not carried out—largely because, soon after data collection, subjects entered practice teaching. It was thought that practice teaching activities, such as lesson preparation and teaching, would improve prospective teachers' ability to explain phenomena.

The questionnaire included three problems, focusing on phenomena that can be explained through air-pressure variation. *Air pressure* is a theoretical concept that cannot be simply induced from evidence. This fact may be the reason why air pressure is a science concept that causes trouble for students of diverse ages. In fact, research indicates that students usually use several alternative conceptions (Driver, Squires, Rushworth, & Wood-Robinson, 1994) when explaining phenomena dealing with air pressure. On the other hand, air pressure is a concept needed to explain natural phenomena, as well as planned laboratory experiments. Therefore, air pressure seems to be an adequate science concept for the attainment of the objectives of this study.

The problems used in this study are the following: the bottle and the balloon; the burning candle; the egg and the bottle (see Table 1). All three involved the concept of air pressure and dealt with phenomena in such a way that either data were provided to the PTs to be explained or the PTs were asked to predict and explain the behaviour of a part of the world. The problems had been previously used by other researchers (Driver et al., 1997; Friedl, 2000) and had been shown to be adequate to investigate students' forms of reasoning. However, these problems were modified somewhat so that explain-and-predict questions were asked about each of them. According to Leach (1999), this question format requires students to use their own theories to predict or explain rather than to choose among theories. The choice of this format was based on the facts both that PTs are supposed to know the scientific theory sufficiently well to answer the questions and that, according to the literature mentioned earlier, they are supposed to be able to differentiate between theory and evidence. Following Leach, the format we selected allows us to concentrate on the subjects' performance rather than on their ability.

Table 1: Characteristics of the forms of reasoning used in data analysis

Form of Reasoning	Form of Scientific Enquiry	Nature of Explanation	Relationship between Explanation and Description
Phenomena-Based	Focus on phenomena Enquiry as observation	Explanation as description	No distinction between explanation and description
Relation-Based	Correlating variables Observations need to be *controlled or planned*	Empirical generalisations An explanation is a *relation between* observable features	Inductive relationship Explanations are generalisations *from empirical data*
Model-Based	Evaluate theory Theories or models must be evaluated against evidence	Theories and models are conjectural	Hypothetical-deductive relationship Description is different from explanation Explanation involves conjectures about theoretical entities that are different from the observed features

The questions were analysed by two colleagues having some expertise in science education and science-teacher education. They were asked to comment on the adequacy of the questions to both the objectives of the study and the subjects. Also, three prospective teachers, different from those involved in the research, were asked to answer the questions. Some minor modifications to the formulation of the questions were introduced as a consequence of this process. The content of the questions is described in Table 1.

Table 2: Elements of the correct model-based reasoning

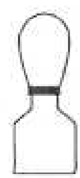
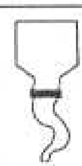
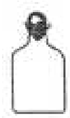
Problem	Question		Elements of Correct Model-Based Reasoning
1. Bottle and balloon	1.1. Explain the inflation of a balloon stretched across the neck of a bottle placed in hot water		Heating increases the temperature of the air inside the bottle. The kinetic energy of the particles increases. Medium distance between particles increases. Number of collisions increases. Pressure inside bottle and balloon becomes higher than outside.
	1.2. Predict and explain what happens to the balloon when cooling down occurs		The balloon shrinks. Cooling down decreases air temperature inside bottle and balloon. Kinetic energy of particles decreases. Medium distance between particles decreases. Number of collisions decreases. Pressure inside the bottle and balloon becomes lower than outside.
	1.3. Predict and explain what happens to a balloon stretched across the neck of a bottle that is heated upside down		The balloon blows up. The same as 1.1
2. Burning candle	2.1. Explain why the level of water rises inside a bell-shaped glass cover that covers a burning candle		During the combustion: Temperature inside the bell-shaped glass cover increases. Kinetic energy of air particles increases. Medium distance between particles increases. Number of collisions increases. Pressure inside the bell-shaped glass cover becomes higher than outside. Some air goes out of the bell-shaped glass cover. When the flame goes out: Temperature inside the bell-shaped glass cover decreases. Kinetic energy of air particles decreases. Medium distance between particles decreases. Number of collisions decreases. Pressure inside the bell-shaped glass cover becomes lower than outside. Water is pulled into the bell-shaped glass cover.
	2.2. Predict and explain what would happen to the level of water inside the bell-shaped glass cover if two candles were burning		Level of water inside the bell-shaped glass cover would be higher than in 2.1 The same as 2.1 but the variations are bigger (because two candles produce a greater change in temperature)
3. Bottle and egg	3.1. Explain why (during cooling) a boiled and shelled egg goes inside a previously heated bottle		The same as 2.1 (egg instead of water)

Table 2 continued

	3.2. Predict and explain if the egg can be taken out of the bottle		*Can be taken out by inverting the bottle and (a) increasing pressure inside the bottle (by heating the bottle or by blowing into the bottle) or (b) decreasing the pressure outside the bottle.* (a) The same as 1.1—Number of particles increases and so does pressure inside the bottle (b) Pressure outside the bottle becomes lower than pressure inside it; the egg is pulled out of the bottle

The questionnaire was administered to the subjects, under examination conditions, by one of the authors. Prospective teachers took about 30 minutes to complete it. The answers to the questions were content analysed in order to find out both the prevailing forms of reasoning used by PTs to explain evidence given to them and the prevailing reasoning they used to predict and explain the behaviour of some natural phenomenon. The main categories used for the analysis of PTs' reasoning were those formerly used by Driver et al. (1997) to analyse the features of students' epistemological representations: *phenomenon-based reasoning* (PBR), *relation-based reasoning* (RBR), and *model-based reasoning* (MBR). These three forms of reasoning can be characterized in relation to the form of scientific inquiry, the nature of explanation, and the relationship between theory and evidence (Driver et al., 1997). Table 2 gives a synopsis of the main characteristics of each form of reasoning. The form of reasoning used by the PTs to answer a question was inferred from PTs' explanations of evidence and from the way they explained the predictions they were asked to make, as will be illustrated in the next section of the paper.

It should be pointed out that the set of categories used for data analysis comprises two additional categories: The category *other* includes answers containing internal contradictions (namely, with regard to forms of reasoning), as well as incomprehensible or irrelevant answers; and the category *no answer* includes subjects that did not give any answer to a certain question.

Content analysis of PTs' answers revealed the existence of several patterns of answers (that could be considered as sub-categories) for each form of reasoning. Patterns, whose frequencies were counted, differed from each other with regard to the depth of the explanation and the concepts they involved. It must be emphasized that model-based reasoning can be either correct or incorrect, from a scientific point of view. Incorrect reasoning may be based on PTs' alternative conceptions—that is, on alternative models; correct reasoning is taken as consistent with the scientifically accepted point of view. Table 1 synthesizes the elements that needed to be included in subjects' answers if they were to be considered correct, model-based reasoning.

In order to improve the reliability of the analysis, data were analysed separately by the authors. The results presented in the next section were obtained by consensus between the two authors. Frequencies and percentages per category of answer are given for each question. In addition, within and across problems, consistency of reasoning was analysed. To obtain data on these issues, each PT's answer to each problem (within-problem consistency) or answers to the whole set of questions pertaining to a given type of request (across-problem consistency) were analysed. These analyses provide information on the number of students that used each possible combination of forms of reasoning.

Results

The presentation of results is organized in three steps. First, quantitative synthesis of the results is presented so that some comparisons between problems, as well as between explain-and-predict questions, can be made. Second, results are presented and analysed by problem and question. Finally, across-problem analysis is described so that some evidence on students' (in)consistency in using the different forms of reasoning can be obtained.

Synthesis of the results

Table 3 summarizes the results obtained, by problem and type of request (explanation or prediction) made to the subjects and by category of answer.

Data given in the table show some variation from problem to problem, as well as from one type of request to another. Thus, in the case of the bottle-and-balloon problem, at least 50% of the participants used model-based reasoning, whatever the request made to them, while for the other two problems, relation-based reasoning was found to be the prevalent form of reasoning. However, it should be noticed that the sum of *other* answers and *no answer* is especially high in the case of the egg-and-bottle problem.

Table 3: PTs' performance by problem and type of request (f) ($N = 38$)

Problem	Focus of the Question	Type of Request	Category of Answer				
			PBR	RBR	MBR	Other	No Answer
Bottle and Balloon	Inflating of balloon	Explain	—	9	23	6	—
	Effect of cooling down	Predict	2	3	19	7	7
	Effect of inverting bottle	Predict	2	10	19	7	—
Burning Candle	Raising of water	Explain	—	26	5	3	4
	Effect of more candles	Predict	1	25	6	4	2
Egg and Bottle	Entrance of the egg	Explain	1	22	1	5	9
	Possibility of taking egg out	Predict	1	15	1	6	15

As far as *explanation* and *explanation of prediction* are concerned, no great within-problem differences were revealed by the data, except for in the case of the third problem, where the number of understandable explanations was higher than the number of understandable explanations of prediction.

Results by problem and question

1. The bottle-and-balloon problem

The bottle-and-balloon problem included three questions: one *explain* question and two *predict* questions. Whatever the question, model-based reasoning was the predominant form of reasoning shown by this group of PTs (see Table 3). However, PTs' performance seemed to depend on the question. In fact, contrary to what happened for the other two questions, 7 subjects did not give an answer to the question on the effect of cooling down the bottle. Relation-based reasoning was much less frequent in response to this question, too.

In accounting for the inflation of a balloon stretched over the neck of a bottle when the bottle is placed in a basin of hot water, the majority (23 out of 38) of the PTs used model-based reasoning.

The remaining subjects used relation-based reasoning (9) or gave answers that could not be classified into the models of reasoning considered for data analysis purposes (6).

Several patterns of answer were identified in the case of relation-based reasoning, as well as in the case of model-based reasoning. In the former case, the patterns of answer differed with regard to the concepts that mediated the relationship between heating (and the consequent increase in the temperature) and the increase in the volume of the balloon. These concepts were dilation (R1, R2), used by 4 PTs; density (R3), used by 3 PTs; and pressure (R4), used by 2 PTs. Despite the fact that this type of explanation is not expected to be complete, it should be noticed that R3 is based on an alternative idea: Air moves in blocks, from one place to the other (Driver et al., 1994). These patterns of answer are illustrated below:

- R1—Bodies dilate with heating; the balloon inflates.
- R2—Temperature inside the bottle increases, then the volume of air increases and the balloon inflates.
- R3—Hot water heats the air inside the bottle, the air becomes lighter and rises up and the balloon inflates.
- R4—Air is heated, pressure inside the recipient increases the pressure, and the balloon inflates.

In the case of model-based reasoning, two groups of patterns were found: scientifically accepted patterns and alternative patterns. The latter type of pattern corresponds to answers that included alternative conceptions. Thus, two alternative patterns of answers were identified: One was due to the belief (held by 3 PTs) that heating causes a chemical reaction, leading to the production of hydrogen (M1); the other was due to the attribution by 3 PTs of macroscopic properties to particles (M2). They are as follows:

- M1—Hot water heats the air inside the bottle, a chemical reaction occurs, hydrogen is formed from the air, and the balloon inflates.
- M2—The temperature of the particles increases, particles expand, and the balloon inflates.

As far as scientifically accepted patterns of model-based reasoning are concerned, four patterns were identified: Patterns M3 (the most frequent pattern of answer, shown by 13 PTs), M4, and M5 (each one shown by 1 PT) are incomplete explanations of the phenomena. In fact, M3 does not make explicit how the increase in the particles' kinetic energy exerts influence upon the blowing up of the balloon, M4 does not explain how the air expands, and M5 does not clarify how the number of collisions affects the volume of the balloon. Pattern M6 is deduced from two complete explanations; it is based on the kinetic model and includes the concepts of kinetic energy, collision and pressure. These patterns are:

- M3—Temperature increases, molecular movement/kinetic energy increases, and the balloon inflates.
- M4—Temperature increases, molecular movement/kinetic energy increases, the air expands, and the balloon inflates.
- M5—The air temperature inside the bottle increases, the kinetic energy of the particles increases, the number of collisions between particles increases, and the balloon inflates.
- M6—The air temperature inside the bottle increases, the kinetic energy if the particles increases, the number of collisions between particles increases, pressure inside the balloon becomes higher, and the balloon inflates.

The second question asked PTs to predict what would happen to the inflated balloon if the bottle were placed in a basin of iced water. The majority (19) of the 24 students gave understandable answers predicting correctly a decrease in the volume of the balloon, but a few (5) stated that the volume of the balloon would remain constant.

The understandable answers stating that the volume of the balloon would remain the same were categorized either as phenomenon-based reasoning or as model-based reasoning. However, they all revealed a PT's difficulty in dealing with reversible phenomena. In fact, they all mentioned that once a certain state was reached, the volume of the balloon (P1), the mixture of gases (M2), or the state of the particles (M1), would remain constant, independently of what happened afterwards. The types of explanations put forward are

- P1—Temperature decreases, inflation cannot continue, and so the volume remains constant.
- M1—The air particles are expanded and the temperature decreases, but the expansion will not be altered and volume of the balloon remains the same.
- M2—Gases formed in the chemical reaction do not escape; thus the volume will remain the same.

The explanations for the (correct) prediction of a decrease in the volume of the balloon were found to be either relation-based or model-based. Relation-based explanations include a relationship between the decrease in the air temperature (inside the bottle and the balloon) and either a decrease in the air density, having as a consequence the air's falling (R1, shown by 1 PT) or a decrease in the pressure exerted by it (R2, shown by 2 PTs). Hence, the shrinking of the balloon was explained through the following types of reasoning:

- R1—The air temperature decreases, air density decreases, and the air falls.
- R2—Temperature decreases, pressure inside the system decreases, and the balloon becomes more empty.

Model-based explanations for the correct prediction are based on the same concepts used for explaining the inflation of the balloon. The absence of a chemical reaction (M3, mentioned by 1 PT), a reduction in the speed of the particles (M4, mentioned by 12 PTs), a reduction in either the movement (M5) or the number of collisions (M6) and a decrease in pressure (each one mentioned by 1 PT), and a 'getting closer' of the particles (M7, also mentioned by 1 PT) were used to justify the prediction made. Thus, the patterns of answer shown by PTs are

- M3—There is no heating, no chemical reaction occurs, no gases are formed, and volume decreases.
- M4—Temperature decreases, the movement of the particles slows down, and volume decreases.
- M5—Temperature decreases, the movement of the particles slows down, pressure inside the system decreases, and volume decreases.
- M6—Temperature decreases, collisions between particles decrease, pressure inside the system decreases, and volume decreases.
- M7—Temperature decreases, particles get closer, and volume decreases.

The third question asked PTs to predict what would happen to the volume of a balloon stretched over the neck of a bottle when the bottle was heated in an upside down position. While the majority of the PTs who gave understandable answers (26 out of 31) predicted that the balloon would inflate, a few of them (5) stated that its volume would decrease. In the latter case, all the answers were classified as relation-based reasoning. These were based on the assumption that hot air rises (R1, R2), although three of them also used explicitly the concept of density (R2) and related it to heating to explain the ascension of the air and the consequent shrinking of the balloon.

- R1—The air inside the bottle is heated; hot air rises.
- R2—The air inside the bottle is heated, becomes less dense, and rises.

As far as the inflation of the balloon is concerned, the 26 PTs who gave understandable answers when justifying their predictions used the three forms of reasoning considered in this analysis. Phenomenon-based reasoning was less frequent (shown by 2 PTs) than model-based reasoning (shown by 19). With regard to phenomenon-based reasoning, only one pattern of answer was found:

P1—The bottle is heated and then the balloon inflates.

In the case of relation-based reasoning, PTs used the ideas of the expansion of air (R3, shown by 1 PT), an increase in volume (R4, shown by 1 PT), an increase in pressure (R5, shown by 2 PTs), and gravity (R6, shown by 1 PT) to explain the predicted inflation of the balloon.

- R3—The air is heated and therefore it expands.
- R4—The temperature inside the bottle increases; then the volume of air increases.
- R5—The air is heated; then pressure inside the bottle increases.
- R6—Gravity pulls the air down.

Answers categorized as model-based reasoning included correct (although in some cases incomplete) and alternative ideas and seemed to be based on patterns of reasoning that were similar to those described for the inflation of the balloon when the bottle was heated in the upright position. Thus, the PTs that used alternative ideas based their explanations on the idea of the formation of hydrogen, due to a chemical reaction caused by heating the air (M1, shown by 2 PTs) and on the attribution of macroscopic properties to the particles of air (M2, shown by 1 PT), as follows:

- M1—Hot water heats the air, a chemical reaction occurs in the air, and hydrogen/gas is formed.
- M2—The temperature of the particles increases and they expand.

The accepted ideas used to build up an explanation for the prediction were also similar to those used to explain the evidence previously given. In fact, PTs used concepts like molecular movement (M3, 12 PTs), kinetic energy (M4, 1 PT; M5, 2 PTs; M6, 1 PT), collision (M5, M6), and pressure (M4, M6) to relate heating (and the consequent increase in the temperature) to the inflation of the balloon. Nevertheless, the explanations based on correct ideas were, in some cases, incomplete (M3, M4, M5), since they omitted some explanatory steps (e.g., M4) rather than presenting a chain of reasoning such as the one given in M6 (accepted pattern). These patterns of reasoning are

- M3—The temperature inside the bottle increases; molecular movement increases.
- M4—The temperature inside the bottle increases, the kinetic energy of the air particles increases, and the particles exert pressure on the internal surface of the balloon.
- M5—The temperature inside the bottle increases, the kinetic energy of the air particles increases, and the number of collisions between particles increases.
- M6—The temperature inside the bottle increases, the kinetic energy of the air particles increases, the number of collisions between particles increases, and the pressure on the internal surface of the balloon increases.

2. The burning-candle problem

The questionnaire included two items focusing on the burning-candle problem. The first question on the candle problem asked PTs to explain why, when the bottom of a burning candle is placed in a basin of water and the candle is covered with a bell-shaped glass, water rises inside the glass. PTs were informed that the bell-shaped glass cover becomes foggy, some air bubbles can be seen, and the flame is extinguished. Table 3 shows that no PT used phenomenon-based reasoning and that relation-based reasoning was the prevalent form of reasoning (26 out of 38).

The second question required PTs to predict and explain what would happen to the level of water if there were two candles instead of one. Results given in Table 3 show that relation-based reasoning was again the most frequent form of reasoning (25 out of 38) and phenomenon-based reasoning the form of reasoning less used (just 1 PT).

As far as the first question is concerned, most of the PTs who used relation-based reasoning (17 out of 26) to explain the rise of the water level, based their explanations on the idea that oxygen was consumed (R1). Four students explained the event in terms of the formation of water (R2) and 3 cited the air bubbles released from the inside of the bell-shaped glass cover (R3). Four PTs used the concept of pressure but it is not clear from their explanations how pressure decreases (R4) or increases (R5) inside the bell-shaped glass cover. They merely invoked a relationship between the level of water and the increase (R5) or decrease (R4) in pressure inside the bell-shaped glass cover. These patterns of answer are as follows:

- R1—Oxygen is consumed; then water rushes in to fill the space left empty by the oxygen.
- R2—The glass cover gets foggy, water is formed, and the water level rises.
- R3—Air bubbles are released; then pressure inside the bell-shaped glass cover decreases, and water rushes in to fill the space left empty by the air.
- R4—Pressure inside the bell-shaped glass cover decreases and water rushes in.
- R5—Pressure inside the bell-shaped glass cover increases and water rushes in.

Although fewer PTs showed model-based reasoning than for the balloon problems (5 out of 38), they nevertheless showed four patterns of answers. One pattern of answer, which explained directly the rise in water level (M1, shown by 1 PT), was based on the occurrence of a chemical reaction leading to the production of water. M2 answers (shown by 2 PTs) justified the rise in water level by focusing on the concept of pressure but relating the change (decrease) in pressure to the amount of oxygen consumed. Another PT used the concept of expansion (pattern M3)—particles expanded due to the increase in temperature—but it was unclear both what was meant by the expansion of particles or how this related to a rise in water level. Finally, only 1 PT gave an explanation that included the majority of the elements taken as necessary for an instance of correct model-based reasoning (see Table 2). This explanation is coded as pattern M4. The patterns of answers for model-based reasoning that were identified in this question were defined as follows:

- M1—A chemical reaction produces water vapour that condenses on the bell-shaped glass-cover walls and the water level rises.
- M2—Oxygen is consumed, the pressure inside the bell-shaped glass cover decreases, and the water rushes in.
- M3—The temperature inside the bell-shaped glass cover increases, particles expand, and water rushes in.
- M4—Movement of particles increases, pressure inside the bell-shaped glass cover increases, some air escapes from the bell-shaped glass cover, the flame extinguishes, and water rushes in.

Thus, it seems that, despite the fact that some PTs tried to use model-based reasoning to explain the rise in water level, they did not do so successfully.

The second question about the candle problem required PTs to predict and explain what would happen to the level of water if there were two candles instead of one. The majority of the PTs who gave understandable answers (26 out of 32) predicted incorrectly that water would rise to the same level as with one only candle and the remaining 6 subjects predicted that the level of water would rise more than with one candle. The former subjects showed the three forms of reasoning considered in the analysis and the explanations given by them focused on one of the aspects of the experiment that would remain constant. As far as phenomenon-based reasoning is concerned, only one pattern of answer (shown by 1 PT) was identified. It focused on the amount of water (P1).

P1—The amount of water is the same; the level of water will be the same.

As far as relation-based reasoning is concerned, the concepts used were the same as in the case of one candle. In fact, the prevalent pattern of answer (16 out of 38) focused again on the available amount of oxygen (R1). The other patterns of answer concentrated on the amount of air available (R2, shown by 2 PTs), the bubbles coming out (R3, shown by 2 PTs), and pressure (R4, shown by 1 PT), as described below:

- R1—The amount of oxygen inside the bell-shaped glass cover is the same, the space available is the same, and the level of water rises as much as with one candle.
- R2—The amount of air inside the bell-shaped glass cover is the same, the same amount of water will condense.
- R3—The same quantity of air bubbles go out, the space available is the same, water rises as much as with one candle.
- R4—Pressure inside the bell-shaped glass cover is lower than outside to the same extent as with one candle; water rises as much as with one candle.

The amount of oxygen was also used by the 4 PTs who used model-based reasoning (M1) to explain why they predicted that water would rise as much as with one only candle. However, this idea was integrated with the idea of a chemical reaction, before being related to the concept of pressure, as follows:

M1—The amount of oxygen that is consumed in the chemical reaction is equal that in the case of one candle, so pressure inside the bell-shaped glass cover decreases as much as in the case of one candle and water rises as much as with one candle

With regard to the correct prediction of an increase in the level of water, PTs' explanations were classified either as relation-based reasoning (4 PTs) or model-based reasoning (2 PTs). In the case of relation-based reasoning, they concentrated again on the production of water (R5) and the increase in pressure (R6). The underlying ideas were that more candles burning means more water formed or a greater increase in pressure. However, nothing was said, again, about why pressure increases.

- R5—There are more candles, the bell-shaped glass cover is more foggy; and the water level rises more.
- R6—Pressure inside the bell-shaped glass cover increases more; the level of water rises more.

The two model-based-reasoning explanations of prediction of the rising of the water level include the ideas of expansion of particles (M2) and increase in the movement (M3) in ways that are rather similar to those found in the previous question. Again, only 1 participant in the study gave an answer similar to the accepted one (M3). These patterns of reasoning are

- M2—The temperature inside the bell-shaped glass cover increases more than in the case of one candle; then the particles expand more too, and the level of water rises more.
- M3—More candles, more heat, more movement of particles, greater increase in pressure inside the bell-shaped glass cover, more air escaping from the bell-shaped glass cover, and more water rushing in.

3. *The egg-and-bottle problem*

Table 3 gives the results for the two questions on the egg-and-bottle problem. The first question asked PTs to explain how a boiled egg, without the shell, could enter a previously heated bottle without being smashed. In this case, a large number of *no answer* and *other* answers (14 out of 38) were obtained, along with models of reasoning corresponding to the main categories of analysis. Relation-based reasoning was the prevalent model of reasoning (22 PTs). The second question required PTs to predict whether or not the egg could come out of the bottle again (without being touched) and to explain their predictions. Table 3 shows that 15 PTs (out of 38) did not answer this question and 6 students gave incomplete or incomprehensible answers (*other*). Relation-based reasoning was again the prevalent model of reasoning identified among the understandable answers to this question (15 PTs).

In the question focusing on the entrance of the egg, only 1 PT showed phenomenon-based reasoning (P1) and 1 showed model-based reasoning (M1), the latter being similar to the correct model-based reasoning characterized in Table 2.

- P1—Egg gets in through the bottleneck.
- M1—The kinetic energy of the particles increases; the pressure inside the bottle increases; some air gets out; cooling down decreases the movement of the particles; the pressure inside the bottle decreases, becoming lower than that outside; and the egg gets in.

Relation-based reasoning was the most common form of reasoning. Responses concentrated on the bottleneck (R3, shown by 9 PTs; R7, shown by 1 PT), on the inside of the bottle (R4, shown by 1 PT; R5, shown by 4 PTs; R6, shown by 3 PTs), or on both the bottle and the egg (R1, shown by 1 PT; R2, shown by 3 PTs). Ideas like dilation, vacuum, changes in pressure, and changes in friction were put forward but not explained, as illustrated below:

- R1—The bottle is heated; the egg becomes flexible and gets in.
- R2—The temperature rises; the egg is compressed and gets in.
- R3—The bottleneck dilates with heating and egg gets in.
- R4—The air is heated, a vacuum is formed, and egg gets in.
- R5—Pressure inside the bottle becomes lower than outside and the egg gets in.
- R6—Pressure inside the bottle increases and the egg gets in.
- R7—The bottle is heated, friction between the egg and the bottleneck decreases, and the egg gets in.

In response to the second question about the egg and the bottle, 4 of the 17 PTs gave understandable answers predicting that the egg could not be taken out of the bottle. The explanations of these predictions included phenomenon-based reasoning (one answer) and relation-based reasoning (three answers). The phenomenon-based reasoning answer showed the following pattern:

P1—The bottle cooled down; then the egg does not fit on the bottleneck.

Analysis of the relation-based answers indicates that their authors rejected the possibility of taking the egg out again because dilation (R1), a force (R2), or a difference between inside and outside pressure (R3) did not exist. Their reasoning was as follows:

- R1—After heating is stopped, the volume of the bottle returns to the initial value, and the egg cannot come out.
- R2—There is no outside force able to pull the egg out.
- R3—Without heating, internal pressure will become equal to external pressure and the egg will not come out.

Thirteen PTs predicted that the egg could be taken out again. Relation-based reasoning was again the most frequent (12 out of 13) form of reasoning, with only 1 subject using model-based reasoning. The student whose answer was classified as model-based reasoning (M1) gave an explanation that was underpinned by the use of the correct model (see Table 2) and can be summarized as follows:

M1—Heat the bottle upside (having the egg in the bottleneck); the movement of the air particles increases, the pressure inside the bottle increases, too, and the egg comes out.

PTs who gave relation-based reasoning answers suggested that the egg could be taken out by dilating (by heating) the bottle (R3, 3 PTs), dilating (by heating) the bottle upside down (R4, 5 PTs), dilating (by heating) the air inside the bottle (R5, 1 PT), increasing the inside pressure (by introducing air into the bottle or burning something inside it) (R6, 3 PTs), or decreasing the outside pressure (without further explanation) (R7, 1 PT).

These patterns of answers are as follows:

- R3—Heating the bottle, the bottleneck dilates and the egg comes out.
- R4—Heating the bottle upside down, the bottleneck dilates and the egg comes out.
- R5—Inverting the bottle and increasing the inside pressure, the egg will be pushed out.
- R6—Heating the bottle, air dilates and pulls out the egg.
- R7—Inverting the bottle and decreasing air pressure outside, the egg will be pulled out.

Cross-comparisons: Within-problem and across-problem

Table 4 shows that more than half of the students used either MBR or RBR in a consistent way when answering the questions on the bottle-and-balloon and burning-candle problems. In the case of the egg-and-bottle problem, the consistency of PTs' answers to the two questions was lower than for the other two problems.

The form of reasoning used consistently by the highest number of students varied from problem to problem. MBR was the most frequent for the bottle-and-balloon problem (44.7%), and RBR was the most frequent in the other cases (burning candle—60.5%; egg and bottle—36.8%).

Table 5 shows the PTs' consistency of reasoning across the three problems, per type of request (explanation/prediction).

Table 4: Analysis of PTs within problem, consistency of reasoning ($N = 38$)

Problem	Combination of Forms of Reasoning	Frequency	Percentage
Bottle and balloon (three questions)	3 MBR	17	44.7
	3 RBR.	3	7.9
	2 MBR + OTA	3	7.9
	2 RBR + OTA	5	13.2
	Other combinations	10	26.3
Burning candle (two questions)	2 MBR	3	7.9
	2 RBR	23	60.5
	Other combinations	12	31.6
Egg and bottle (two questions)	2 MBR	1	2.7
	2 RBR	14	36.8
	Other combinations	23	60.5

OTA = other types of answers

Table 5: Cross-problem analysis of PTs' reasoning by type of request ($N = 38$)

Type of Request	Combination of Forms of Reasoning	Frequency	Percentage
Explain (three questions)	3 MBR	1	2.6
	3 RBR	5	13.2
	2 MBR + OTA	3	7.9
	2 RBR + OTA	12	31.6
	Other combinations	17	44.7
Predict (four questions)	4 MBR	1	2.7
	4 RBR	1	2.7
	3 MBR + OTA	1	2.7
	3 RBR + OTA	4	10.5
	2 MBR + 2RBR	6	15.7
	2 MBR + OTA	10	26.3
	2 RBR + OTA	9	23.7
	Other combinations	6	15.7

OTA = other types of answers

The number of PTs using one only form of reasoning for all questions of the same request-type was greater for explain (three questions) than for predict questions (four questions): While 5 PTs used RBR for all three explain questions, only 1 PT did so for the four predict questions. About 40% of the PTs used the same form of reasoning in two (the majority) of the three explain questions, but only 13.2% did so for the majority (three) of the four predict questions. It is worth noting that 15.7% of the PTs used MBR and RBR for two questions each; and 2.7% (1 participant), MBR for all four predictions. The remaining PTs used several different combinations of answer type.

Discussion

Before starting the discussion, it is worth remembering that the main concern of this study is the form of reasoning used by undergraduate students who have finished all the Physics, Chemistry, and Education courses included in their undergraduate program in Physical Sciences Education. The year after data collection, the participants in the study were expected to be engaged in one year of practice teaching in school in order to become Physical Sciences teachers.

Contrary to our expectations, PTs seldom used model-based reasoning to explain phenomena described to them or to predict and explain their predictions about what would happen during a given intervention. Moreover, the use of *correct* model-based reasoning was even more rare. However, the fact that PTs do not use model-based reasoning in these situations does not necessarily mean that they are unable to use it (Driver et al., 1997). Rather, as stated in the methodology section, literature dealing with this issue from a cognitive-development perspective indicates that subjects of this age (over 20) are expected to be able to use it. It may be that PTs did not feel the need to use models to explain the science phenomena presented to them. Also, there is some evidence that the participants in this study did not make adequate use of data as evidence in their explanations. Not only did PTs concentrate on one part of the data given and ignore the other, they did not seem to feel it necessary to indicate what data supported the explanatory ideas they used (e.g., they used the idea of oxygen consumption to explain the rise in water level after the flame had gone out, without there being any data about oxygen and without mentioning the need to have such data.) Despite the evidence from Kuhn's (1989) study that such behaviour can be expected, it is certainly not desirable in a student reaching the end of an undergraduate science program.

The results of the study may also indicate that PTs see the phenomena they were asked to explain as events too familiar to need explanation through complex models. As students, the participants in the study had encountered some of the phenomena several times in school and in other contexts, with different objectives. In fact, these problem-situations are often used in the fifth-grade Natural Sciences course, as well as in primary school (especially the bottle-and-balloon and the burning-candle problems) and in contexts where science is presented to the public, such as at interactive science centres, in books on science for the people, and in science exhibitions in schools (especially the egg-and-bottle problem, due to the fact that it can easily be associated with magic). It can also be argued that PTs did not feel that the principal form of reasoning under scrutiny (model-based reasoning) was essential to the context of data collection. Of course, they knew that their answers were not going to be used for evaluation purposes but it does not seem reasonable to think that a PT would consciously do something in order to 'underscore.' Obviously, our data do not provide evidence to resolve these doubts. Their eventual resolution would require a discussion of this issue with the PTs involved.

Another possible explanation for the low use of model-based reasoning may be related to the incompleteness of PTs' scientific knowledge of the phenomena used in the study. In fact, data collected here and in literature on alternative conceptions (e.g., Driver et al., 1994) indicate that PTs lack science knowledge and/or hold incorrect (alternative) ideas about phenomena, or aspects of them. Thus, when the participants stated that the oxygen was consumed they may, erroneously (Lucas & Garcia-Rodejo, 1989), have meant that there was no oxygen left (burning-candle problem). Under the experimental conditions described in the questionnaire, the percentage of oxygen is simply reduced to a value between 12 and 16% (Caplan, Gerritsen, & LeDell, 1994). Lower final percentages require the manipulation of several factors. The idea of the expansion/dilation of particles (bottle-and-balloon problem), or the idea of the formation of a vacuum due to heating (egg-and-bottle problem), or the idea of the decomposition of water due to heating (burning-candle situation), are other examples of conceptual difficulties that have been reported in the literature (Driver et al., 1994) as alternative conceptions held by people of diverse ages. This is striking, and disturbing, because the year after data collection these PTs were supposed to be helping school students to change alternative conceptions that closely matched the ideas they themselves held. However, to become sure that PTs hold such alternative conceptions, a follow-up interview would be needed. Unfortunately, it was not possible within the context of this study.

On the other hand, PTs' explanations, even when model-based, are not always accurate. In addition, PTs may put forward ideas without explaining them fully. For example, in the context of explanation-type questions, students providing answers mentioning an increase in the movement of particles due to heating did not always explain what sort of movement they were talking about. This is important because, as Rozier and Viennot (1990) point out, particles could just vibrate more intensely, without changing their position. If this were the case, the movement of the particles would not be enough to explain the inflation of the balloon. A similar lack of accuracy was found in the answers to predict questions (and to explain-the-prediction questions). In the case of the egg-and-bottle problem, a suggestion was made about decreasing the pressure outside the bottle in order to get the egg out, but the PT did not explain how the pressure could be decreased or how this would allow taking the egg out of the bottle.

The number of *no answer* and *other* types of answer was very large, especially for the third problem, which might lead us to think that the PTs were already tired. Yet, although this may have been so, they did not complain about the length of the questionnaire. In any future study, the order of the questions should be altered in order to get evidence for or against this hypothesis. The overall performance of the PTs may also reveal a lack of explanatory ability. Indeed, Ball (1999) has shown that students are seldom asked to explain and are even less frequently asked to make predictions and to explain them, although it seems that by giving students opportunities to explain it is possible to promote their explanatory abilities (Meyer & Woodruff, 1997). In the case of the percentages of *no answer*, it is possible that some PTs did not feel secure about the scientific validity of their explanations and decided not to put them forward.

The number of *no answer* and *other* answers, together with the PTs' poor performance on the egg-and-bottle problem, may partly explain the reduced consistency of reasoning within problems and across problems. Nevertheless, these results raise the question of whether or not the form of reasoning used in an explanation is dependent on the content and the context of the task (as variations were found among the problems). The point is whether or not PTs recognize the questions as focusing on the same phenomena. Another question raised by the results is whether or not PTs activate the appropriate science knowledge when they assemble the answer to each specific question. Prospective teachers had been taught about air pressure at a microscopic level, but maybe the diverse questions led them to activate different pieces of knowledge, leading to different forms of explanation and reducing the consistency of reasoning.

Finally, these rather poor results could partly be due to the fact that data were collected under examination conditions, with participants not allowed to talk to their peers. Possibly, PTs would give better explanations if the tasks were administered to groups, as in the study reported by Driver et al. (1997). However, PTs are about to become teachers, and because science teachers are alone when teaching science to their students, individual performance was deemed to be more important than group performance.

Conclusions and implications for teacher education

This study focuses on PTs' forms of reasoning when explaining natural phenomena. The results suggest that they prefer relation-based reasoning (empirical generalizations) although in some cases they try to use models (most of the time in an incomplete way) to explain phenomena or to explain predictions about eventual phenomena. Hence, PTs' performance may indicate that they do not feel the need to or do not know how to use models to build up explanations from evidence or to predict the behaviour of the world.

The explanatory difficulties found among this group of PTs reinforce the idea already advanced by several authors (e.g., Ogborn et al., 1997) that science-teacher education needs to take the issue of explanation seriously. It can be argued that the let's-think-it-through-together type of explanation identified by Ogborn et al. (1997) is probably the most appropriate type of explanation to teach prospective and in-service teachers, with respect to both scientific explanation and explanation in science education, in order to give them some insight into how they can deal with these issues in their classrooms. This argument is based on the constructivist assumptions that should guide teacher education (Leite & Afonso, 2002) and on the role of action for lifelong learning. Hodson (1998) states that 'doing science successfully involves learning to "think on one's feet"' (p. 210). Adapting this statement to explanation, it can be said that explaining successfully involves learning to 'explain on one's feet.' This means that prospective teachers need to have opportunities to explain in their undergraduate program in order to improve their explanatory abilities (Horwood, 1988; Ogborn et al., 1997) and in-service courses for teachers need to provide similar opportunities.

This study provides some evidence that PTs lack knowledge of the science concept under study. While everyday explanations are based on a world accessible to the senses, scientific explanations rely on formal, sometimes mathematical, constructions and created entities (Ogborn et al., 1997). Thus, scientific explanations are dependent on a content that was once established and accepted by the scientific community. Therefore, nobody can explain from a scientific point of view what s/he does not know from this perspective. This means that any intervention aiming to improve prospective teachers' abilities to explain science to their students should concentrate on improving prospective teachers' scientific knowledge base.

Prospective teachers were found to have some difficulty relating evidence and theory to build up explanations and make predictions about phenomena. Data, evidence, explanation, and theory are inter-related concepts (Gott & Duggan, 1995; Leach, 1999) and their inter-relationships need to be understood if evidence-based explanations are to be built and predictions are to be made from theories and submitted to empirical tests.

In this study, PTs were asked to explain natural phenomena. A few of them succeeded and others did not. In their future classrooms, they will not be asked to explain a given phenomenon but to teach the accepted scientific explanation for that phenomenon to their students or to organize learning contexts to help students to build up scientific explanations about the phenomena they want to teach about. As Ogborn et al. (1997) point out, explaining in science (building up scientific explanations) is different from explaining science (that is, explaining the scientific explanations to someone else). Thus, ability to explain in science is not enough to guarantee the success of teaching scientific explanations. Hence, teacher education programs should also deal with the teaching of explanation in the science classroom. In doing so, those programs should focus on the analysis of teachers' explanatory styles and difficulties, as well as on the characteristics of students' and textbooks' explanations. This analysis may make them more aware of the complexities of explaining something to someone else and of the need to be critical about textbook proposals and to take the learner into account. However, it seems necessary to be clear about whether the only thing that matters is to teach the scientific explanation or whether it is also important to enhance the power of students as independent explainers (Horwood, 1988). If the latter is the case, then both pre-service and in-service teacher education programs should concentrate on teaching how to explain science in the classroom and how to teach about the characteristics of scientific explanations (Kolstø, 2001). This latter approach is also necessary if a more authentic view of science is to be promoted (see 'Introduction').

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