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Understanding the Idea of Chemical Elements and Their Periodic Classification in Spanish Students Aged 16–18 Years

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Abstract The work reported here involved a comparative study regarding the understanding that high school students (16–18 years) have of the concept of chemical elements and their periodic classification. More specifically, the level of knowledge on this topic was compared before and after the completion of baccalaureate studies in a sample of Spanish students. In order to achieve this goal, a questionnaire was developed that included 14 items in an open format, through which various aspects of the students' understanding of the idea of chemical element and their periodic classification were assessed. In addition, the application of this knowledge to interpret and predict the behaviour and properties of elements and to carry out calculations on the atomic composition of the elements was evaluated. Aspects concerning the acquisition of scientific knowledge, the application of knowledge to different contexts and situations, and the use of scientific evidence to draw conclusions and knowledge about the nature and history of science were evaluated. The questionnaire was previously validated with a large group of students. The results of this study show that improvements occur primarily in addressing higher level cognitive questions (analysis, synthesis and evaluation) in comparison to the lower level tasks (capacity for retention, understanding or direct application of learning). In addition, students who start high school have a very limited understanding of the ideas behind the Periodic Table of the chemical elements and that their lack of understanding, to a large extent, remains upon

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completion of the baccalaureate. These results suggest that there are real difficulties in understanding this topic and show the limited influence of the studies completed in high school.

Keywords High school/baccalaureate · Learning problems in chemistry education · Periodic Table of the chemical elements · Secondary education · Student understanding

Introduction

The concept of chemical elements, their properties and the law of periodicity are amongst the topics that are now considered as cornerstones both in history (Schmidt, Baumgärtner & Eybe, 2003; Scerri, 2007, 2011; Esteban, 2009) and the teaching of chemistry (Ben-Zvi & Gemut, 1998; Demircioğlua, Demircioğlua & Çalikb, 2009). This situation means that this topic is one of the most frequently discussed in chemical education publications, as evidenced by a review of articles published in journals such as *The Journal of Chemical Education* (Linares, 2004; Linares & Izquierdo, 2007).

Most publications in this field have focused on historical and epistemological problems or have concerned search-related strategies and resources for teaching at different educational levels. However, less attention has been devoted to identifying the difficulties and shortcomings in student learning or to investigating the effects of proposed strategies and resources to improve the teaching and learning of this subject. As a consequence, with some exceptions (Ben-Zvi & Gemut, 1998; Franco-Mariscal, 2011; Linares, 2004; Taber, 1999; Taber & Tan, 2007; Talanquer, 2006, 2010; Wang & Barrow, 2013), this can be considered to be an area in which very few research studies have been carried out. This situation exists despite the importance of this topic in introductory chemistry courses at the high school and university levels (Scerri, 2007) and despite the fact that students often struggle to learn and understand this topic, indicating that the various obstacles to learning should be analysed and clarified (Franco-Mariscal & Oliva-Martínez, 2012; Schmidt, 1998). As a result, it is of interest to define these shortcomings in teaching/learning and to identify strategies and resources that can contribute to overcoming them.

In the work described here, we carried out a study on the understanding that Spanish students (aged 16–18 years) have the concept of the chemical element and the Periodic Table and compared their knowledge before and after baccalaureate studies. Our aim was to evaluate the performance of the students in this area at the beginning of their university studies and to assess the contribution that baccalaureate studies made to their performance. This type of study is of interest in order to identify gaps in the teaching/learning process and to provide a basis for the development of future innovations aimed at addressing any problems in the learning process.

Theoretical Background

The theoretical foundations of the research described here concern two basic areas. The first area concerns the type of knowledge required and the nature of the questions posed in an assessment of the scientific content. The second area is related to the background that exists in the literature on learning difficulties and problems related to the notion of chemical elements and the Periodic Table. A brief review of the literature on these topics was carried out in order to define and justify the structure and nature of the questionnaire.

The Types of Knowledge and Reasoning Required

In the first area under consideration, both the type of learning to be assessed and the level of cognitive skills required can be analysed by posing questions to gauge the students learning or the learning pursued.

From the point of view of the type of learning, one must return to the classical differentiation made by Ausubel between 'rote learning' and 'meaningful learning' (Ausubel, Novak & Hanesfan, 1978; Novak & Gowin, 1984). Rote learning is the simple storage of information, which consists of data as facts, statements and definitions that are retained and then recalled in a literal way. In contrast, Ausubel defined meaningful learning as that in which the student assimilates and owns knowledge and relates it to understanding that they already have. Meaningful learning is very desirable since it allows students to understand and gives meaning to knowledge handling in order to provide more stable and enduring knowledge. However, Ausubel stated that rote learning is also necessary. In fact, in terms of the chemical elements and the Periodic Table in particular, rote learning is important to familiarize students with the Periodic Table and it enables them to memorize the names and symbols of the chemical elements and to identify their position in the Periodic Table.

Such rote learning, which is related to the retention and recall of information, encompasses one of the categories listed by Bloom, Engelhart, Fust, Hill & Krathwohl (1956) for the reasoning skills required in assessment tasks. Specifically, this category of 'knowledge'—as opposed to other types such as comprehension, application, analysis, synthesis and evaluation—increasingly contributes to higher order skills, the development of which would require significant learning to take effect. This hierarchy has been reviewed and reformulated by various authors and has even been combined with other criteria for other forms of categorization (Krathwohl, 2002).

In the specific case of learning chemistry, there is broad consensus that learning and assessment involve components that are both conceptual and algorithmic in nature, in addition to memory and reasoning skills. As a consequence, various types of questions have been categorized into different classes in terms of their cognitive complexity (Smith, Nakhleh & Bretz, 2010; Stamovlasis, Tsaparlis, Kamilatos, Papaoikonomou & Zarotiadou, 2005; Zoller, Lubesky, Nakhleh, Tessier & Dori, 1995). These different types of question are associated with terminology that does not necessarily mean the same thing in each case and they include a number of categories that are often divergent. Hence, in many cases, categories overlap each other and this makes comparison between rankings difficult, although some interesting approaches to address this issue have been reported (Smith et al., 2010). Selected examples of the taxonomies used by various authors are shown in Table 1.

Table 1 Taxonomies employed by several authors to categorize different kinds of questions

Zoller et al. (1995)	Stamovlasis et al. (2005)	Smith et al. (2010)
Algorithmic	Knowledge-recall	Definition
Conceptual	Simple algorithmic	Algorithmic
Lower-order cognitive skills (LOCS)	Demanding algorithmic	Conceptual
Higher-order cognitive skills (HOCS)	Conceptual	

Although the algorithmic component was not evaluated in this study, it is important to consider this issue here when providing an overview of the areas that can be assessed.

From the point of view of the purpose of the learning to be achieved, one must consider the purposes outlined by Hodson (1992) for learning science. Hodson identified three basic dimensions for the learning of science and these correspond to the tasks of 'learning science', 'learning to do science' and 'learning about science'. The first two aspects are included within the taxonomies shown in Table 1. However, the third aspect concerns new areas that must be examined and related to the nature and history of science itself. This aspect is also considered in this study. Finally, according to Millar & Osborne (1998), there are four important areas in learning science: the acquisition of scientific knowledge, the application of knowledge to different contexts and situations, and the use of scientific evidence to draw conclusions and learn about the nature and history of science. In this classification, there are differences in the level of cognitive demand for various types of questions such that only the first category requires knowledge and understanding, the second requires the application of learning, while the third requires a capacity for analysis and synthesis. The fourth category, meanwhile, is likely to involve further capacity for evaluation, namely in matters that require an assessment of the usefulness and limitations of scientific knowledge.

In this study, we opted for the latter classification, which addresses the evaluation of the specific topic in question here. As a consequence, we considered those dimensions that are most appropriate to this area. For example, the algorithmic component, which is very much a part of other topics such as stoichiometry, thermochemistry or balance, is not relevant in the study of issues related to the chemical elements and the Periodic Table. In fact, as discussed below, the focus of research is aimed primarily on the analysis of conceptual learning difficulties or more complex handling of the Periodic Table, either to solve qualitative issues related to the direct application or inferences associated with high-level cognitive skills.

Difficulties Encountered in Learning About the Chemical Elements and Their Periodic Classification

In the limited amount of educational research conducted on issues and gaps in students' comprehension of the elements and the Periodic Table, we have to distinguish three areas. Firstly, there are studies that focus on the difficulty and complexity of the concept of the chemical element. Secondly, another area relates to the interpretation of properties and the Periodic Table of chemical elements. Finally, there are studies that concern curricular decisions and the methodology adopted by the faculty for the teaching of these topics and the possible difficulties that may be encountered.

The first of these areas concerns the idea of an element as a chemical substance (Furió & Domínguez, 2001, 2007; Raviolo, Garritz & Sosa, 2011) and, in turn, the distinction between elements and compounds (Briggs & Holding, 1986; Franco-Mariscal & Oliva-Martínez, 2012, 2013). Within this profile of learning problems, one must consider the work of Linares (2004), who described how one of the main difficulties with the concept of chemical elements lies in the ambiguous and ambivalent nature of this term. Thus, from the point of view of science, two definitions of 'chemical element' are provided by International Union of Pure and Applied Chemistry (IUPAC) (McNaught & Wilkinson, 1997). These two definitions correspond to two different meanings of the concept of chemical element: one of which is conceived in an abstract manner as a kind of atom, and the other understood as a real substance present in daily life and/or in laboratories. Due to this ambiguity in the idea of an element, the Periodic Table is considered both as a table of elements as substances and as a table of atoms of the elements. This double function may confuse students and lead to the use of the term element as a synonym for atom (Schmidt, 1998, 2000).

The second of the profiles outlined above is exemplified by the work of Taber (Taber, 1998, 1999, 2003; Taber & Tan, 2007) and Talanquer (2006, 2007, 2010). These studies concerned the analysis of misconceptions and intuitive explanations used by chemistry students, some of which are particularly relevant in the analysis of the properties of chemical elements and their compounds, as well as on their use and interpretation of the Periodic Table. Thus, in Taber's studies, students commonly misunderstood the scientific model for explaining and predicting trends in ionisation energy. For example, Taber (2003) described his findings in terms of a number of alternative conceptions. In particular, students commonly used the scientifically invalid ideas that (a) ions with full shells had some special inherent stability (more than octets or noble gas configurations), and (b) a positive nucleus gives rise to a fixed amount of nuclear force that is distributed or shared-out among the electrons present (conservation of force thinking).

Talanquer (2006, 2007, 2010) defined a set of heuristic reasoning patterns or different concepts common to the alternatives described in the chemical literature. This is the case for teleological reasoning, through which causal explanations are replaced by tendencies or inclinations of the systems to evolve in such a way that they satisfy some objective or purpose (Talanquer, 2007). For example, for many students, the octet rule becomes an explanation when considering the stability of atoms, so that they 'tend' to gain or lose electrons just to 'get to' a noble gas electronic structure. This leads to an overestimation of the octet rule as an explanatory model to understand the stability of atoms (Taber, 2001). Closely related to this type of reasoning are other explanations based on anthropomorphic or animistic reasoning, in which phenomena are attributed to the physical and chemical behaviours caused by the feelings and desires of humans. Other heuristic reasoning described by Talanquer (2010) is based on 'Recognition' and 'Representativeness' schemes. Furthermore, Talanquer (2006, 2010) described a heuristic of the type 'One-reason decision making', which is a cognitive shortcut that reduces the number of indicators and alternatives to be considered when making a decision, prompting several choices based on a single indicator. However, this heuristic suffers from a significant drawback when working with periodic properties, the development of which in the Periodic system depends on more than one factor at a time. Furthermore, among the heuristics described by Talanquer, of particular relevance is the one denoted as 'Periodic trend', which is based on decisions and comparisons between elements and compounds and only depends on the relative position in the Periodic Table of the different atoms in the substances being compared. For example, the reason that the bromine atom has a larger atomic volume that fluorine is simply 'because it is lower in the Periodic Table'.

Finally, the third of the profiles outlined above includes, for example, publications by Lehman, Koran & Koran (1984), Agudelo, Marzábal & Izquierdo (2009) and Linares (2004), which can shed light on the learning difficulties that can arise depending on the type of instructional method followed. The research by Lehman et al. (1984) explored the effects that the format of the Periodic Table and complementary written materials had on students when extracting and managing information from these sources. These authors found that the aforementioned factors did influence student performance, with interactions even found between the degree of the student's previous experience and the degree of understanding shown. For example, the results revealed that subjects with less experience in the use of the Periodic Table showed better performance when they used a version of the table that included more visual information. In contrast, for subjects who were more familiar with the Periodic Table, there were also advantages in the use of more visual tables but only for those with a higher level of verbal comprehension. Meanwhile, those with a lower level of verbal comprehension tended to process more effectively the traditional Periodic Table. The latter group benefited more when the Periodic Table came with additional written material.

Linares (2004) investigated the different ways in which undergraduate textbooks approach teaching the general chemistry of the Periodic Table. Linares identified three different methods, which he called 'substantialist', 'historic' and 'quantum mechanical/atomistic'. In the substantialist approach, the observed properties of the substances are used to define the periodicity, whereas the historical path introduces the presentation of the Periodic Table from a historical perspective. Finally, in the atomistic quantum mechanical approach, the atomic structure is employed to explain the configuration of the Periodic Table and the variation in the properties of the elements.

On assessing the studies reviewed in this work, it was found that the most common barriers to learning involve conceptual understanding, problems related to the direct application of concepts and difficulties in the development of complex inferences. Although these studies collectively provide valuable information concerning many areas of learning involved in this topic, major gaps are evident in the aspects investigated to date in this field. These gaps include basic issues such as the presence of chemical elements in our lives, the way in which the elements are arranged in the Periodic Table, the usefulness of the Periodic Table, the criteria by which the elements are organized and the limitations of the current Periodic System. Similarly, there is a dearth of studies that provide an overview to analyse the different causes of learning difficulties for these issues and to evaluate progress made by students as they proceed through the education system, particularly in Spain.

The Periodic Table in the Spanish Educational System

From an educational point of view, the Spanish curriculum (Ministerio de Ciencia y Educación, 2007a, b) addresses content related to the Periodic Table repeatedly and continuously from the 3rd year of Compulsory Secondary Education (CSE) (15–16 years of age)[1] up to the 2nd year of the baccalaureate in Science (17–18 years)[2] (see Appendix), albeit with some significant differences between the two cases. For example, in the 3rd year CSE (Year 10), the curriculum begins with a macroscopic description of the chemical element that is addressed by considering the historical predecessor—the 'simple substance'—and the experimental processes involved in differentiating composite substances. Subsequently, the submicroscopic view is approached by considering Dalton's atomic theory, the language of symbols and the models proposed by Thomson and Rutherford. In contrast, in the 4th year CSE (Year 11), which is the first course considered in this study, these topics are addressed using a

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[1] Equivalent to 4th Form or Year 10 (General Certificate of Secondary Education) in the UK.

[2] Equivalent to Upper 6th Form or Year 13 in the UK.

more advanced deductive model in the opposite sense to the previous year, i.e. a more in-depth study of atomic models is presented initially and, from these, the Periodic Table of elements is considered as a basis from which to infer and explain properties.

Although this alternative approach may appear relevant, the change in emphasis may be premature for two reasons. Firstly, the students have not yet acquired sufficient phenomenological experience to understand fully the topics that will be studied in subsequent years. Secondly, considering that, in practice, even in the 3rd year CSE (Year 10), the sequence of instruction is usually based on an operational approach to chemistry that begins by presenting the Periodic Table as a tool to support the rules of chemical nomenclature.

In these circumstances, significant gaps are expected in the knowledge of students who complete high school because the curriculum then moves directly to the analysis of atomic models as a basis for building electronic configurations. The baccalaureate course (Years 12 and 13) generally does not provide sufficient experimental and phenomenological knowledge, albeit in a deductive way, since the properties that are discussed in these courses, in terms of the application of the Periodic Table, usually only concern atomic properties, namely atomic volume, electronegativity, etc., all of which are related to the more abstract idea of the chemical element.

Furthermore, the textbooks do not generally contribute to this area as they tend to be based on conclusions and do not address the 'heuristic principles' that facilitate the development of knowledge through the history of science (Niaz, 2005).

Research Design

The main aim of this work was to conduct a comparative study into the understanding of a sample of Spanish school students (16–18 years) of the concept of the chemical element and the Periodic Table, both before and after completing their studies. To achieve this aim, a questionnaire was developed and validated, a process that is also described in this article. Thus, the objectives of the study were twofold:

1. To validate an exploratory questionnaire to assess students' knowledge on the concept of the chemical element and the Periodic Table.
2. To use the questionnaire to assess the students' knowledge before and after completing their baccalaureate and to evaluate the changes due to the teaching received prior to university entrance.

The questionnaire consisted of a total of 12 questions in open format (Table 2). The questions were designed to assess the understanding of the idea of the chemical element and its periodic classification and the application of this knowledge to interpret and predict phenomena and properties and to perform calculations on the atomic composition of the elements. Two of these questions were broken down into two sections, meaning that the total number of items evaluated was 14. These questions addressed four areas around the Periodic Table that are considered important in learning science (Millar & Osborne, 1998): the acquisition of scientific knowledge (K), the application of knowledge to different contexts and situations (A), the use of scientific evidence to draw conclusions (U) and knowledge about the nature and history of science (N). The composition of the questions and the writing style was developed,

Table 2 Questionnaire

Item	Learning area and tasks	
Acquisition of scientific knowledge (K)		
1	What do you think differentiates an element from a chemical compound?	Understanding of ideas and information retention
2A	Give the names and symbols of five metallic chemical elements.	
2B	Give the names and symbols of five non-metals.	
5A	List some properties that distinguish elements from one another.	
Application of knowledge in different contexts and situations (A)		
4	A large proportion of the chemical elements form part of objects and materials that are present in our daily lives. Try to identify all the chemicals you know (up to a maximum of ten) along with the materials or objects in which they are present in items that you have at home. It does not matter if the elements are components of chemical compounds.	Using the Periodic Table and/or electronic configurations for solving tasks. Relationship between learning and specific situations in daily life
6	Classify the following elements according to their similarities to one another: sulfur, hydrogen, fluorine, sodium, calcium, oxygen, chlorine, copper, silver, potassium. Explain your criteria for grouping the elements.	
9	List the following atoms in ascending order of size and explain the reasons for the order given: oxygen, hydrogen, uranium, iron, chlorine.	
10	With the help of the Periodic Table, can you state how many protons, electrons and neutrons there are in an atom of iron? Give an explanation.	
12	Explain why chlorine tends to form negative ions (Cl^-) while sodium forms positive ions (Na^+).	
Use of scientific evidence to draw conclusions (U)		
3	Imagine a spaceship that takes you to a faraway place in the universe. Do you think you would find the same chemical elements as on Earth? Or do you think there would be other totally different elements? Give an explanation.	Making inferences and predictions from a given situation or based on known or supplied information
5B	Do you think there are elements that have similar properties to each other? Why?	
11	The element chlorine has an atomic mass of 35.45 amu. Why is this value not an integer unlike the mass numbers of other elements?	
Understanding the nature of science (N)		
7	How old do you think the Periodic Table is? Do you think that it has always had the same form and structure or do you think that it has changed?	Origin, evolution, utility and limitations of the Periodic Table
8	Do you think that the Periodic Table is able to explain everything relating to the atoms or does it have its limitations? If 'yes' give reasons and if not give some of the limitations and defects that you know.	

by consensus, by the first two authors of this paper and by a teacher of Chemistry at the University of Cádiz (Spain) who has extensive teaching and research experience.

Analysis of the responses obtained for each item was conducted to develop a typology of responses through a system of categories for each individual item (Franco-Mariscal, 2011). The categorization process was developed jointly by two judges who had previously analysed the criteria and had agreed on a process for their implementation. After this initial categorization process, we performed a subsequent analysis in which the responses were classified into three levels: appropriate responses, partially appropriate responses and inappropriate responses (or blanks). A summary of the different situations is presented in Table 3, which shows the nature of the questions and the evaluation criteria used to assess student responses.

The questionnaire was used to carry out two studies, one for each of the proposals made. The first study was conducted to validate the instrument used and for this purpose the questionnaire was completed, without a time limit, by a sample of 176 students aged between 15 and 18 years. The students came from six different secondary schools in southern Spain with students of a middle socioeconomic level. All of the students had received traditional teaching from the methodological point of view.

In the second study, the questionnaire was given at the end of the course to a sample of 136 students. Of these, 67 came from three different high schools and they were enrolled in the optional subject Chemistry in the 4th year CSE (Year 11). The remaining 69 students were in five classes in the 2nd year of the Baccalaureate in Science (Year 13), which included the subject of Chemistry in the curriculum. Three of these groups were from the same secondary schools as mentioned previously, whereas the other two institutions had very similar characteristics. As in the previous case, all of the students had received traditional education that was not innovative.

The results obtained by the students in the 4th year CSE (Year 11) were adopted to assess the level of students in these subjects at the start of their baccalaureate. The results obtained by the students in the 2nd year of the baccalaureate (Year 13) were adopted to define the level of knowledge at the end of this educational stage and, therefore, the level for those who would enter university. The difference between these levels can therefore be regarded as an index to assess the evolution between the two points, i.e. the improvement during baccalaureate studies.

The data were processed with the statistical software package SPSS 21.0 using descriptive analysis, principal components analysis, scale reliability analysis and tests to compare independent parametric (ANOVA) and non-parametric (Mann–Whitney *U*) groups.

Results and Discussion

Study 1: Validation of the Questionnaire

For validation of the questionnaire, we considered two types of validity. Firstly, the internal validity was assessed through factor analysis and a subsequent study of the internal consistency and, secondly, the external validity was evaluated by correlation with a small sample of students through their academic performance.

The first step in the analysis involved a descriptive study of the results for each item taken individually. The percentages obtained in each of the three categories of response

Table 3 Scope of the analysis, items developed and criteria considered for appropriate and partially appropriate responses for each question

Scope of analysis	Question	Criteria considered for appropriate responses	Criteria considered for partially appropriate responses
Acquisition of scientific knowledge (K)			
Concepts of the chemical element and compound	1. Formulating the difference between an element and a compound	Conception of chemical element as a substance made from atoms with the same atomic number, and of a compound made up from two or more types of atoms or elements (submicroscopic explanation)	Understand the element as a simple substance denoted by a single symbol. Understand that a compound is formed by various elements. Compound is sometimes defined without stating what is meant by element (macroscopic or symbolic explanation)
Names and symbols of chemical elements	2A. Name 5 metals	List the names and symbols of 5 metals	List the names and symbols of 4 metals
	2B. Name 5 non-metals	List the names and symbols of 5 non-metals	List the names and symbols of 4 non-metals
Properties of the chemical elements	5A. Identify physical and chemical properties	State at least 2 properties: metallic character, melting or boiling point, atomic properties, chemical reactivity, etc.	State at least 1 property
Application of knowledge in different contexts and situations (A)			
Presence of chemical elements in the environment	4. Identify materials in the environment and the elements present in them	List 9 or 10 elements and materials	List 5 to 8 elements and materials
Criteria to classify the chemical elements	6. Given a set of known elements, classify them and explain the criteria used	Perform broad classifications of elements in accordance with the main families of the periodic table	Combine criteria based on the metallic or non-metallic character with other states based on aggregation states or non-chemical concepts
Ordering of the chemical elements	9. Given a set of known elements, rank them in order of atomic size and explain the criteria used	Give the correct order with reference to the electronic configuration	Give the correct order but with an incomplete explanation. For example use only a single factor as a criterion
Atomic composition through atomic number and atomic mass data	10. Give the number of protons, neutrons and electrons in iron	Correctly list the correct number of the three types of particle: protons, neutrons and electrons	Correctly state the number of protons and electrons but not the number of neutrons

Table 3 (continued)

Scope of analysis	Question	Criteria considered for appropriate responses	Criteria considered for partially appropriate responses
Octet rule	12. Explain the stability of Cl^- and Na^+ ions	Use the shell model with reference to the octet rule as a criterion to explain the stability of the atom	Provide an argument based on teleological reasons (tendency to complete shells) or heuristics as a function of the relative position in the Periodic Table of each of the atoms (*periodic property*)
Use of scientific evidence to draw conclusions (U)			
Atomic number (number of protons) as a way to identify chemical elements	3. Universality or not of the chemical elements	The atomic number uniquely identifies a chemical element; thus, the presence of the same elements in all the universe is explained	Explain the universality of the chemical elements through reasons that do not involve a submicroscopic model based on the existence of elemental particles
Properties of the chemical elements	5B. Explain the existence of trends in properties	List elements with similar properties based on the electronic configuration	List elements with similar properties with reference to trends in the Periodic Table and/or give examples
Presence of isotopes of the chemical elements	11. Explain why the atomic mass of chlorine is not an integer	Explain that a mixture of isotopes leads to an atomic number that is not an integer	Not use the concept of isotopes but provide a rational explanation (such as carry out a calculation using the mass of the particles, etc.)
Understanding the nature of science (N)			
Development of the Periodic Table in history	7. Constancy versus variability in the Periodic Table	Identify changes to the Periodic Table through history	State changes without providing an explanation
The Periodic Table as a model	8. Copy of reality versus approach with limits	Understand that the Periodic Table has limitations. Ability to describe a problem or limitation on the basis of chemical knowledge	Understand that the Periodic Table has limitations but unable to outline the limitations. Understand that the Periodic Table lacks certain information

(inappropriate or blank, partially appropriate and appropriate) in the analysis of each item are shown in Table 4.

It can be seen that student performance varies markedly from one item to another. The best results were obtained for items 5A, 6 and 7, for which around two thirds of the students provided acceptable answers. These items concern, respectively, knowledge about characteristic properties of the chemical elements, the students' ability to classify a group given elements from the Periodic Table and their appreciation of the historical nature of, and changes to, the Periodic Table. In contrast, inappropriate responses were given by over two thirds of the students for item 11. This item concerned the idea of isotopes of elements to explain atomic masses that are not integers. Items 1, 3 and 9 fall in the middle, with the majority of students (around two thirds) falling in the central category of the distribution. These items concerned their understanding of the difference between element and chemical compound, the universality of the chemical elements and their relationship to atomic number as an identifier of the nature of each element, and the ranking of elements by atomic volumes. Many inappropriate or partially appropriate responses corresponded with memory failure or a lack of understanding of the content studied. However, an important part of the answers also reflected several of the ideas and misconceptions about this topic described by other authors (Furió & Domínguez, 2007; Raviolo et al., 2011; Taber, 1999, 2003; Talanquer, 2006, 2007).

Overall, it appears that the questions concerned the use of evidence to draw conclusions (U) and these proved to be more complex for the students as they involved high level cognitive tasks.

However, only one of the two questions that assess aspects of the nature of science (N) yielded poor results, as one would expect. This question required students to evaluate the limitations of the Periodic Table (item 8). The other item (item 7) yielded significantly better results, probably because the answer to the question can be limited to a

Table 4 Percentages obtained in the three analysis categories for each item taken individually

Learning area	Item	% (*N* = 176)		
		Inappropriate responses or blanks	Partially appropriate responses	Appropriate responses
Acquisition of scientific knowledge (K)	1	16.7	73.0	10.3
	2A	30.5	12.6	56.9
	2B	38.5	16.1	45.4
	5A	13.2	15.5	71.3
Application of knowledge in different contexts and situations (A)	4	6.3	32.8	60.9
	6	19.5	14.4	66.1
	9	30.5	62.1	7.5
	10	30.5	46.0	23.6
	12	32.2	56.3	11.5
Use of scientific evidence to draw conclusions (U)	3	25.9	65.5	8.6
	5B	40.2	21.8	37.9
	11	68.4	22.4	9.2
Understanding the nature of science (N)	7	5.2	28.2	66.7
	8	28.2	42.5	29.3

descriptive analysis that simply requires various examples of periodic classifications used throughout history—an area that was studied in class. The second step consisted of a correlation analysis between items to check whether global assessments should be made in the questionnaire to provide more reliable results than the individual items. To achieve this goal, the responses were quantified on a scale that assigned 2 points to completely appropriate responses, 1 point to partially appropriate responses and 0 points to inappropriate responses or blanks. All Pearson coefficients between items were positive and were in the range 0.74–0.10, although these were only statistically significant in two out of three correlations. These results led us to perform a principal components analysis in order to study the underlying structure of these correlations. The Kaiser–Meyer–Olkin sampling adequacy ratio had a value of 0.76, which can be considered medium-high, with $\chi^2 = 528.1$ (d.f. = 91) for the Bartlett's sphericity test, which is statistically significant ($p < 0.001$). These results support the applicability of this analysis.

The exploratory analysis yielded a solution with four factors, which together explained 53 % of the total variance. This means that more than half of the information provided by the questionnaire items can be summarized by the combination of only four mutually independent factors. A Varimax rotation analysis revealed some difficulties to define the meaning of each factor. First of all, the factor loadings values were only moderate, with 0.72 as highest value. Second of all, a significant part of the items loaded on two or more factors simultaneously. And finally, all the factors saturated on items of a very different nature, making difficult to obtain patterns in order to define each factor. Furthermore, tests performed showed that the scales constructed from these factors were not sufficiently reliable (Cronbach's alpha coefficients between 0.62 and 0.45). In fact, the Scree plot (Fig. 1) shows a pronounced gap between the first and second factors and this indicates the conservation of a single factor. This factor accounted for 28 % of the variance. For all these reasons, it was hard to establish a connection between the content of the questionnaire and the statistical information. Consequently, we did not define partial scales based on these four factors and instead define a single global scale. It is important to note that these dimensions did not correspond to any of the four areas in which the questionnaire was structured.

The factor matrix for a single-factor analysis is shown in Table 5. All items show a positive and acceptable factor loading on the first factor, indicating that this is a common factor to all test items. This finding demonstrates the overall applicability of the assessment questionnaire.

The reliability of the test was measured by Cronbach's alpha coefficient, which had a value of 0.80. This value can be considered as moderately high and shows the internal consistency of the scale (DeVellis, 1991).

Therefore, the data support the construction of a single scale to summarize the information from the various questionnaire items through the same overall score obtained from the sum of the 14 items. This scale, whose possible values range from 0 to 28 points, yielded a mean of 15.2 ± 0.4, with a minimum of 3.0 and a maximum of 25.0.

In addition to the analysis of internal consistency for the scale obtained from the questionnaire, we also assessed the external validity. To do this, based on Cohen & Swerdlik (2001), we constructed a subsample of 38 students from 4th year CSE (Year 11) and correlated the scale values built with the marks obtained in the subject of Chemistry in the corresponding quarter. These students corresponded to two groups taught by the first author. The students were monitored in order to assess the learning outcomes bearing in mind different sources of information: exams, portfolios, participation in class, etc. The results showed a Pearson

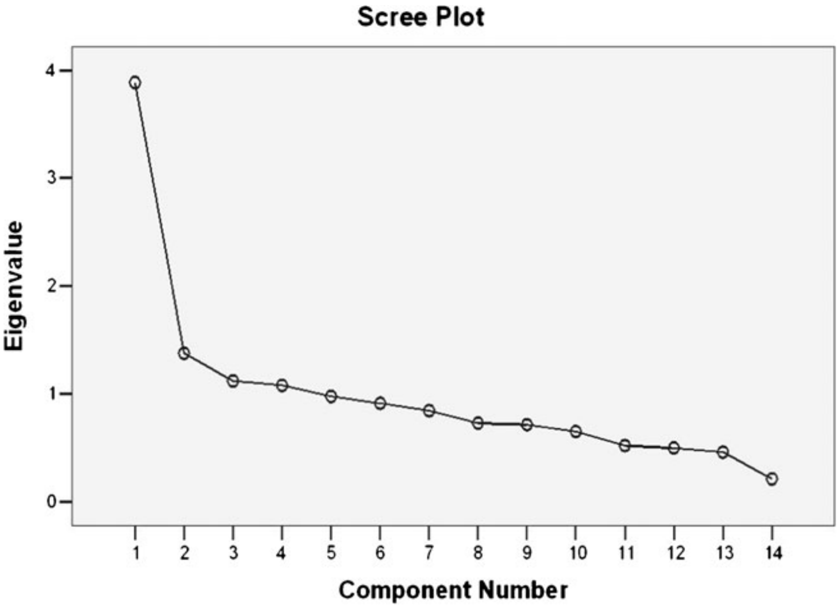

Fig. 1 Scree plot for factor analysis

correlation coefficient of $r = 0.60$, which is a relatively high value and is statistically significant ($p < 0.001$). This demonstrates the predictive value of the test, thus providing another indicator of validity.

Study 2: Change of the Knowledge of Students During Their Baccalaureate

In order to analyse the change of the students' knowledge during their baccalaureate, a cross-sectional study was carried out in which we compared the responses of students

Table 5 Matrix component factorial analysis of a single factor, with four components extracted. Extraction method: Principal Components Analysis

Item	Component
1	0.428
2A	0.681
2B	0.692
3	0.424
4	0.432
5A	0.493
5B	0.393
6	0.631
7	0.485
8	0.623
9	0.374
10	0.573
11	0.449
12	0.555

who had finished their 4th year CSE and 2nd year baccalaureate, respectively, using variables that were dependent on the results of the previously validated questionnaire. The percentages obtained for each of the items are shown in Table 6 and, as described above, the responses were differentiated into appropriate responses, partially appropriate responses and inappropriate responses (or blanks). The results of the Mann–Whitney *U* test are also shown as this is the most suitable basis for the comparison of ordinal data from two independent groups. It is indicated in each case whether or not significant differences, and to what extent, were found between the two groups of students.

It can be seen from the results in Table 6 that half of the items have statistically significant differences and, in some cases, significant changes were found in the percentage distributions between the three levels considered. The results show, at least in these cases, positive developments in the knowledge of students during their studies. In the other half of items, however, the improvements observed are not large, although small variations that are detected finally reach statistical significance thresholds.

In relative terms, fewer cases of significant progress were found for students answering questions related to the acquisition and application of knowledge (K and A) than for the development of inferences from evidence (U) or questions that address the nature of science (N). This finding indicates that improvements occur primarily through questions that address aspects with a higher level of cognitive demand (analysis, synthesis and evaluation), while those that concern the capacity for retention, understanding or direct application of learning are associated with lower levels of progress. This improvement should be considered as a substantial progress, despite the results are still quite poor in the 2nd year of baccalaureate studies (Year 13).

It should also be noted that the smallest differences are obtained for items 1 to 4 and these are related to more elemental content and structuring for later learning and they do have an impact on the concept of the chemical element. This area is covered in the Spanish curriculum from 3rd year CSE (Year 10), suggesting that the knowledge of the baccalaureate students did not improve on that acquired at the more basic level.

An alternative analysis for comparisons between groups would be to consider the scale constructed from the overall scores from the questionnaire, which would be a scale from 0 to 28 points. For this subsample, the reliability of the scale was measured by Cronbach's alpha coefficient, which had a value of 0.79. This value indicates that the scale has a reasonably high reliability.

The mean values obtained for this scale were 12.8 ± 0.5 for 4th year CSE and 15.7 ± 0.7 for 2nd year baccalaureate (see Fig. 2). A parametric analysis of variance revealed the presence of statistically significant differences between the two groups of students (ANOVA: $F_{1,134} = 10.281$, $p < 0.001$), although the homogeneity of variances test allowed us to reject the null hypothesis (Levene = 4.055, $\text{d.f.}_1 = 1$, $\text{d.f.}_2 = 134$, $p < 0.05$), which prompted us to carry out a comparison by the Mann–Whitney test. This test also showed significant differences between groups, thus indicating a statistically significant evolution in knowledge (Mann–Whitney *U*: $U = 1504.5$, $n_1 = 67$, $n_2 = 69$, $p < 0.001$). However, the averages obtained for the overall scale of the questionnaire show small differences in relative terms, since a value of only 10 % is reached at the total of the scale and 23 % of the initial value. The variations observed clearly appear to be insufficient bearing in mind the emphasis that the Spanish curriculum places on these topics, which are covered in the 2 years of the baccalaureate (Years 12 and 13).

Table 6 Percentages obtained in the three categories for each item individually considered by students of the 4th year CSE (Year 11) and 2nd year baccalaureate (Year 13)

Learning area	Item	4th year CSE ($N = 67$)			2nd year baccalaureate ($N = 69$)			Mann–Whitney *U*	
		% Inappropriate responses	% Partially appropriate responses	% Appropriate responses	% Inappropriate responses	% Partially appropriate responses	% Appropriate responses	*U*	Significance
K	1	17.9	80.6	1.5	17.4	69.6	13.0	2,080.5	NS
	2A	35.8	16.4	47.8	34.8	8.7	56.5	2,169.0	NS
	2B	43.3	22.4	34.3	43.5	10.1	46.4	2,156.5	NS
	5A	19.4	26.9	53.7	13.0	11.6	75.4	1,840.5	*
A	4	1.5	35.9	62.7	13.0	29.0	58.0	2,104.5	NS
	6	25.4	19.4	55.2	23.2	13.0	63.8	2,141.5	NS
	9	23.9	74.6	1.5	44.9	39.1	15.9	2,086.5	NS
	10	41.8	55.2	3.0	27.5	43.5	29.0	1,642.0	**
	12	47.8	47.8	4.5	18.8	59.4	21.7	1,464.5	***
U	3	32.8	61.2	6.0	33.3	59.4	7.2	2,302.5	NS
	5B	56.7	23.9	19.4	31.9	23.2	44.9	1,593.5	**
	11	68.7	28.4	3.0	56.5	23.2	20.3	1,914.0	*
N	7	9.0	43.3	47.8	2.9	21.7	75.4	1,657.5	**
	8	46.3	44.8	9.0	24.6	49.3	26.1	1,643.5	**

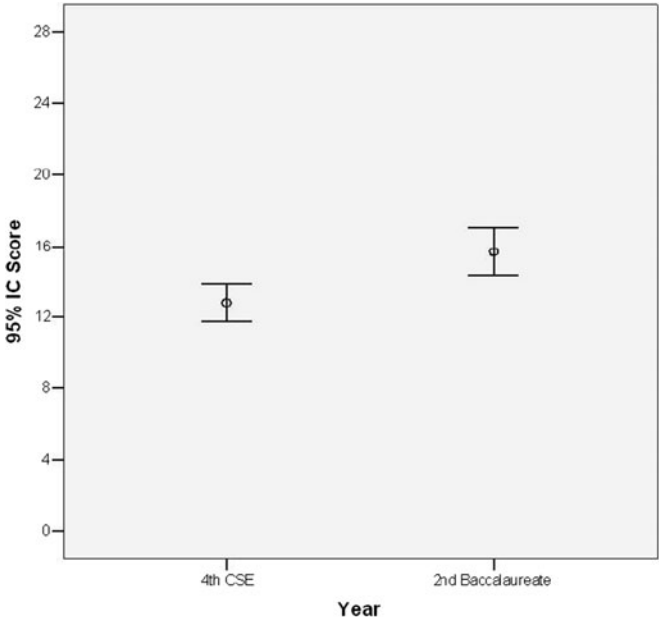

Fig. 2 Average scores for each group on the global scale (standard error is indicated)

It can be inferred from the results discussed above that the education received by students only partially succeeds in cementing the studied content and leads to only a slight improvement in the capabilities that have greater cognitive demand. This improvement occurs without an improvement in the basic skills of the students and the skills of lower level students are not developed significantly, with serious deficiencies remaining. This finding indicates a clear and significant failing in the education offered. This situation is probably due to the premature transition in the Spanish education system, as discussed above, from the first contact with this topic through an inductive and phenomenological approach to the more deductive approach that is focused on linking the properties of elements and their position in the Periodic Table with electronic configuration. Moreover, despite the fact that from Year 11 to Year 13 the Spanish curriculum (Ministerio de Ciencia y Educación, 2007a, b) focuses on the sub-microscopic aspects, specifically the internal structure of atoms, it appears that insufficient emphasis is placed on the expected learning outcomes.

Conclusions

The first contribution of this work was the validation, with a sample of 176 high school students aged between 15 and 18, of a 14-item questionnaire that enables an assessment of the level of understanding of students around the concept of the chemical element and the Periodic Table. This is one of the most important topics in high school chemistry. Satisfactory results were obtained from the point of view of internal and external validity. The first of these techniques was assessed by principal components analysis and evaluation of the reliability or internal consistency, and the second technique was assessed through its correlation with academic performance in a small sample of students.

The second contribution of this research concerns the existence of significant differences between the sample of students in the 4th year CSE (Year 11) and the 2nd year of baccalaureate studies (Year 13) in half of the questionnaire items. Specifically, the results suggest that improvements occur primarily in addressing higher level cognitive questions (analysis, synthesis and evaluation) compared to the lower level tasks (capacity for retention, understanding or direct application of learning). This finding clearly indicates that a breakthrough occurred for students completing their baccalaureate in comparison to those in the 4th year CSE. However, significant progress was not identified in the other half of the items, indicating a lack of progress in learning for the students in a significant proportion of the topics studied. It can be seen that it is in the first half of the questionnaire where the differences between groups are less marked, coinciding precisely with the items whose content it is assumed that students should have learned at the end of compulsory secondary education. It is possible that the teachers have paid less attention in subsequent courses and the learning difficulties that they encounter may have been underestimated.

Overall, the results indicate a limited degree of progression in students' knowledge around the notion of the chemical elements and their classification during Baccalaureate schooling. This limited progress can be interpreted by considering the existence of significant difficulties and obstacles in understanding the concept of the chemical element in its different aspects, a problem that would require a particular didactic treatment to overcome it. In contrast, the Spanish school curriculum does not devote sufficient time to these areas in the early grades through a descriptive phenomenological study of the subject matter. Furthermore, subsequent courses the curriculum do not provide mechanisms to review learning or offset shortcomings and gaps in knowledge.

The study has some limitations that should be considered when drawing conclusions and educational implications. The wide variety of proposed topics and the limited number of items set for each topic are factors that complicate the task of inferring what students actually learnt after completing their studies, beyond providing general quantitative data on the overall level of performance achieved. However, despite everything, what does seem clear is that the traditional teaching method is not able, in its own right, to overcome these difficulties (Taber, 2001; Çalık, 2005; Fernández-González, 2013). This highlights the need to identify strategies and procedures to provide more stimulating and creative teaching methods that are particularly sensitive to these difficulties (Levine, 1990; Schmidt, 2000; Farrer, Monk, Heron, Lough & Sadler, 2010). In particular, we are interested in the development and use of strategies and resources committed to the following areas:

- Promote a more active learning environment that is more participative and challenging than the methods commonly used in class
- Consistent with the above, to take into account the students' explanatory models and the need to contribute to their evolution through strategies that refer to scientific modelling processes
- Contribute to an improvement in the motivation of students in the study of these topics through approaches and recreational teaching resources and by linking the content with daily life. The use of educational games, informative videos, analogies and practical work, such as small research projects, are amongst the areas that support our proposals
- Encourage collaborative work in the classroom and carry out work in small groups

- Develop a context of continuous interaction between students and the teacher in a climate that facilitates ongoing dialogue and feedback between the two

From this standpoint, we are currently developing teaching methods that articulate all of the above aspects. We intend to present the results obtained with these methods in future publications through the assessment of the progress made by students.

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Appendix

Table 7 Related to the concept of chemical elements in the Curriculum in the Spanish Educational System (Ministerio de Educación y Ciencia, 2007a, b)

Subject/course	Nature	Age	Description of content
Physics and Chemistry Year 10	Compulsory for all students	14–15 years	• Simple substances and compounds. Differences between mixtures and compounds • The hypothesis of atoms and molecules to explain the diversity of materials (mixtures, simple substances and compounds): introduction of the concept of the chemical element. Representation of elements and substances by symbols • Abundance of elements in nature. The importance of elements in the human body • Problems that led to the development of theories for the existence of an internal structure in atoms. Explanation and description of the first atomic models. Atomic models of Thomson and Rutherford • Characterization of isotopes. Importance of the applications of radioactive substances and evaluation of the consequences of their use for living beings and the environment
Physics and Chemistry Year 11	Optional	15–16 years	• The structure of the atom • The Periodic System for the chemical elements • Classification of substances according to their properties. Experimental studies • Importance of the Periodic classification • Experimental study and interpretation of selected properties of substances: physical state at room temperature, conductivity and solubility
Physics and Chemistry Year 12	Compulsory for all students of Science and Technology	16–17 years	• Review and more in-depth view of Dalton’s atomic theory. Interpretation of the basic laws by which this theory was developed • Atomic and molecular mass • First atomic models: Thomson and Rutherford. Electronic distribution of energy levels. Spectra and the Bohr model. Qualitative introduction to the quantum model

Table 7 (continued)

Subject/course	Nature	Age	Description of content
			• Abundance and importance of elements in nature. The Periodic System • Formulae and nomenclature of inorganic compounds according to IUPAC rules
Chemistry Year 13	Optional for students of Science and Technology	17–18 years	• From the Bohr atom to the quantum model. Importance of quantum mechanics in the development of chemistry • Historical evolution of the Periodic order of the elements • Electronic structure and periodicity. Periodic trends in the properties of the elements

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