

Students' performance in the scientific skills during secondary education

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Abstract

One of the goals of secondary science education is to help students develop skills related to scientific inquiry. However, the results of previous studies have shown that students have difficulties in identifying problems, formulating hypotheses, drawing conclusions, and designing experiments. The main objective of this contribution is to indicate the situation in the southeast of Spain in this regard, comparing progress throughout secondary education. Four instruments were designed based on specific problematic situations in biology that were solved by 260 students from three different educational levels (12, 14, and 16 years old). The results show that high school students learn very little in terms of the development of the aforementioned skills and have difficulty understanding their meaning in the science texts used in the classroom. In this paper, some of the reasons that could explain this situation are analyzed and suggestions are made as to how the teaching of the desired skills could be improved.

Keywords: experimental design, hypotheses, problem identification, scientific skills, secondary school

INTRODUCTION AND ANTECEDENTS

The need to improve the quality of the science education received by secondary school students, including those with no special science-related aspirations (Sheldrake, 2018), is widely accepted and, in many countries, such as Spain, justified by recent Programme for International Student Assessment (PISA) reports (Organisation for Economic Co-operation and Development [OECD], 2007, 2016). To a certain extent, this view is explained by the fact that, for a long time, science education has concentrated on developing students' substantive scientific knowledge, rather than other dimensions that have great value for students (Abrahams & Millar, 2008). The latter, besides providing them with an understanding of the knowledge and structure of various disciplines, help students adapt this information to the demands of a constantly evolving society, in which scientific knowledge has taken on a particular relevance in daily life (Mkimbili & Ødegaard, 2019).

In recent years, many countries have been characterized by a remarkable interest in redirecting the aims of the secondary science curriculum (Cheung, 2018; Gomes et al., 2008), due to the fact that, as future

consumers, voters and policymakers, secondary students—both science, technology, engineering and mathematics (STEM) and non-STEM majors—must be prepared to examine and understand socio-scientific issues and make responsible, science-informed decisions about them (Dauer et al., 2017).

Students' Performance in Several Scientific Skills During Secondary Education

From the perspective of this study, understanding the nature of scientific enterprise, as well as the role of science in society and personal life, must be included as educational objectives at this level. They also involve developing the intellectual abilities related to the skills used in scientific methods of inquiry (Charney et al., 2007; Vossen et al., 2018; among others), of which the skills that are the object of our study form an important part, as mentioned below. Some of them could include recognizing the importance of accurately formulating a problem which can be scientifically investigated and its implications for developing the research; the formulation of hypotheses that will mark the pathway of the research as a creative process that arises in response to a given problem; the elaboration of conclusions, establishing the relations between the results of scientific

Contribution to the literature

- The difficulties detected among secondary students in scientific research skills including problem identification, hypothesis building, drawing conclusions, or proposing an experimental design persist throughout the educational stage.
- The scientific skills of identifying the problem of an investigation and the establishment of hypotheses present more difficulty among secondary students at the three levels analyzed: at the beginning of secondary school, during it, and at the end of this stage.
- The difficulty for secondary students in proposing an experimental design is dependent on the context of the research and the number of variables involved, an aspect that can help teachers in their gradual approach.

research and the theoretical models under which it has been carried out; and planning how a given research problem should be developed, a task which involves the different scientific abilities mentioned above, to confirm the extent to which any hypothesis is fulfilled.

Despite the fact that certain learning skills may be developed to some extent without any formal instruction, systematic teaching could have a significant impact on their cultivation (Spektor-Levy et al., 2009). The practices of inquiry involve asking questions and problem-solving, as well as being largely motivated by the pleasurable discomfort of a difficult question, and the satisfaction or disappointment in having an idea confirmed or refuted, in addition to the search itself.

These feelings and emotions are important in professional disciplinary practices and in learning sciences because students could understand what doing science implies by learning how these moments feel (Jaber & Hammer, 2016). In this way, students can understand the cause and effect of the phenomena that surround them, ask questions about complex problems that compromise their future, make predictions, and develop their logical skills from a scientific point of view to start functional learning through the development of scientific competence (Levrini et al., 2019).

Background of the Research

In terms of a literature review of empirical research on scientific inquiry activities, where students become involved in learning diverse scientific skills, a vast number of studies contain tests on students' conceptual knowledge, but a more integrated perspective is necessary in order to understand the role of science in student inquiry (Rönnebeck et al., 2016).

The results of some researchers who have examined integrated science processes (formulating hypotheses, identifying, and defining variables, designing experiments, collecting, and transforming data, drawing conclusions, and providing evidence), have provided information on the learning achieved by students as a consequence of their education and the difficulties they still have in learning scientific skills.

For example, Germann and Aram (1996) proposed different tasks in which students have to formulate hypotheses, control variables, record and analyze data, draw conclusions, and prove evidence, and they focused on the processes of the latter three elements. They showed the difficulties that students have in performing the activities and recording data successfully, considering the hypothesis when reaching their conclusions or providing specific evidence for their inferences. Toh and Woolnough (1993) used different situations to analyze integrated science processing skills, such as the identification and control of variables, data interpretation, hypothesis formulation and experimentation.

Oh (2010) assessed two cases of earth science teaching where secondary students were engaged to generate hypotheses concerning fossil evidence. Other studies have focused on identifying students' performance concerning the elaboration of hypotheses, including providing alternative theories, implementing models, and advancing logical arguments and explanations, connecting ideas, extending concepts, and asking questions (Charney et al., 2007). In this respect, an alternative approach in teaching and learning scientific skills in secondary education showed how Spanish compulsory secondary students researched corrosion and developed different abilities, such as proposing research ideas, planning experiments, or drawing conclusions, among others, which are included in the seven dimensions of scientific competence (Franco-Mariscal, 2015).

Nevertheless, several studies have pointed to the emphasis placed on the learning of substantive scientific knowledge, while the majority of practical activities carried out in the science classroom require a lower level of reasoning and teach, at most, manual dexterity, rather than high-order skills, such as the formulation of hypotheses or the ability to design experiments (Cordón, 2009). These findings suggest that the learning of scientific skills by students during their compulsory school career (6-16 years) has not reached the expected levels.

Recently, the scientific skills that represent competence in inquiry, such as problem identification,

formulating hypotheses, designing experiments, and identifying and defining variables, shown by a group of students of the scientific baccalaureate in carrying out autonomous research work, have been investigated (Ferrés et al., 2015). The results obtained demonstrated that the level of understanding of the fundamental elements of an investigation and, therefore, of the research competence established by the curriculum, was insufficient, with very few students using their knowledge to elaborate predictions or give explanations, as well as analyze the data of a scientific study, identify the ideas or investigable problems, and draw up their conclusions (Ferrés, 2017; Ferrés et al., 2015).

As such, these studies highlight the difficulties encountered by the students in identifying the question or problem of the investigation, to the point that this aspect may be more complex than designing an experiment to answer it (Oliveras et al., 2013). For example, the formulation of hypotheses is usually confused with simple predictions not related to the most appropriate methodology to respond to the research problem, and that part of their daily knowledge is disconnected from the known scientific type (Friedler & Tamir, 1990).

The problems students have in the identification of the variables of an investigation and the design of experiences to investigate have also been revealed (D'Costa & Schlueter, 2013), with authors pointing out the lack of understanding of the impact of such variables on the results obtained in the research (Grunwald & Hartman, 2010).

Other studies have shown that inquiry-based learning has made significant progress in developing inquiry and thinking skills (Furtak et al., 2012), as well as promoting those related to integrated processes (the identification and control of variables, data interpretation, hypotheses formulation and experimentation), as Crujeiras and Jiménez-Aleixandre (2017) maintained. New research that analyzed the learning of students as a response to authentic science inquiry (Charney et al., 2007) found an increasing ability to generate hypotheses and consider alternative ones, as well as implement models and advance logical argumentation in explanations, connect ideas, extend concepts, and ask questions.

The results suggested that, by meaningfully engaging students in the practice of real science, it would be possible to improve their understanding and beliefs. Gomes et al. (2008) examined the relationships between students' understanding of the aims of an investigative activity and their performance when conducting it. They found that, although a proportion of the students had some difficulties recalling the declared aims of the activities, those who succeeded in recognizing the stated aims of the tasks showed superior performance in conducting their investigations. Students in a secondary

school science class who participated in an extended problem-based activity that included designing investigations, as well as multivariable causal analysis and argumentation, showed more advanced scientific skills in those areas than a group that did not take part, in addition to superior epistemological understanding regarding science (Kuhn et al., 2017).

It can therefore be concluded that for the learning of scientific research skills to be fruitful, it must be part of a process made up of different components that are related to each other, allowing students to experience the reality of science. That is, it must involve work in a similar way to a scientific project, but on a small scale, building a bridge between the center itself and research (Vorholzer et al., 2020). Thus, the most effective way to promote their learning is based on shifting from general objectives to specific actions and moving from global issues to local contexts through socio-scientific problems that allow them to be aware of the impact and usefulness of science in their lives (Levrini et al., 2019; Zowada et al., 2020).

Research Aims

Considering these antecedents, our main objectives are focused on diagnosing the state of learning of scientific competences among Spanish students at different levels of secondary education. More specifically, in this study we intend to discover how the scientific abilities to identify problems, formulate hypotheses, draw conclusions, and design experiments evolve during high school and the problems involved in the development of these skills. This information should help identify the difficulties that students have in correctly applying their skills in scientific contexts and act as a reference for analyzing the causes that may be responsible for these difficulties, and, consequently, for developing educational initiatives to improve the quality of secondary school science education in the context of attaining scientific literacy.

METHODOLOGICAL APPROACH

The scientific skills analyzed in this work include the identification of the problem to be solved through research, as well as the formulation of hypotheses that will guide it, reaching conclusions that provide evidence to support (or not) the proposed hypothesis, and drawing up experimental designs to solve the problem. All of them are high-order skills and elements, considered fundamental to scientific research, as described below.

1. Problem identification is the starting point of any research and is, therefore, of fundamental importance. Recognizing the significance of accurately formulating the problem and its implications for developing the research are important points to learn in science classes, since

Table 1. Characteristics of the sample

Educational level	Nº of students	Learning corresponding to...
1st year of secondary education (aged 12)	89	End of primary school
3rd year of secondary education (aged 14)	70	Middle of secondary compulsory education
1st year of baccalaureate (aged 16)	101	End of compulsory education

they represent the beginning of research that will enable secondary students to “do” science (Hodson, 1994). This research should also help students identify and understand complex socio-ecological problems (Wei et al., 2015).

2. Formulating hypotheses that will mark the pathway the research will follow is a creative process that arises in response to a given problem. Furthermore, establishing predictions as to the outcome of a hypothesis is one of the basic references for elaborating experimental designs. From a constructivist point of view, when students formulate hypotheses, they express their ideas on the content of the subject (substantive scientific knowledge) and when these hypotheses are evaluated, changed, or even reformulated as a consequence of work done in the classroom, students' ideas not only evolve, favoring the construction of new knowledge, but new competences related to scientific skills can also be acquired (Oh, 2010).
3. Elaborating conclusions, that is, establishing the relations between the results of scientific research and the theoretical models under which it has been carried out, is an essential part in the construction of scientific knowledge and is also a skill to which special attention should be paid during secondary schooling. To successfully perform this task, students should be involved in rigorously analyzing the results of their investigation and comparing them with the hypothesis formed at the outset. This implies making an integrated interpretation of the different phases of the analysis, which is not an easy task for many students (Zohar, 1998).
4. Planning how a given research problem should be developed is also a fundamental aspect of science. This is a complex task because it involves different scientific abilities, such as clearly identifying a problem and formulating initial hypotheses and predictions, which will result in the elaboration of an experimental design (analyzing and making decisions concerning variables, the way in which they can be controlled and measured, the materials and instruments needed to obtain data, etc.) and, in turn, confirm the extent to which any hypotheses are fulfilled. This is not easy, and it is to be expected that secondary students will have problems with this skill. Therefore, the elaboration of experimental designs with increasing rigor is a skill that students must learn,

although to teach it, teachers must consider the complexity of the experimental situations that need to be resolved and the prior experience of the students (Germann & Aram, 1996).

Characteristics of the Sample

Three groups of students of different educational levels (a total number of 260) were chosen from 11 schools from the region of Murcia (Spain): four in the regional capital (two in the city center and two from the suburbs); the other seven schools were from various towns of different sizes. Through this process we hoped to obtain a sample that was typical of a school population derived from widely varying catchment areas. In each school, we asked the teachers to select classes that they considered to be “average” (classes without a very high number of brilliant students or the opposite).

Since the tests were administered at the beginning of the school year, the results are expected to demonstrate the learning that resulted from attending the last year of primary school and the way in which this knowledge had evolved halfway through and at the end of compulsory secondary education (**Table 1**).

Instruments for Gathering Information

Due to the investigation involving different educational levels and a broad sample of students, it was decided to collect the information through different questionnaires. For that purpose, we adapted those found in Córdón (2009), whose questionnaires had been previously contrasted with interviews involving small samples of students and validated by secondary school teachers. Thus, the tests given to students were chosen from among those widely used for teaching natural sciences at the secondary level, referring to simple situations related to themes familiar to the students and accompanied by schemes and pictures to facilitate understanding.

After a few questions of a general nature to see whether the students remembered or considered that their academic experience in relation to problems, hypotheses, experimental designs, and conclusions had been frequent, we described several situations which enabled us to analyze whether their knowledge permitted them to carry out the tasks outlined in **Table 2**.

Considering the results of those previous interviews (Córdón, 2009), the more complex situations were not presented to the youngest groups and the simplest ones

Table 2. Characteristics of the questionnaires

Situations	Abilities	Scientific skills
Expressions taken from school textbooks	Identify phases of the investigation	Identification of the scientific problem
School activities: - Germination of seeds - Redi's experiments - Behavior of woodlice - Van Helmont's experiments	Identify and express abilities in a scientific research context	Formulating hypotheses Elaboration of experimental designs Drawing conclusions
Behavior of woodlice Van Helmont's experiments Behavior of snails	Plan scientific research	Elaboration of experimental designs

Table 3. Situations presented to different levels

Age	Redi's experiments	Behavior of snails	Germination of seeds	Behavior of woodlice (Armadillidium vulgare)	Van Helmont's experiments
12	X	X	X		
14	X	X	X	X	
16			X	X	X

were not presented to the oldest pupils, as shown in **Table 3**.

The characteristics and objectives of the activities presented to students mentioned in both **Table 2** and **Table 3** are included in the supplemental materials (**Appendix A** and **Appendix B**).

In terms of the school activities, that allowed us to analyze whether their knowledge allowed them to carry out the tasks described, we must point out that in order to obtain this information, different situations were presented to the students, accompanied by drawings and diagrams to help clarify the texts. The tasks corresponded to different levels of complexity in regard to the number and difficulty of the concepts implied, the intervening variables and the context in which the activity was presented.

Consequently, as **Table 3** shows, not all the tasks were presented to the same students. Although this might partially limit the conclusions of this study, the decision was made for the following reasons: based on Cordón (2009), it was clear that the more complex situations were unsuitable for the first two grades (12- and 14-year-olds); moreover, since our main goal was to identify the capacities of students in relation to these skills, regardless of the context in which they had to be used—as long as they were familiar ones—we thought it was necessary to present more complex situations to those students who had finished their compulsory education (16-year-olds). This was accomplished by presenting Van Helmont's experiment, which requires a certain level of knowledge on plant nutrition. Although we could have presented the same situations to lower-level students, the total number of situations (five) was high, and it would have meant maintaining their attention for too extended a time. Hence, in accordance with **Table 2** and **Table 3**:

1. Redi's experiments and those concerning the germination of seeds and the behavior of snails

were given to the two youngest groups (12- and 14-year-olds).

2. The experiments relating to the behavior of woodlice and the germination of seeds were presented to the older students (14- and 16-year-olds).
3. The seed germination experiment was completed by students at the three educational levels analyzed.

In any case, so that this did not invalidate the comparisons of the groups and hinder the identification of possible differences between them, we took the two following precautions:

1. maintain the same experiments for every two consecutive educational levels tested and
2. set an experiment of intermediate difficulty to all the students of the different levels.

The open-ended nature of the questions led to a wide variety of answers being provided in relation to each, which we categorized as below, in accordance with the criteria which will be described alongside the results for each of the skill areas analyzed.

Analysis of Results

The results were analyzed based on the review of the students' answers and by comparing the results between schools. Thus, three categories (presented as percentages) were established to reflect the students' experience, knowledge and ability with respect to the skills being analyzed: correct (students whose answers showed that they were capable of resolving the tasks presented), inadequate (although the students seemed to understand the tasks, their answers were incorrect or bore no relation to the question or situation presented), or no answer (students who did not answer the question, suggesting they did not have the necessary knowledge or they did not understand the query). On the other

Table 4. Identification of scientific skills (%)

Skills and age	Number	Correct	Inadequate*	No answer
Problem				
12	89	14.5	30.4 (ED)	11.6
14	70	36.4	20.0 (C)	14.5
16	101	51.2	26.7 (ED)	10.5
Pairwise comparisons**		W	p	
12-14		3.1	0.072	
12-16		6.4	<.001	
14-16		2.6	0.157	
Hypothesis				
12	89	27.5	26.1 (P)	7.2
14	70	50.9	18.2 (P)	9.1
16	101	82.6	5.8 (P)	2.3
Pairwise comparisons**		W	p	
12-14		3.53	0.034	
12-16		10.6	<.001	
14-16		6.33	<.001	
Conclusion				
12	89	36.2	26.1 (H)	5.8
14	70	58.2	16.4 (H)	5.4
16	101	91.9	3.5 (H)	2.3
Pairwise comparisons**		W	p	
12-14		3.66	0.026	
12-16		11.21	<.001	
14-16		7.27	<.001	
Experimental design				
12	89	39.1	21.7 (P)	7.2
14	70	49.1	14.5 (P)	18.2
16	101	87.2	4.6 (H)	3.5
Pairwise comparisons**		W	p	
12-14		0.243	0.984	
12-16		9.282	<.001	
14-16		7.703	<.001	

Note. *Skills with which it is most frequently confused; P: Problem; H: Hypothesis; C: Conclusion; ED: Experimental design; & **Kruskal-Wallis test, statistically meaningful difference ($p < 0.05$)

hand, the data were statistically analyzed by using Jamovi computer software version 2.2.2. The Kruskal-Wallis test was used for observing the differences between more than two groups depending on variables. The Kruskal-Wallis test is the non-parametric alternative to the one-way analysis of variance (ANOVA).

FINDINGS

Relation of Skills to the Phases of Investigation

To ascertain whether students were capable of relating the different scientific skills with the various stages of research, they were presented with a variety of expressions that explain the development of scientific research. **Appendix A**, included in the supplemental materials, contains the questionnaire used to recognize the elements of an investigation in textbook phrases. Thus, our findings were the following (**Table 4**):

1. In regard to identifying the problem involved in the research, very few students who had just finished primary education (12-year-olds)

provided the correct answer. Although the percentage of correct answers improved in older students, the number of correct answers cannot be considered satisfactory, even in higher grades.

At all the levels, students particularly confused the problem with the experimental design or conclusions. When asked for examples, the students mentioned issues connected to everyday life, or problems that could be solved mathematically but were not related to scientific inquiry.

2. When the students were asked to recognize expressions related to research hypotheses, the correct answer was the one most chosen from the options presented. Furthermore, there was a substantial degree of progress made in regard to this question, since a high percentage of final-year students recognized both examples that referred to the hypothesis and very few confused the hypothesis with the problem. However, the good results obtained in the final year were not the

consequence of understanding the meaning of this term, as became clear when we asked the students to write an example. Only 20% students could do so correctly and refer to a possible explanation to try to solve a practical problem in the laboratory or a pen and paper exercise, a choice, which lent a degree of credibility to their answers. Nonetheless, 50% of the students at this level provided no reply and the rest provided phrases that revealed that they did not understand the meaning of the term hypothesis in the context of research.

3. In regard to the identification of the conclusions of research, most students answered correctly at all grades. The percentage increased with age until almost all those in the final grade analyzed chose the correct option. However, in the first two grades analyzed the students tended to confuse the expression with the hypothesis.

Since this term is closely linked to everyday language, the written examples that students provided were not accurate enough to demonstrate that they had really understood the meaning of this skill in the context of scientific research.

4. Lastly, when the students had to identify the expression referring to experimental design, although once again the correct answer was the most frequently chosen at all levels, only at the end of compulsory education could the number of correct answers be considered satisfactory, since in the first two grades examined the correct answers did not reach 50% and the students tended to confuse the experimental design with the research problem.

As expected, when the students were asked to give examples, the answers were worse than those given for the other skills. More than three quarters of the students did not reply, while among those that did provide an answer, only 8% could do so in an acceptable manner. Other answers essentially referred to activities related to some piece of practical work the students had carried out, with little connection to experimental design.

Many students made mistakes, but the number of blank answers given for all the skills analyzed was not high, which suggests that they understood the questions and answered with confidence, although the results cannot be used to confirm this. In general, the results of the 16-year-old students are better than those of the rest of the ages, with statistically significant differences being observed between the 12- and 16-year-old students for all skills and between the 14 and 16-year-olds for all skills, except in the identification of problems. This may indicate that the skill to identify a research problem is the one that has been least achieved.

In addition to the information presented up to this point, it was necessary to complement these results with others that would reveal in greater depth the capacities developed by students in relation to the skills under study.

Capacity to Identify and Express Scientific Skills in the Context of Research

In regard to the capacity of students to identify and express scientific skills in the context of research through different school activities (**Appendix B**, included in the supplemental materials, contains the problems used), our findings were the following:

1. In order to analyze how students identify the scientific problem behind the research, we considered correct those answers that adequately expressed the problem, suggesting some relationship between the variables, and as inadequate those that did not adequately formulate the problem or that allude to another process. The results obtained (**Table 5**) show that, on the one hand, the percentage of those students just starting their secondary education (12-year-olds) providing the correct replies is very low, for all the problems described.

On the other hand, although statistically significant differences have been found between 12- and 16-year-old students for common activity at the three levels of seed germination and, in general, student performance improves during secondary education, only a third of those completing the first cycle of compulsory education (14-year-olds) provided adequate answers. Of those who had completed compulsory education (16-year-olds), the figure was less than 50%.

Some examples of student responses include:

“The test of whether the temperature in which the seeds are found does not affect germination or if it does affect germination with the same humidity, soil and lighting” (Germination/correct answer/14-year-old).

“The problem is that you don’t have to be neither too hot nor too hot cold” (Germination/wrong answer/12-year-old).

2. In terms of the hypothesis that will guide the research, we considered correct those answers that expressed a significant relation between the independent variable/s and the dependent one. For example:
 - a. In the studies of Redi (in whose preamble one can see how he doubted the idea of spontaneous generation, which was widely accepted in his time), the hypothesis should be

Table 5. Results for scientific problem (%)

Age (number)	Activity	Correct	Inadequate	No answer
12 years old (89)	Redi	17.98	74.10	7.87
	Germination	17.98	47.19	34.83
14 years old (70)	Redi	21.43	61.43	17.14
	Germination	34.29	40.00	25.71
	Woodlice	15.71	58.57	25.71
16 years old (101)	Germination	48.51	36.63	14.85
	Woodlice	29.70	64.36	5.94
*Pairwise comparisons germination activity		W	p	
12-14		2.97	0.09	
12-16		6.52	<.001	
14-16		3	0.086	

Note. *Kruskal-Wallis test, statistically meaningful difference ($p < 0.05$)

related to the fact that the larvae appear or not, depending on whether the flies come into contact with the meat; therefore, the students should relate these two variables.

- b. In the experiment involving seeds, there should be reference to the relation between temperature and germination, without this being expressed as a conclusion, which can be deduced from the results obtained as a consequence of later experiments.
- c. In the case of the woodlice, for the answer to be considered correct, the hypothesis should suggest the possibility of a relation between the independent variables (light and temperature) and the dependent one (hiding).
- d. Van Helmont doubted the view (prevalent in his time) that green plants obtain nourishment only from earth. Since his research considered two variables (earth and water), students' replies should refer to the possible relation between nourishment and these two elements.

When the replies did not reflect the above relations, expressed an unsuitable hypothesis, or referred to a different scientific process, we considered them inadequate.

Based on the number of blank replies and the reduced number of correct answers, the results obtained (Table 6) show that students, particularly the younger ones, found it more difficult to formulate hypotheses than to recognize problems.

Examples of answers received include:

"Woodlice hide, for the light and for the thermal sensation" (Woodlice/correct answer/14-year-old).

"Woodlice hide there because they are protected" (Woodlice/wrong answer/14-year-old).

The results were better for the oldest group studied, with statistically significant differences for germination activity between 14-16-year-old students and 12-16-

year-old students. Nevertheless, even in the case of Van Helmont's experiment (which obtained the greatest number of correct answers), only about 57% of final-year students expressed the working hypothesis. These results reveal the difficulty students have in understanding what a research hypothesis is, and the relation between the hypothesis and other scientific skills, as the previous studies of Germann and Aram (1996) described, as well as Windschitl et al. (2008) for higher educational levels.

3. In regard to conclusions that can be deduced from a piece of research, we considered correct those answers in which students showed themselves capable of interpreting the data and did not simply describe them, whether totally or partially, or make affirmations that could not be deduced from the data presented.
 - a. In Redi's experiment (which involved understanding the text since no quantitative data were offered), the students had to deduce that larvae do not form when contact between the meat and flies is prevented.
 - b. In the case of the seeds, the replies had to refer to the temperature at which the greatest number germinated (25°C).
 - c. In the experiments involving woodlice, the answers considered correct referenced the results that could be deduced from the experiments described, and which were compared with the hypothesis they formulated.
 - d. Lastly, since the text corresponding to Van Helmont's studies contained the problem, hypothesis, experimental plan and results, the students had to draw the conclusion that the experimental data provided.

The answers that did not contain all these characteristics were considered inadequate. This was the case, for example, when the conclusions were incomplete or were unrelated to the problem or corresponding hypothesis.

Table 6. Results for expressing hypothesis (%)

Age (number)	Activity	Correct	Inadequate	No answer
12 years old (89)	Redi	11.24	37.08	51.69
	Germination	10.11	39.33	50.56
14 years old (70)	Redi	17.14	18.57	64.29
	Germination	20.00	21.43	58.57
	Woodlice	8.57	30.00	61.43
16 years old (101)	Germination	35.64	40.59	23.76
	Woodlice	43.56	43.56	22.77
*Pairwise comparisons germination activity		W	p	
12-14		-0.393	0.958	
12-16		6.596	<.001	
14-16		5.731	<.001	

Note. *Kruskal-Wallis test, statistically meaningful difference ($p < 0.05$)

Table 7. Results for reaching conclusions (%)

Age (number)	Activity	Correct	Inadequate	No answer
12 years old (89)	Redi	14.61	47.19	38.2
	Germination	17.98	40.45	41.57
14 years old (70)	Redi	37.14	34.29	28.57
	Germination	22.86	44.29	32.86
	Woodlice	17.14	21.43	61.43
16 years old (101)	Germination	33.66	60.4	5.94
	Woodlice	36.63	33.66	29.7
*Pairwise comparisons germination activity		W	p	
12-14		1.65	0.475	
12-16		7.05	<.001	
14-16		4.88	0.002	

Note. *Kruskal-Wallis test, statistically meaningful difference ($p < 0.05$)

Unlike other skills analyzed, extracting conclusions after a practical activity or pen and paper exercise is a relatively common activity among students. Nonetheless, both the qualitative (students' answers) and quantitative (Table 7) results obtained, although again they show statistically significant differences between older students for germination activity, they clearly express the difficulty many students have in understanding whether a given hypothesis is supported.

Some examples include:

"The insects did not come out of the rotten meat" (Redi/correct answer/14-year-old).

"That I could not close the jar with the meat inside because it would turn bad, and they would come out larvae" (Redi/wrong answer/14-year-old).

This agrees with the findings of German and Aram (1996), and those of Zohar (1998), who observed that distinguishing between results and conclusions was not easy for many students. Jiménez-Aleixandre (1998) also mentioned the tendency of students to generalize conclusions drawn from a particular situation or to confuse them with personal opinions.

4. The elaboration of experimental designs requires several skills to be applied simultaneously (problem identification, formulating hypotheses

and predictions, selection, and control of variables, etc.).

To ascertain the ability of students to design experiments, we used the last three tasks of Table 8, which, as can be gathered from reading them in the supplemental materials, have different levels of difficulty. The simplest of these situations, the behavior of snails, which only involves one independent variable and can be presented in few words, was used with the youngest students. However, to have data available for comparison purposes, the woodlice experiment was used with the students of the first two grades and Van Helmont's experiments with those of the last two.

In regard to the replies of the students, the following findings are highlighted:

- The answers concerning the snails were considered correct if the students recognized the need for a test or control experiment; without this, it would not be possible to deduce that the effect observed was due to salt water. The replies which were simple suppositions on the students' part with no test to verify the same were viewed as inadequate.
- Regarding the woodlice, there were two independent variables, each with two possibilities: light/dark and temperatures of 20°C and 10°C. Correct answers had to mention

Table 8. Ability of students to design experiments (%)

Age (number)	Activity	Correct	Inadequate	No answer
12 years old (89)	Behavior of snail	43.82	42.70	13.48
14 years old (70)	Behavior of snail	50.00	35.71	14.29
	Behavior of woodlice	10.00	42.86	47.14
16 years old (101)	Behavior of woodlice	19.80	62.38	17.82
	Van Helmont	16.83	64.36	18.81
		W	p	
*Pairwise comparisons behavior of snail 12-14		0.82	0.563	
*Pairwise comparisons behavior of woodlice 14-16		5.51	<.001	

Note. *Kruskal-Wallis test, statistically meaningful difference ($p < 0.05$)

the four possible combinations of these factors, while those which only considered one variable or did not adequately describe the experimental design were assessed as inadequate.

- c. In the plant nutrition-related experiments, answers were correct if they considered the different factors and described the four experiments that would have to be carried out to deduce the conditions necessary for plant growth and development.

In terms of quantitative results (**Table 8**), as expected, the snail experiment was the simplest and the youngest students could solve the task even more successfully than other apparently easier tasks.

Some of the answers received include:

"I would put two snails, one in a ring of water and the other in a ring of salt. If one comes out of the water ring, it is the salt that it cannot touch, and if it comes out of the salt, it is the water that prevents it from passing." (Behavior of snail/correct answer/12-year-old).

"Well, before the ring with salt, I would put a pinch of salt in a side and in another water and would observe or put a camera to see his reaction" (Behavior of snail/wrong answer/14-year-old).

Nevertheless, as shown in **Appendix B** (supplemental materials), when the situations became more complex, as in the other two problems, the results were much worse. For example, in the experiment involving woodlice, very few 14-year-olds answered correctly, and although the results show significant differences, less than 20% of those completing compulsory secondary education gave satisfactory replies. As may be expected, the results were even worse for the plant nutrition experiment, when only 16% of answers were considered acceptable. Indeed, the results served to justify our initial decision—based on Cordon (2009)—not to include the last two mentioned experiments in the exercise for the youngest students.

These difficulties which students had in designing science experiments to resolve every day or academic

problems, particularly when they involve a certain degree of complexity, may be considered the consequence of students' inadequate command of scientific skills, such as defining a question or formulating a hypothesis (Germann & Aram, 1996). These findings should be borne in mind when selecting and sequencing inquiry-based activities for primary and secondary school students.

CONCLUSIONS

Based on the information obtained, the following considerations are suggested:

1. During the years of compulsory secondary education, students develop little capacity to understand the meaning of the scientific research skills analyzed, and, as a consequence, to apply them to the texts commonly used in the classroom concerning school or scientific research, which was also described by Dori et al. (2018).

The fact that most students, regardless of their age, answered the questions suggests that they think they know the meaning of the skills. This, however, is no guarantee that they actually understand, as seen from the written examples students had to provide, especially in the first two educational grades analyzed, when one skill tended to be confused with another. The lowest number of correct answers in this respect was obtained when students had to identify the expression referring to the problem, while the best results were obtained for the questions on conclusions.

As expected, the results were worse when more complex situations were presented, in which students had to identify and/or express skills in the context of research. The large number of students who did not answer—especially in the first two grades studied—suggests that students found the tasks difficult. The small number of correct answers shows how difficult they found these tasks.

While the elaboration of experimental designs may appear to be the most difficult task for students to learn for all the educational levels of our study, the actual difficulty seems to depend on the context and the number of variables.

Nonetheless, the results do not permit any clear conclusions to be drawn concerning the relations that might exist between the difficulties the students encountered in deducing the different scientific skills in the context of a research task and the nature of the characteristics of the different situations presented to them.

Furthermore, Van Helmont's experiment, which might be found the most difficult, even for the more advanced students, generated the best results with regard to identifying the problem, hypothesis, and conclusions, but was the most complicated in terms of the experimental design.

Although it was not our original intention to analyze such relations in detail, it would seem opportune to investigate these in greater detail in further studies.

2. Although statistically significant differences have been found between 12- and 16-year-old students, many of the difficulties experienced by students persist during secondary schooling. According to our results, the capacity of students in regard to the skills studied is hardly developed during primary education, and although they improve during subsequent years, the aims of the official curriculum, including hypothesis formation, planning, and carrying out activities to contrast them, or the systematization and analysis of results and communicating (Ministry of Education and Vocational Training [MEFP], 2022), are not achieved. This became particularly clear in the germination experiment, which was presented in a similar way to all the levels analyzed.
3. Some of the reasons that explain these difficulties may be related to, on the one hand, the development of students' intellectual capacities. Piagetian psychology argues that carrying out tasks related to scientific activity requires that students must have acquired hypothetical-deductive thought, an aspect influenced by age. Without providing new information to this debate, our results clearly suggest that this type of reasoning had not been acquired by most of the students taking part in this study.

On the other hand, some reasons related to the poor command of certain linguistic skills may have had some influence. Despite the fact that the situations presented to the students were based on the previous work of Cordón (2009) and the questions were tested beforehand to make sure that they could be understood, the results could have been affected by problems related to an inadequate capacity of expression and a poor command of specific vocabulary. For instance, some terms, such as problem or hypothesis, do not have the same meaning in everyday life as in a scientific context. There may also have been a sense that they felt they understood what

had to be done without carefully reading the situation (Germann & Aram, 1996).

Nevertheless, the shortcomings might have been, to a great extent, a consequence of the little attention paid in classrooms to the skills involved in research. That is, teaching is basically aimed at instilling concepts, theories and laws, which are taught through repetitive routine activities that do not favour the development of skills related to research (Cordón, 2009). In addition, in most cases, learning programs are conceptually based, as proposed by the textbooks used, and the evaluation of learning focuses on conceptual knowledge, since exam questions do not refer to scientific skills.

Furthermore, according to Cordón (2009), the textbooks generally employed do not contribute to learning these skills, and their analysis shows that pencil and paper exercises predominate, with most being of a routine memory-based nature, whose purpose is to reinforce or complete conceptual learning. Practical work occupies a secondary plane and, when set, the approach is excessively controlled (like recipes) which limits the participation and autonomy of students (Ferreira & Morais, 2018). Moreover, there is an almost complete absence of activities involving planning, as well as the development and analysis of investigation, or problem-solving, which does not favor the promotion of abilities related to scientific activity (formulating hypotheses, designing experiments, etc.).

Educational Implications

One of the principal goals of scientific education is to provide all citizens with a basic culture organized around themes of personal and social relevance, which will enable them to apply their scientific knowledge to everyday life and to make relatively well-founded judgements concerning scientific and technological aspects (Crujeiras & Jiménez-Aleixandre, 2017; Ferreira & Morais, 2018). Developing suitable knowledge on the nature of science and the strategies that characterize scientific activity doubtless constitutes a great part of this culture. However, these last objectives are not always reflected in the practices of teachers. One of the reasons for this is the fact that the selection of educational focuses that promote the learning of the scientific skills studied requires special attention and, therefore, time, which can only be found by reducing that dedicated to conceptual contents. In our opinion, teachers should combat this point of view so that educational programs are developed in sufficient depth, favoring understanding over memorizing. Programs should include, among their objectives, the aim that students should develop scientific skills such as those we have analyzed. Familiarization with these research strategies will contribute to the understanding of the nature of science and scientific endeavor, besides favoring intellectual development. Such a path will promote critical thinking, objectivity, and the rigorous

analysis of data, as well as the need to justify one's own point of view and to respect that of others, which will make science more accessible, interesting, meaningful, and relevant to students (Stuckey et al., 2013)

Nonetheless, to impart science classes in which scientific skills such as those we have analyzed are to be taught, it is important to make certain points in this respect:

1. First, teachers and textbook authors must realize that the learning of scientific skills is an obligatory and desirable part of the secondary school syllabus, and, in agreement with Gomes et al. (2008), sufficient opportunity should be given to students to practice them in a research context.

Learning and understanding science is important for knowing the methods and recognizing that science is dynamic and is in a state of constant research, so memorizing laws, concepts and models is not enough for their learning. It is necessary that students have the possibility of appropriating the procedural bases and understanding of the scientific methodology during their education, which will allow them, finally, to carry out investigative work (Ferrés et al., 2015).

The learning of these skills should be encouraged by inquiry-based teaching, which, with the help of careful planning, should foment their gradual assumption by students. As Abrahams and Miller (2008) pointed out, training programs should help teachers differentiate between activities with a relatively low learning demand from those that are more demanding to identify the tasks where students will need greater help and orientation.

The results of our study seem to lend weight to the points of view of those who support a teaching approach based on inquiry from an early age (Borgerding & Raven, 2018), using activities in which students (with greater guidance from the teacher initially) plan and conduct experiments in which they put into practice the different skills that characterize scientific research from a holistic view of scientific inquiry (proposing hypotheses, designing strategies to test them, analyzing results, drawing conclusions, etc.). At the beginning, there should be a limited number of variables (as in the experiment with snails described herein) and activities should be adapted to students' previous knowledge and abilities. As students mature, they can be given tasks that require more independent thinking where it will be necessary, for example, to understand the need for control experiments.

2. The order in which scientific skills are taught should consider the difficulty that each presents for the students. To counter the random nature with which textbooks seem to include such activities, we propose some suggestions that may help teachers and authors choose and sequence teaching activities, so that students will be able to develop some abilities gradually (atomistic

perspective) and/or put into practice different strategies related to scientific activity as a whole (holistic approach).

2.1. In regard to the ability to identify problems and to understand the importance of this skill in scientific inquiry, activities should bear in mind the importance for students to:

- a. Understand the meaning of the term in a scientific context, establishing the differences between its use in scientific inquiry and in other academic situations (e.g., calculus) or daily life.
- b. Identify the most outstanding characteristics: problems are formulated as questions and refer to open situations, for which there is no immediate solution, but which demand specific strategies.
- c. Recognize the problems involved in simple texts, related to situations that are familiar to them; initially it is the teacher who must explicitly establish the relations between formulating problems and developing an investigation.
- d. Formulate and resolve problems in the context of simple classroom-based activities, checking the suitability of the problem formulation at the end of the activity.
- e. Identify the problems to be solved in more complex texts, using situations not explicitly mentioned in the text.
- f. Differentiate the problems that can be the object of scientific research from others that are simply the object of non-scientific conjecture.

2.2. To help students with formulating and contrasting hypotheses, activities should:

- a. Clarify the meaning of the term, differentiating it from mere conjecture, establishing similarities with and differences from other scientific skills.
- b. Encourage, initially with the teacher's help, the identification of hypotheses which underlie certain areas of investigation, taking as reference situations proposed by the students or others contained in simple texts whose content is familiar to students, paying special attention to the relation to other processes involved in scientific inquiry (problem, prediction, experimental design, conclusions).
- c. Promote increasing autonomy in relation to this skill, encouraging students to formulate academic or quotidian problems and their corresponding hypotheses, and choosing the most suitable.

- d. Permit students to formulate simple scientific hypotheses in the context of scientific inquiry, which can be developed and contrasted in the classroom.
 - e. Enable students to identify the hypothesis that may explain the results and conclusions in more complex texts, even if they are not mentioned explicitly, relating them to the original problems.
 - f. Allow students to formulate hypotheses to resolve complex problems/situations, which can be developed into the corresponding experiments.
- 2.3. In order to develop students' ability to reach conclusions as the final stage of an inquiry-based activity, while opening up new perspectives for studying new problems, activities should:
- a. Introduce students to the importance of this activity, establishing differences between conclusions and the results of research, as well as their relationships with the study problem and hypothesis, using simple texts that are familiar to students.
 - b. Encourage students to write reports that include and interpret the results of inquiry-based activities carried out in class according to previously established guides, recognizing the importance of organization and the suitable presentation of the conclusions obtained.
 - c. Favor the establishment of conclusions of experiments carried out by the students themselves based on the data obtained, contrasting these with the hypothesis formulated, analyzing those aspects of scientific inquiry that were not conducted in a satisfactory way.
 - d. Encourage students to interpret the results of more complex investigation, either described in writing or performed by students.
 - e. Permit the application of conclusions obtained from reading a text or carrying out a research task to other situations and propose new research lines based on the conclusions.
- 2.4. The learning of skills related to designing experiments is, of course, linked with other scientific skills. To help in this task, activities should:
- a. Explicitly introduce students to the meaning of this term and its importance in scientific activity.
 - b. Promote the analysis of experimental designs taken from easy texts, emphasizing the relation to the problem and the research hypothesis, with special attention paid to the elements that need to be considered in experimental design (experiments necessary to consider the different predictions derived from the hypotheses, materials, etc.); in addition, given the difficulty that students have with it, the significance of the concept of variables (both dependent and independent) should be emphasized, developing the capacity to identify them in suitable examples, and showing the importance of control experiments.
 - c. Propose that students analyze and develop experiments that need simple experimental designs, following a guide established by the teacher or the class.
 - d. Offer situations in which students elaborate experimental designs for simple everyday problems (experimental or pen and paper activities), formulating the corresponding hypotheses, identifying the variables that intervene, the experiments necessary and the need for control experiments).
 - e. Promote the design and putting into practice of scientific investigatory tasks related to more complex problems, increasing the theoretical context, the difficulty as a result of the number of variables involved, or the experiments necessary to solve the problem.

These suggestions do not propose a sequence or imply that the different skills should be taught separately but do emphasize the importance of certain initiatives that will help students learn about the nature of science and of scientific inquiry by applying holistic methodologies.

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APPENDIX A

Recognize Elements of an Investigation in Textbook Phrases

Of the following sentences, indicate which one expresses a scientific problem (P), a hypothesis (H), a conclusion (C), or an experimental design (ED). Place the correct letter at the beginning of the sentence:

1. ... we believe that lead, contained in these contaminated foods, is the substance that causes this disease, to prove it we will analyze ...
2. ... once the experiment is done, it is shown that red blood cells are the cells that transport oxygen ...
3. ... we want to know what is the highest concentration of salt that allows the growth of this plant. Answering this may take time, but it is the way to ...
4. ... light and humidity do not vary, however, we change the temperature between 0°C and 50°C. We measure and record the growth of the plant daily ...
5. ... we must choose the plant that provides us with the most abundant harvest in this field. For this we will have to ...
6. ... we suppose that with this method it can be easily detected if an athlete has taken prohibited substances ...

APPENDIX B

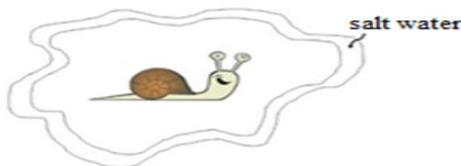
Questionnaire on Scientific Competence

1. Until the 18th century, it was thought that some small living things (for example, insects) formed in putrefactive meat without the need for females to lay eggs. The Italian Francesco Redi in 1660 thought that this was not possible and did following experiment to prove it:

“He took jars containing pieces of meat, then closed half of them and left the other half open. The flies could only enter the latter and only in them the larvae (small worms that transform into flies) developed. In the closed jars the meat decomposed and rotted, but no fly larvae appeared. Redi repeated the experience by covering the jars with gauze, instead of sealing them tightly; in this way air entered the meat, but not the flies. In this case, larvae did not appear either.”

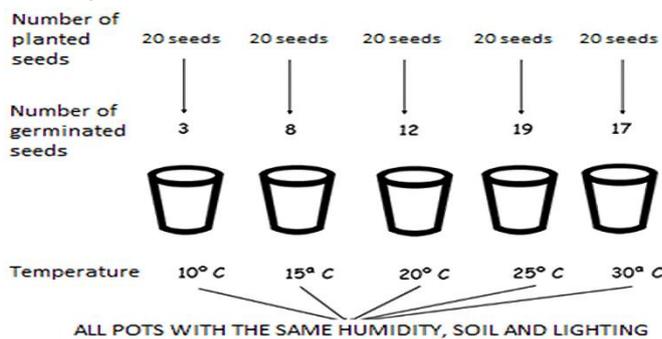


- a. Give this text a title.
 - b. What problem was Redi trying to solve?
 - c. Write down the hypothesis for this experiment.
 - d. What conclusion did Redi reach?
2. During a school project, some students made a ring of salt water around a snail and observed that it did not pass through it. According to some it was due to the water, according to others to the salt.



What tests would you do to find out who is right? Explain it in detail.

3. In an investigation on the germination of certain seeds, 20 seeds were sown in five equal pots and all with the same growing conditions (humidity, soil, lighting), in each of the five pots. Each of them was placed at a different ambient temperature (in degrees Celsius: 10, 15, 20, 25, and 30). The following figure represents the investigation:



After two weeks, the number of seeds that had germinated in each pot was counted, obtaining the result shown in **Table B1**.

Table B1.

T ^a (°C)	Number of germinated seeds
10	3
15	18
20	12
25	19
30	18

- a. Write the scientific problem that you are trying to solve with this experiment.
 - b. Write a hypothesis for this experiment.
 - c. Write the conclusion or conclusions that can be deduced from this investigation.
4. Woodlice are small animals, and they live hidden, for example, under the leaf litter. You decide to find out if the following factors influence this:
- ✓ light/darkness
 - ✓ high temperature (e.g., 30°C)/low temperature (e.g., 10°C).

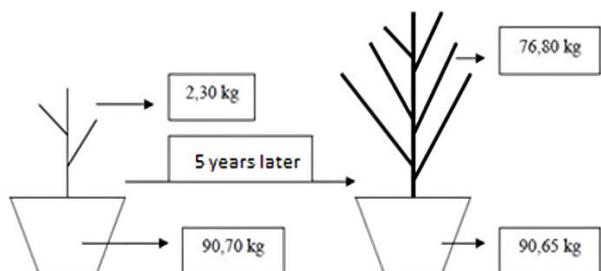


Imagine that you have the material you need (woodlice, boxes, leaf litter, devices to regulate the temperature, etc.).

Write, in as much detail as you can, the experiment or experiments you would do to show whether these factors influence woodlice to be hidden.

- a. Write the scientific problem that arises in this investigation.
 - b. Write your hypothesis or hypotheses for this problem.
 - c. Describe, in as much detail as you can, the experiment or experiments you would do. Help yourself with drawings.
 - d. State the conclusion you think you would reach and justify what you would base it on.
5. Until the 17th century, the idea prevailed those green plants fed exclusively on the earth. Jan van Helmont (1577-1644), however, doubted that idea and set out to investigate it experimentally. Van Helmont's own description is as follows:

"In a pot I placed 90.70 kg of soil that I previously dried in a stove. Then I moistened it with rainwater and planted a willow stem that weighed 2.30 kg. After five years the tree grew quite large and weighed 76.80 kg. I periodically watered the little tree with rainwater or distilled water... At the end of the experiment, I dried the soil in the pot again and found that it weighed practically the same; the weight had only been reduced by 50 g. So, the 74.50 kg of roots, bark and foliage were due ..."



- a. What problem was van Helmont trying to solve?
- b. What hypothesis (one or several) do you think van Helmont had regarding the feeding of green plants?
- c. What variables did he not control in the experiment?
- d. What conclusion do you think he came to?
- e. Later it was discovered that in addition to soil and water, air is also involved in the nutrition of green plants. At the end of the 18th century, it was shown that CO₂ is the substance that plants take from the air. What experience would you develop to show that water, soil, and CO₂ (all of them) are necessary for the growth and development of plants?