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ARTICLE

Scientific Thinking and Critical Thinking in Science Education

Two Distinct but Symbiotically Related Intellectual Processes

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Abstract
Scientific thinking and critical thinking are two intellectual processes that are considered keys in the basic and comprehensive education of citizens. For this reason, their development is also contemplated as among the main objectives of science education. However, in the literature about the two types of thinking in the context of science education, there are quite frequent allusions to one or the other indistinctly to refer to the same cognitive and metacognitive skills, usually leaving unclear what are their differences and what are their common aspects. The present work therefore was aimed at elucidating what the differences and relationships between these two types of thinking are. The conclusion reached was that, while they differ in regard to the purposes of their application and some skills or processes, they also share others and are related symbiotically in a metaphorical sense; i.e., each one makes sense or develops appropriately when it is nourished or enriched by the other. Finally, an orientative proposal is presented for an integrated development of the two types of thinking in science classes.

> *Education is not the learning of facts, but the training of the mind to think.* Albert Einstein

1 Introduction

In consulting technical reports, theoretical frameworks, research, and curricular reforms related to science education, one commonly finds appeals to *scientific thinking* and *critical thinking* as essential educational processes or objectives. This is confirmed in some studies that include exhaustive reviews of the literature in this regard such as those of Bailin (2002), Costa et al. (2020), and Santos (2017) on critical thinking, and of Klarh et al. (2019) and Lehrer and Schauble (2006) on scientific thinking. However, conceptualizing and differentiating between both types of thinking based on the above-mentioned documents of science education are generally difficult. In many cases, they are referred to without defining them,

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or they are used interchangeably to represent virtually the same thing. Thus, for example, the document *A Framework for K-12 Science Education* points out that "Critical thinking is required, whether in developing and refining an idea (an explanation or design) or in conducting an investigation" (National Research Council (NRC), 2012, p. 46). The same document also refers to scientific thinking when it suggests that basic scientific education should "provide students with opportunities for a range of scientific activities and *scientific thinking*, including, but not limited to inquiry and investigation, collection and analysis of evidence, logical reasoning, and communication and application of information" (NRC, 2012, p. 251).

A few years earlier, the report *Science Teaching in Schools in Europe: Policies and Research* (European Commission/Eurydice, 2006) included the dimension "scientific thinking" as part of standardized national science tests in European countries. This dimension consisted of three basic abilities: (i) *to solve problems formulated in theoretical terms*, (ii) *to frame a problem in scientific terms*, and (iii) *to formulate scientific hypotheses*. In contrast, critical thinking was not even mentioned in such a report. However, in subsequent similar reports by the European Commission/Eurydice (2011, 2022), there are some references to the fact that the development of critical thinking should be a basic objective of science teaching, although these reports do not define it at any point.

The *ENCIENDE* report on early-year science education in Spain also includes an explicit allusion to critical thinking among its recommendations: "Providing students with learning tools means helping them to develop *critical thinking*, to form their own opinions, to distinguish between knowledge founded on the evidence available at a certain moment (evidence which can change) and unfounded beliefs" (Confederation of Scientific Societies in Spain (COSCE), 2011, p. 62). However, the report makes no explicit mention to scientific thinking. More recently, the document "*Enseñando ciencia con ciencia*" (Teaching science with science) (Couso et al., 2020), sponsored by Spain's Ministry of Education, also addresses critical thinking:

> (…) with the teaching approach through guided inquiry students learn scientific content, learn to do science (procedures), learn what science is and how it is built, and this (...) helps to develop *critical thinking*, that is, to question any statement that is not supported by evidence. (Couso et al., 2020, p. 54)

On the other hand, in referring to what is practically the same thing, the European report *Science Education for Responsible Citizenship* speaks of scientific thinking when it establishes that one of the challenges of scientific education should be: "To promote a culture of *scientific thinking* and inspire citizens to use evidence-based reasoning for decision making" (European Commission, 2015, p. 14). However, the *Pisa 2024 Strategic Vision and Direction for Science* report does not mention scientific thinking but does mention critical thinking in noting that "More generally, (students) should be able to recognize the limitations of scientific inquiry and apply *critical thinking* when engaging with its results" (Organization for Economic Co-operation and Development (OECD), 2020, p. 9).

The new Spanish science curriculum for basic education (Royal Decree 217/2022) does make explicit reference to scientific thinking. For example, one of the STEM (Science, Technology, Engineering, and Mathematics) competency descriptors for compulsory secondary education reads:

> Use *scientific thinking* to understand and explain the phenomena that occur around them, trusting in knowledge as a motor for development, asking questions and check-

ing hypotheses through experimentation and inquiry (...) showing a critical attitude about the scope and limitations of science. (p. 41,599)

Furthermore, when developing the curriculum for the subjects of physics and chemistry, the same provision clarifies that “The essence of *scientific thinking* is to understand what are the reasons for the phenomena that occur in the natural environment to then try to explain them through the appropriate laws of physics and chemistry” (Royal Decree 217/2022, p. 41,659). However, within the science subjects (i.e., Biology and Geology, and Physics and Chemistry), critical thinking is not mentioned as such.[1] It is only more or less directly alluded to with such expressions as “critical analysis”, “critical assessment”, “critical reflection”, “critical attitude”, and “critical spirit”, with no attempt to conceptualize it as is done with regard to scientific thinking.

The above is just a small sample of the concepts of *scientific thinking* and *critical thinking* only being differentiated in some cases, while in others they are presented as interchangeable, using one or the other indistinctly to talk about the same cognitive/metacognitive processes or practices. In fairness, however, it has to be acknowledged—as said at the beginning—that it is far from easy to conceptualize these two types of thinking (Bailin, 2002; Dwyer et al., 2014; Ennis, 2018; Lehrer & Schauble, 2006; Kuhn, 1993, 1999) since they feed back on each other, partially overlap, and share certain features (Cáceres et al., 2020; Vázquez-Alonso & Manassero-Mas, 2018). Neither is there unanimity in the literature on how to characterize each of them, and rarely have they been analyzed comparatively (e.g., Hyytinen et al., 2019). For these reasons, I believed it necessary to address this issue with the present work in order to offer some guidelines for science teachers interested in deepening into these two intellectual processes to promote them in their classes.

2 An Attempt to Delimit Scientific Thinking in Science Education

For many years, cognitive science has been interested in studying what scientific thinking is and how it can be taught in order to improve students’ science learning (Klarh et al., 2019; Zimmerman & Klarh, 2018). To this end, Kuhn et al. propose taking a characterization of *science as argument* (Kuhn, 1993; Kuhn et al., 2008). They argue that this is a suitable way of linking the activity of how scientists think with that of the students and of the public in general, since science is a social activity which is subject to ongoing debate, in which the construction of arguments plays a key role. Lehrer and Schauble (2006) link scientific thinking with scientific literacy, paying especial attention to the different *images* of science. According to those authors, these images would guide the development of the said literacy in class. The *images* of science that Leherer and Schauble highlight as characterizing scientific thinking are: (i) *science-as-logical reasoning* (role of domain-general forms of scientific reasoning, including formal logic, heuristic, and strategies applied in different fields of science), (ii) *science-as-theory change* (science is subject to permanent revision and change), and (iii) *science-as-practice* (scientific knowledge and reasoning are components of a larger set of activities that include rules of participation, procedural skills, epistemological knowledge, etc.).

[1] Critical thinking is mentioned literally in other of the curricular provisions’ subjects such as in *Education in Civics and Ethical Values* or in *Geography and History* (Royal Decree 217/2022).

Based on a literature review, Jirout (2020) defines scientific thinking as an intellectual process whose purpose is the intentional search for information about a phenomenon or facts by formulating questions, checking hypotheses, carrying out observations, recognizing patterns, and making inferences (a detailed description of all these scientific practices or competencies can be found, for example, in NRC, 2012; OECD, 2019). Therefore, for Jirout, the development of scientific thinking would involve bringing into play the basic science skills/practices common to the inquiry-based approach to learning science (García-Carmona, 2020; Harlen, 2014). For other authors, scientific thinking would include a whole spectrum of *scientific reasoning competencies* (Krell et al., 2022; Moore, 2019; Tytler & Peterson, 2004). However, these competences usually cover the same science skills/practices mentioned above. Indeed, a conceptual overlap between scientific thinking, scientific reasoning, and scientific inquiry is often found in science education goals (Krell et al., 2022). Although, according to Leherer and Schauble (2006), scientific thinking is a broader construct that encompasses the other two.

It could be said that scientific thinking is a particular way of searching for information using science practices[2] (Klarh et al., 2019; Zimmerman & Klarh, 2018; Vázquez-Alonso & Manassero-Mas, 2018). This intellectual process provides the individual with the ability to evaluate the robustness of evidence for or against a certain idea, in order to explain a phenomenon (Clouse, 2017). But the development of scientific thinking also requires meta-cognition processes. According to what Kuhn (2022) argues, metacognition is fundamental to the permanent control or revision of what an individual thinks and knows, as well as that of the other individuals with whom it interacts, when engaging in scientific practices. In short, scientific thinking demands a good connection between reasoning and metacognition (Kuhn, 2022).[3]

From that perspective, Zimmerman and Klarh (2018) have synthesized a taxonomy categorizing scientific thinking, relating cognitive processes with the corresponding science practices (Table 1). It has to be noted that this taxonomy was prepared in line with the categorization of scientific practices proposed in the document *A Framework for K-12 Science Education* (NRC, 2012). This is why one needs to understand that, for example, the cognitive process of elaboration and refinement of hypotheses is not explicitly associated with the scientific practice of hypothesizing but only with the formulation of questions. Indeed, the K-12 Framework document does not establish hypothesis formulation as a basic scientific practice. Lederman et al. (2014) justify it by arguing that not all scientific research necessarily allows or requires the verification of hypotheses, for example, in cases of exploratory or descriptive research. However, the aforementioned document (NRC, 2012, p. 50) does refer to hypotheses when describing the practice of *developing and using models*, appealing to the fact that they facilitate the testing of *hypothetical explanations*.

[2] García-Carmona (2021a) conceives of them as activities that require the comprehensive application of procedural skills, cognitive and metacognitive processes, and both scientific knowledge and knowledge of the nature of scientific practice .

[3] Kuhn (2021) argues that the relationship between scientific reasoning and metacognition is especially fostered by what she calls *inhibitory control*, which basically consists of breaking down the whole of a thought into parts in such a way that attention is inhibited on some of those parts to allow a focused examination of the intended mental content.

Table 1 Taxonomy of Zimmerman and Klarh (2018) for categorizing scientific thinking

Cognitive processes	Science practices
Forming and refining hypotheses (hypothesis space search)	*Asking questions*
	Developing and using models
Investigation skills (experiment space search)	*Planning and carrying out investigations*
Evaluating evidence	*Analyzing and interpreting data/evidence*
	Constructing explanations

Source: Zimmerman and Klarh (2018, p. 7)

In the literature, there are also other interesting taxonomies characterizing scientific thinking for educational purposes. One of them is that of Vázquez-Alonso and Manassero-Mas (2018) who, instead of science practices, refer to *skills associated with scientific thinking*. Their characterization basically consists of breaking down into greater detail the content of those science practices that would be related to the different cognitive and metacognitive processes of scientific thinking. Also, unlike Zimmerman and Klarh's (2018) proposal, Vázquez-Alonso and Manassero-Mas's (2018) proposal explicitly mentions metacognition as one of the aspects of scientific thinking, which they call *meta-process*. In my opinion, the proposal of the latter authors, which shells out scientific thinking into a broader range of skills/practices, can be more conducive in order to favor its approach in science classes, as teachers would have more options to choose from to address components of this intellectual process depending on their teaching interests, the educational needs of their students and/or the learning objectives pursued. Table 2 presents an adapted characterization of the Vázquez-Alonso and Manassero-Mas's (2018) proposal to address scientific thinking in science education.

Table 2 Aspects of scientific thinking and associated basic skills for it to be developed in science education

Aspects of scientific thinking	Basic associated skills
Observe and categorize what has been observed	Observe phenomena; collect, order, organize data; etc.
Recognize patterns	Identify evidence; quantify measurements; discover regularities; synthesize; empirical generalization; etc.
Create and test hypotheses	Ask questions; identify problems; formulate hypotheses; plan and develop research; apply mathematical thinking and statistical analyses; etc.
Think about causes and effects	Control for effects of multiple variables; attribute causality; use logic; make valid and reliable interpretations; etc.
Construct explanations from evidence	Issue critical judgments on what is observed or measured; accept and reject explanations; use available scientific evidence and knowledge (consult the literature); justify and validate ideas; present arguments; develop representative and explanatory models; etc.
Be aware of and control for one's own thinking (meta-processes)	Have a skeptical attitude; show open-mindedness; challenge knowledge with alternatives; evaluate assumptions; predict; seek new ideas and knowledge with creativity and imagination; etc.
Communicate, evaluate, share, collaborate, and think about the information	Communicate and share knowledge; work cooperatively in teams; debate with colleagues on theories and solutions; evaluate the others' results and conclusions; etc.

Source: simplified adaptation of Vázquez-Alonso and Manassero-Mas (2018, p. 314)

3 Contextualization of Critical Thinking in Science Education

Theorization and research about critical thinking also has a long tradition in the field of the psychology of learning (Ennis, 2018; Kuhn, 1999), and its application extends far beyond science education (Dwyer et al., 2014). Indeed, the development of critical thinking is commonly accepted as being an essential goal of people's overall education (Ennis, 2018; Hitchcock, 2017; Kuhn, 1999; Willingham, 2008). However, its conceptualization is not simple and there is no unanimous position taken on it in the literature (Costa et al., 2020; Dwyer et al., 2014); especially when trying to relate it to scientific thinking. Thus, while Tena-Sánchez and León-Medina (2022)[4] and McBain et al. (2020) consider critical thinking to be the basis of or forms part of scientific thinking, Dowd et al. (2018) understand scientific thinking to be just a subset of critical thinking. However, Vázquez-Alonso and Manassero-Mas (2018) do not seek to determine whether critical thinking encompasses scientific thinking or vice versa. They consider that both types of knowledge share numerous skills/practices and the progressive development of one fosters the development of the other as a virtuous circle of improvement. Other authors, such as Schafersman (1991), even go so far as to say that critical thinking and scientific thinking are the same thing. In addition, some views on the relationship between critical thinking and scientific thinking seem to be context-dependent. For example, Hyytine et al. (2019) point out that in the perspective of scientific thinking as a component of critical thinking, the former is often used to designate evidence-based thinking in the sciences, although this view tends to dominate in Europe but not in the USA context. Perhaps because of this lack of consensus, the two types of thinking are often confused, overlapping, or conceived as interchangeable in education.

Even with such a lack of unanimous or consensus vision, there are some interesting theoretical frameworks and definitions for the development of critical thinking in education. One of the most popular definitions of critical thinking is that proposed by *The National Council for Excellence in Critical Thinking* (1987, cited in Inter-American Teacher Education Network, 2015, p. 6). This conceives of it as "the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief and action". In other words, critical thinking can be regarded as a reflective and reasonable class of thinking that provides people with the ability to evaluate multiple statements or positions that are defensible to then decide which is the most defensible (Clouse, 2017; Ennis, 2018). It thus requires, in addition to a basic scientific competency, notions about *epistemology* (Kuhn, 1999) to understand how knowledge is constructed. Similarly, it requires skills for metacognition (Hyytine et al., 2019; Kuhn, 1999; Magno, 2010) since critical thinking "entails awareness of one's own thinking and reflection on the thinking of self and others as objects of cognition" (Dean & Kuhn, 2003, p. 3).

In science education, one of the most suitable scenarios or resources, but not the only one,[5] to address all these aspects of critical thinking is through the analysis of

[4] Specifically, Tena-Sánchez and León-Medina (2020) assume that critical thinking is at the basis of rational or scientific skepticism that leads to questioning any claim that does not have empirical support.

[5] As discussed in the introduction, the inquiry-based approach is also considered conducive to addressing critical thinking in science education (Couso et al., 2020; NRC, 2012).

socioscientific issues (SSI) (Taylor et al., 2006; Zeidler & Nichols, 2009). Without wishing to expand on this here, I will only say that interesting works can be found in the literature that have analyzed how the discussion of SSIs can favor the development of critical thinking skills (see, e.g., López-Fernández et al., 2022; Solbes et al., 2018). For example, López-Fernández et al. (2022) focused their teaching-learning sequence on the following critical thinking skills: information analysis, argumentation, decision making, and communication of decisions. Even some authors add the *nature of science* (NOS) to this framework (i.e., SSI-NOS-critical thinking), as, for example, Yacoubian and Khishfe (2018) in order to develop critical thinking and how this can also favor the understanding of NOS (Yacoubian, 2020). In effect, as I argued in another work on the COVID-19 pandemic as an SSI, in which special emphasis was placed on critical thinking, an informed understanding of how science works would have helped the public understand why scientists were changing their criteria to face the pandemic in the light of new data and its reinterpretations, or that it was not possible to go faster to get an effective and secure medical treatment for the disease (García-Carmona, 2021b).

In the recent literature, there have also been some proposals intended to characterize critical thinking in the context of science education. Table 3 presents two of these by way of example. As can be seen, both proposals share various components for the development of critical thinking (respect for evidence, critically analyzing/assessing the validity/reliability of information, adoption of independent opinions/decisions, participation, etc.), but that of Blanco et al. (2017) is more clearly contextualized in science education. Likewise, that of these authors includes some more aspects (or at least does so more explicitly), such as

Table 3 Two proposals of critical-thinking components to be developed in science education

Proposal of Blanco-López et al. (2017)	Proposal of Jiménez-Aleixandre and Puig (2022)
Vision of science as a human activity with multiple relationships with technology, society, and the environment	Cognitive and epistemic skills: criteria and evidence for knowledge evaluation
Knowledge of the topics addressed, without being limited to dominant discourses but knowing about alternative standpoints	Critical character and disposition to consider refutatory evidence, to evaluate the reliability of sources, to revise views, etc.
Critical analysis of the information (the sources' credibility, the authors' underlying interests…)	Capacity to develop independent opinions and to challenge socially and culturally established ideas
Comprehensive treatment of the problems, taking into account the scientific, technical, ethical, cultural, philosophical, social, environmental, economic, and other dimensions	Critical action: critical consciousness and participation
Discussion to question the validity of the arguments, reject conclusions not based on evidence, and detect fallacies in argumentation	
Personal autonomy to develop an independent opinion, acquiring the skill to reflect upon society and participate in it	
Decision-making to form rational choices and well-founded judgments as elements of the decisions used to resolve problems	
Communication of decisions using language appropriate for the context and the objectives or intentions	

Source: Blanco-López et al. (2017) and Aleixandre and Puig (2022) developing epistemological[6] knowledge of science (vision of science…) and on its interactions with technology, society, and environment (STSA relationships), and communication skills. Therefore, it offers a wider range of options for choosing critical thinking skills/processes to promote it in science classes. However, neither proposal refers to metacognitive skills, which are also essential for developing critical thinking (Kuhn, 1999).

3.1 Critical thinking vs. scientific thinking in science education: differences and similarities

In accordance with the above, it could be said that scientific thinking is nourished by critical thinking, especially when deciding between several possible interpretations and explanations of the same phenomenon since this generally takes place in a context of debate in the scientific community (Acevedo-Díaz & García-Carmona, 2017). Thus, the scientific attitude that is perhaps most clearly linked to critical thinking is the *skepticism* with which scientists tend to welcome new ideas (Normand, 2008; Sagan, 1987; Tena-Sánchez and León-Medina, 2022), especially if they are contrary to well-established scientific knowledge (Bell, 2009). A good example of this was the OPERA experiment (García-Carmona & Acevedo-Díaz, 2016a), which initially seemed to find that neutrinos could move faster than the speed of light. This finding was supposed to invalidate Albert Einstein's theory of relativity (the finding was later proved wrong). In response, Nobel laureate in physics Sheldon L. Glashow went so far as to state that:

> the result obtained by the OPERA collaboration cannot be correct. If it were, we would have to give up so many things, it would be such a huge sacrifice... But if it is, I am officially announcing it: I will shout to Mother Nature: I'm giving up! And I will give up Physics. (BBVA Foundation, 2011)

Indeed, scientific thinking is ultimately focused on getting evidence that may support an idea or explanation about a phenomenon, and consequently allow others that are less convincing or precise to be discarded. Therefore when, with the evidence available, science has more than one equally defensible position with respect to a problem, the investigation is considered inconclusive (Clouse, 2017). In certain cases, this gives rise to scientific controversies (Acevedo-Díaz & García-Carmona, 2017) which are not always resolved based exclusively on epistemic or rational factors (Elliott & McKaughan, 2014; Vallverdú, 2005). Hence, it is also necessary to integrate *non-epistemic practices* into the framework of scientific thinking (García-Carmona, 2021a; García-Carmona & Acevedo-Díaz, 2018), practices that transcend the purely rational or cognitive processes, including, for example, those related to emotional or affective issues (Sinatra & Hofer, 2021). From an educational point of view, this suggests that for students to become more authentically immersed in the way of working or thinking scientifically, they should also learn *to feel* as scientists do when they carry out their work (Davidson et al., 2020). Davidson et al. (2020) call it *epistemic affect*, and they suggest that it could be approach in science classes by teaching students to manage their *frustrations* when they fail to achieve the expected results;[7] or, for example, to

[6] Epistemic skills should not be confused with epistemological knowledge (García-Carmona, 2021a). The former refers to skills to construct, evaluate, and use knowledge, and the latter to understanding about the origin, nature, scope, and limits of scientific knowledge.

[7] For this purpose, it can be very useful to address in class, with the help of the history and philosophy of science, that scientists get more wrong than right in their research, and that error is always an opportunity to learn (García-Carmona & Acevedo-Díaz, 2018).

moderate their *enthusiasm* with favorable results in a scientific inquiry by activating a certain *skepticism* that encourages them to do more testing. And, as mentioned above, for some authors, having a skeptical attitude is one of the actions that best visualize the application of critical thinking in the framework of scientific thinking (Normand, 2008; Sagan, 1987; Tena-Sánchez and León-Medina, 2022).

On the other hand, critical thinking also draws on many of the skills or practices of scientific thinking, as discussed above. However, in contrast to scientific thinking, the coexistence of two or more defensible ideas is not, in principle, a problem for critical thinking since its purpose is not so much to invalidate some ideas or explanations with respect to others, but rather to provide the individual with the foundations on which to position themself with the idea/argument they find most defensible among several that are possible (Ennis, 2018). For example, science with its methods has managed to explain the greenhouse effect, the phenomenon of the tides, or the transmission mechanism of the coronavirus. For this, it had to discard other possible explanations as they were less valid in the investigations carried out. These are therefore issues resolved by the scientific community which create hardly any discussion at the present time. However, taking a position for or against the production of energy in nuclear power plants transcends the scope of scientific thinking since both positions are, in principle, equally defensible. Indeed, within the scientific community itself there are supporters and detractors of the two positions, based on the same scientific knowledge. Consequently, it is critical thinking, which requires the management of knowledge and scientific skills, a basic understanding of epistemic (rational or cognitive) and non-epistemic (social, ethical/moral, economic, psychological, cultural, ...) aspects of the nature of science, as well as metacognitive skills, which helps the individual forge a personal foundation on which to position themself in one place or another, or maintain an uncertain, undecided opinion.

In view of the above, one can summarize that scientific thinking and critical thinking are two different intellectual processes in terms of purpose, but are related symbiotically (i.e., one would make no sense without the other or both feed on each other) and that, in their performance, they share a fair number of features, actions, or mental skills. According to Cáceres et al. (2020) and Hyytine et al. (2019), the intellectual skills that are most clearly common to both types of thinking would be *searching for relationships between evidence and explanations*, as well as *investigating and logical thinking to make inferences*. To this common space, I would also add skills for metacognition in accordance with what has been discussed about both types of knowledge (Khun, 1999, 2022).

In order to compile in a compact way all that has been argued so far, in Table 4, I present my overview of the relationship between scientific thinking and critical thinking. I would like to point out that I do not intend to be extremely extensive in the compilation, in the sense that possibly more elements could be added in the different sections, but rather to represent above all the aspects that distinguish and share them, as well as the mutual enrichment (or symbiosis) between them.

4 A Proposal for the Integrated Development of Critical Thinking and Scientific Thinking in Science Classes

Once the differences, common aspects, and relationships between critical thinking and scientific thinking have been discussed, it would be relevant to establish some type of specific proposal to foster them in science classes. Table 5 includes a possible script to address

Table 4 Differences and relationships between scientific and critical thinking

Purpose of		
Scientific thinking	Critical thinking	
Finding the best rational explanation of a phenomenon among different possible explanatory proposals (i.e., generating scientific knowledge)	Choosing the most defensible idea/position among others that are also defensible	
Skills or actions to		
Scientific thinking	Critical thinking)	Both (common)
Manage scientific knowledge related to the issue to be investigated Formulate researchable questions and hypotheses (where appropriate) to initiate scientific inquiry Obtain data or evidence through the planning and development of scientific inquiries Look for patterns of behavior and generalizations to elaborate explanations (models, causal relationships, etc.) Apply logical reasoning Elaborate explanations from evidence Discard those ideas that have no logical/rational or empirical support	Make moral/ethical, political, etc., as well as scientific assessments/analysis related to the issue in order to construct complex arguments Make decisions or take one's own position on the issue on the basis of arguments Maintain a skeptical attitude towards new data, information or ideas Emotionally manage frustrations in the face of errors or unexpected results Respect ideas or opinions different from one's own if they are argued and do not incur illegalities.	Have respect for evidence Possess an informed understanding of epistemic and non-epistemic aspects of NOS Assess the reliability of data or information Interpret data and information (inference) Construct arguments from evidence Communicate ideas or opinions in an understandable way Discuss different ideas, opinions Being aware of the strengths and weaknesses of one's own ideas or opinions as well as those of others (metacognition)
Symbiosis between both types of thinking		
Application of critical thinking in scientific thinking	Application of scientific thinking in critical thinking	
Activate a skeptical attitude (or critical judgment) towards new data or information Emotionally manage error, frustrations, and euphoria Apply extra-scientific arguments (e.g., ethical, moral, political, etc.) in planning and carrying out scientific inquiries Admit and, therefore, respect that other ideas or interpretations of evidence than one's own are also possible in the absence of more conclusive research	Handling scientific knowledge Search for evidence through inquiry processes Identify patterns and behaviors in numerical data sources (e.g., statistical results related to an SSI) in order to develop a personal opinion Apply logical reasoning	

Source: own elaboration

Table 5 Motivational, cognitive, and metacognitive skills or processes for the integrated development of critical thinking and scientific thinking in science classes

i. Motivation and predisposition to reflect on and discuss the issue being analyzed
ii. Respect for the scientific evidence related to the issue
iii. Appropriate scientific knowledge (concepts, laws, models, theories, …) and epistemological understanding (how knowledge is constructed) with which to address the issue
iv. Obtaining information from reliable sources and differentiate it from that coming from unreliable sources
v. Understanding and critical analysis of information
vi. Making inferences from the information analyzed
vii. When faced with various defensible statements or situations, elaborating explanations and/or adopting one's own position (or decision) with arguments based on scientific evidence and knowledge, as well as other extra-scientific factors (ethical and moral, social, economic, …)
viii. Communication and discussion of ideas or opinions
ix. Metacognition:
(1) Reflection on and awareness of one's own knowledge and the personal cognitive processes that come into play), and
(2) Self-regulation of one's own knowledge and opinions (self-criticism, review of one's own ideas and, where appropriate, rectifying, qualifying, and amplifying them; recognition of other ideas/arguments…)

Source: own elaboration

various skills or processes of both types of thinking in an integrated manner. However, before giving guidance on how such skills/processes could be approached, I would like to clarify that while all of them could be dealt within the context of a single school activity, I will not do so in this way. First, because I think that it can give the impression that the proposal is only valid if it is applied all at once in a specific learning situation, which can also discourage science teachers from implementing it in class due to lack of time or training to do so. Second, I think it can be more interesting to conceive the proposal as a set of thinking skills or actions that can be dealt with throughout the different science contents, selecting only (if so decided) some of them, according to educational needs or characteristics of the learning situation posed in each case. Therefore, in the orientations for each point of the script or grouping of these, I will use different examples and/or contexts. Likewise, these orientations in the form of comments, although founded in the literature, should be considered only as possibilities to do so, among many others possible.

Motivation and predisposition to reflect and discuss (point *i*) demands, on the one hand, that issues are chosen which are attractive for the students. This can be achieved, for example, by asking the students directly what current issues, related to science and its impact or repercussions, they would like to learn about, and then decide on which issue to focus on (García-Carmona, 2008). Or the teacher puts forward the issue directly in class, trying for it be current, to be present in the media, social networks, etc., or what they think may be of interest to their students based on their teaching experience. In this way, each student is encouraged to feel questioned or concerned as a citizen because of the issue that is going to be addressed (García-Carmona, 2008). Also of possible interest is the analysis of contemporary, as yet unresolved socioscientific affairs (Solbes et al., 2018), such as climate change, science and social justice, transgenic foods, homeopathy, and alcohol and drug use in society. But also, everyday questions can be investigated which demand a decision to be made, such as "What car to buy?" (Moreno-Fontiveros et al., 2022), or "How can we prevent the arrival of another pandemic?" (Ushola & Puig, 2023).

On the other hand, it is essential that the discussion about the chosen issue is planned through an instructional process that generates an environment conducive to reflection and debate, with a view to engaging the students' participation in it. This can be achieved, for example, by setting up a role-play game (Blanco-López et al., 2017), especially if the issue is socioscientific, or by critical and reflective reading of advertisements with scientific content (Campanario et al., 2001) or of science-related news in the daily media (García-Carmona, 2014, 2021a; Guerrero-Márquez & García-Carmona, 2020; Oliveras et al., 2013), etc., for subsequent discussion—all this, in a collaborative learning setting and with a clear democratic spirit.

Respect for scientific evidence (point *ii*) should be the indispensable condition in any analysis and discussion from the prisms of scientific and of critical thinking (Erduran, 2021). Although scientific knowledge may be impregnated with subjectivity during its construction and is revisable in the light of new evidence (*tentativeness* of scientific knowledge), when it is accepted by the scientific community it is as objective as possible (García-Carmona & Acevedo-Díaz, 2016b). Therefore, promoting trust and respect for scientific evidence should be one of the primary educational challenges to combating pseudoscientists and science deniers (Díaz & Cabrera, 2022), whose arguments are based on false beliefs and assumptions, anecdotes, and conspiracy theories (Normand, 2008). Nevertheless, it is no simple task to achieve the promotion or respect for scientific evidence (Fackler, 2021) since science deniers, for example, consider that science is unreliable because it is imperfect (McIntyre, 2021). Hence the need to promote a basic understanding of NOS (point *iii*) as a fundamental pillar for the development of both scientific thinking and critical thinking. A good way to do this would be through explicit and reflective discussion about controversies from the history of science (Acevedo-Díaz & García-Carmona, 2017) or contemporary controversies (García-Carmona, 2021b; García-Carmona & Acevedo-Díaz, 2016a).

Also, with respect to point *iii* of the proposal, it is necessary *to manage basic scientific knowledge* in the development of scientific and critical thinking skills (Willingham, 2008). Without this, it will be impossible to develop a minimally serious and convincing argument on the issue being analyzed. For example, if one does not know the transmission mechanism of a certain disease, it is likely to be very difficult to understand or justify certain patterns of social behavior when faced with it. In general, possessing appropriate scientific knowledge on the issue in question helps to make the best interpretation of the data and evidence available on this issue (OECD, 2019).

The search for information from reliable sources, together with its analysis and interpretation (points *iv* to *vi*), are essential practices both in purely scientific contexts (e.g., learning about the behavior of a given physical phenomenon from literature or through enquiry) and in the application of critical thinking (e.g., when one wishes to take a personal, but informed, position on a particular socio-scientific issue). With regard to determining the credibility of information with scientific content on the Internet, Osborne et al. (2022) propose, among other strategies, to check whether the source is free of conflicts of interest, i.e., whether or not it is biased by ideological, political or economic motives. Also, it should be checked whether the source and the author(s) of the information are sufficiently reputable.

Regarding the interpretation of data and evidence, several studies have shown the difficulties that students often have with this practice in the context of enquiry activities (e.g., Gobert et al., 2018; Kanari & Millar, 2004; Pols et al., 2021), or when analyzing science news in the press (Norris et al., 2003). It is also found that they have significant difficulties in choosing the most appropriate data to support their arguments in causal analyses (Kuhn & Modrek, 2022). However, it must be recognized that making interpretations or inferences from data is not a simple task; among other reasons, because their construction is influenced by multiple factors, both epistemic (prior knowledge, experimental designs, etc.) and non-epistemic (personal expectations, ideology, sociopolitical context, etc.), which means that such interpretations are not always the same for all scientists (García-Carmona, 2021a; García-Carmona & Acevedo-Díaz, 2018). For this reason, the performance of this scientific practice constitutes one of the phases or processes that generate the most debate or discussion in a scientific community, as long as no consensus is reached. In order to improve the practice of making inferences among students, Kuhn and Lerman (2021) propose activities that help them develop their own epistemological norms to connect causally their statements with the available evidence.

Point *vii* refers, on the one hand, to an essential scientific practice: the elaboration of *evidence-based scientific explanations* which generally, in a reasoned way, account for the causality, properties, and/or behavior of the phenomena (Brigandt, 2016). In addition, point *vii* concerns the *practice of argumentation*. Unlike scientific explanations, argumentation tries to justify an idea, explanation, or position with the clear purpose of persuading those who defend other different ones (Osborne & Patterson, 2011). As noted above, the complexity of most socioscientific issues implies that they have no unique valid solution or response. Therefore, the content of the arguments used to defend one position or another are not always based solely on purely rational factors such as data and scientific evidence. Some authors defend the need to also deal with non-epistemic aspects of the nature of science when teaching it (García-Carmona, 2021a; García-Carmona & Acevedo-Díaz, 2018) since many scientific and socioscientific controversies are resolved by different factors or go beyond just the epistemic (Vallverdú, 2005).

To defend an idea or position taken on an issue, it is not enough to have scientific evidence that supports it. It is also essential to have *skills for the communication and discussion of ideas* (point *viii*). The history of science shows how the difficulties some scientists had in communicating their ideas scientifically led to those ideas not being accepted at the time. A good example for students to become aware of this is the historical case of Semmelweis and puerperal fever (Aragón-Méndez et al., 2019). Its reflective reading makes it possible to conclude that the proposal of this doctor that gynecologists disinfect their hands, when passing from one parturient to another to avoid contagions that provoked the fever, was rejected by the medical community not only for epistemic reasons, but also for the difficulties that he had to communicate his idea. The history of science also reveals that some scientific interpretations were imposed on others at certain historical moments due to the rhetorical skills of their proponents although none of the explanations would convincingly explain the phenomenon studied. An example is the case of the controversy between Pasteur and Liebig about the phenomenon of fermentation (García-Carmona & Acevedo-Díaz, 2017), whose reading and discussion in science class would also be recommended in this context of this critical and scientific thinking skill. With the COVID-19 pandemic, for example, the arguments of some charlatans in the media and on social networks managed to gain a certain influence in the population, even though scientifically they were muddled nonsense (García-Carmona, 2021b). Therefore, the reflective reading of news on current SSIs such as this also constitutes a good resource for the same educational purpose. In general, according to Spektor-Levy et al. (2009), scientific communication skills should be addressed explicitly in class, in a progressive and continuous manner, including tasks of information seeking, reading, scientific writing, representation of information, and representation of the knowledge acquired.

Finally (point *ix*), a good scientific/critical thinker must be aware of what they know, of what they have doubts about or do not know, to this end continuously practicing *metacognitive exercises* (Dean & Kuhn, 2003; Hyytine et al., 2019; Magno, 2010; Willingham, 2008). At the same time, they must recognize the weaknesses and strengths of the arguments of their peers in the debate in order to be self-critical if necessary, as well as to revising their own ideas and arguments to improve and reorient them, etc. (*self-regulation*). I see one of the keys of both scientific and critical thinking being the capacity or willingness to change one's mind, without it being frowned upon. Indeed, quite the opposite since one assumes it to occur thanks to the arguments being enriched and more solidly founded. In other words, scientific and critical thinking and arrogance or haughtiness towards the rectification of ideas or opinions do not stick well together.

5 Final Remarks

For decades, scientific thinking and critical thinking have received particular attention from different disciplines such as psychology, philosophy, pedagogy, and specific areas of this last such as science education. The two types of knowledge represent intellectual processes whose development in students, and in society in general, is considered indispensable for the exercise of responsible citizenship in accord with the demands of today's society (European Commission, 2006, 2015; NRC, 2012; OECD, 2020). As has been shown however, the task of their conceptualization is complex, and teaching students to think scientifically and critically is a difficult educational challenge (Willingham, 2008).

Aware of this, and after many years dedicated to science education, I felt the need to organize my ideas regarding the aforementioned two types of thinking. In consulting the literature about these, I found that, in many publications, scientific thinking and critical thinking are presented or perceived as being interchangeable or indistinguishable; a conclusion also shared by Hyytine et al. (2019). Rarely have their differences, relationships, or common features been explicitly studied. So, I considered that it was a matter needing to be addressed because, in science education, the development of scientific thinking is an inherent objective, but, when critical thinking is added to the learning objectives, there arise more than reasonable doubts about when one or the other would be used, or both at the same time. The present work came about motivated by this, with the intention of making a particular contribution, but based on the relevant literature, to advance in the question raised. This converges in conceiving scientific thinking and critical thinking as two intellectual processes that overlap and feed into each other in many aspects but are different with respect to certain cognitive skills and in terms of their purpose. Thus, in the case of scientific thinking, the aim is to choose the best possible explanation of a phenomenon based on the available evidence, and it therefore involves the rejection of alternative explanatory proposals that are shown to be less coherent or convincing. Whereas, from the perspective of critical thinking, the purpose is to choose the most defensible idea/option among others that are also defensible, using both scientific and extra-scientific (i.e., moral, ethical, political, etc.) arguments. With this in mind, I have described a proposal to guide their development in the classroom, integrating them under a conception that I have called, metaphorically, a symbiotic relationship between two modes of thinking.

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