Critical Attitude and Conceptual Development in Physics: What Connections?[1]

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Abstract: In a changing world, several competences are universally advocated as educational objectives. One of the expected benefits of this choice is transferability across domains, as in the case of critical thinking. But developing various competences in this way may entail some limitations on other planes – for instance, in relation to disciplinary conceptual knowledge. The question arises of the possible links between development of a critical attitude and conceptual progress in a given domain. To document this question, I present a series of investigations involving future physics teachers at the end of their formation. Reporting their evolution during in-depth interviews on various topics in physics, I focus on the extent to which they critiqued incomplete or incoherent explanations. The findings are discussed in terms of 'intellectual dynamics' – that is, differences in the co-evolution of their conceptual understanding and critical attitude. In this context, the most frequently observed intellectual dynamics was 'delayed critique': waiting to reach a certain threshold of conceptual comprehension beyond mere logical necessity before expressing a critique of a given text. I will discuss the process by which the transition from critical passivity to the liberation of critical attitude is triggered in this population, discussing how we might help future teachers (and students more generally) to reduce the duration and effects of their critical passivity when they struggle to master the domain in question. I will argue that much more can be learned from students' responses to an educational setting if analysis of their comments is not confined exclusively to conceptual aspects but attends more to the possible *interconnections* between conceptual and metacognitive-critical-affective awareness.

Keywords: critical attitude, conceptual development, intellectual dynamics, teacher formation

1 Based mainly on investigations conducted with Nicolas Décamp.

In a changing world, several competences are universally advocated as educational objectives. One of the expected benefits of this choice is transferability across domains, as in the case of critical thinking. For instance, one European Commission prescription[2] is '… to develop the competencies for problem-solving and innovation, as well as analytical and critical thinking that are necessary to empower citizens to lead personally fulfilling, socially responsible and professionally-engaged lives'.

However, developing competences in this way may entail limitations at other levels – for instance, in relation to disciplinary conceptual knowledge. In recent years, concern has been expressed that an emphasis on competences might undermine conceptual structuring, arguing for instance that French students at the end of their secondary school 'see physics as disordered and anarchical'.[3] The question therefore arises of possible links between the development of critical attitude and conceptual progress in a given domain. This can be rephrased in operational terms: *Can we help students to develop their critical thinking in the absence of a conceptual basis*? Conversely, we might also ask whether advanced conceptual mastery within a given domain suffices to facilitate efficient critique.

To address these questions, I propose first to show that the latter statement is inaccurate. To characterize the possible connections between conceptual and critical development, I will then refer to a series of investigations involving future physics teachers at the end of their formation. Reporting their evolution during in-depth interviews on various topics in physics, I will focus in particular on the extent to which they criticize incomplete or incoherent explanations. The findings are presented in terms of 'intellectual dynamics' – that is, individual differences in the co-evolution of conceptual understanding and critical attitude. In conclusion, I shall discuss some implications for future research and teacher formation.

2 *Science Education for Responsible Citizenship*, European Commission, Report EUR 26893 EN, chair H. Hazelkorn (Brussels, 2015).

3 L. Villain, '61e congrès national de l'UdPPC', *Bulletin de l'Union des Physiciens*, 107 (959) (2013), 2012.

Conceptual mastery does not always entail critical attitude: 'expert anaesthesia'

On the face of it, it seems reasonable to argue that developing conceptual mastery in our students will necessarily enhance their critical attitude, as evidenced by physics teachers' abilities in this regard. However, the various counter-examples below serve to demonstrate that this common idea is not self-evident.

A helium balloon in empty space

To develop students' critical faculty, a 'popular science' paper on the world freefall record from a French website for Grade 10 students was presented to 23 Ph.D. students and six in-service teachers. According to that account, the record-breaker ascended to an altitude of 40,000 meters in a helium balloon before jumping out and was then in freefall, given 'the absence of an atmosphere'. Among the questions posed on the website, none mentioned the strange circumstance of a helium balloon seemingly situated in a place where there was no air. Additionally, the participants were asked individually whether they would pose any questions to Grade 10 students to help them comprehend this text.[4] Despite their professional expertise, none of the participants mentioned that a helium balloon cannot reach a place where there is no air. This may be explained by various factors – in particular, that the paper focused on 'free' fall, an acceptable hypothesis given the very tenuous atmosphere at that altitude. In relation to the balloon, however, it is impossible to confuse (without serious incoherence) 'very low' with 'zero' pressure. As the website material targeted young students, such an approximate style may have negative consequences. We coined the term 'expert anaesthesia' to describe the lack of critical vigilance among the designers of this activity and the consulted participants, given that (for this topic) they all can be considered 'experts'.

4 Id., 'Les promesses de l'Enseignement Intégré de Science et Technologie (EIST): de la fausse monnaie?', *Spirale*, 52 (2013), 59.

The ray box

While it is very common to 'show rays of light' using a horizontal sheet of paper lit through vertical slits, such experiments have long been criticized.[5]

Consider the 'ray box' often used to 'show rays of light going in straight lines' (Figure 1). One way of avoiding oversimplification in this context is to show how wavy slits produce wavy 'rays'. In both cases, what we see is *not* 'rays' but *shadows* of the mask and its slits. That we see such shadows attests in *both* cases to the rectilinear propagation of light, but neither experiment shows 'rays of light'. Rather, the illuminated streak on the paper is in fact a succession of spots, each lit by different beams. As a demonstration of rectilinear propagation of light, this set-up is visually effective but fundamentally incoherent. Moreover, it reinforces the common idea that light is visible from the side as if it were an ordinary object. This 'teaching ritual'[6] – an accepted and undiscussed teaching practice – is widely used in classrooms and museums. We contend that this implies a lack of critical vigilance in the users of this device, despite their 'expertise' concerning the rectilinear propagation of light.

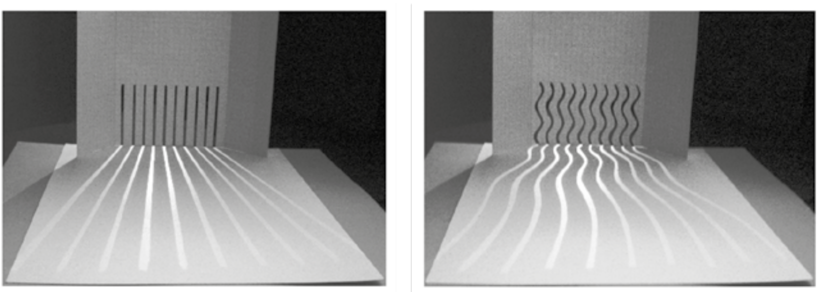

Fig 1. a: A 'ray box' is often used to 'show' the rectilinear propagation of light (there is a lamp behind the mask). b: A device evidencing that what is seen is a set of shadows (Kaminski, personal communication, 2005).

5 See, for instance, L. Viennot, F. Chauvet, P. Colin. and G. Rebmann, 'Designing strategies and tools for teacher training, the role of critical details', *Science Education*, 89 (2005), 16.

6 L. Viennot, 'Teaching rituals and students' intellectual satisfaction', *Physics Education*, 41 (2006), 400–8.

From these and other examples,[7] we posit that topic knowledge does not in itself suffice to support critical analysis of contestable texts or pedagogical suggestions in that same domain.

A series of investigations with future teachers

To analyse in more detail the connections between conceptual development and critical attitude, we conducted a series of investigations involving prospective physics teachers at the end of their formation, using different physics topics to evaluate any possible content dependence in our results.[8] In each case, participants were presented with a series of more or less contestable texts and invited to comment on these during in-depth interviews. In processing the transcripts, we pursued a double line of analysis: conceptual structuring and critical thinking. In conducting our analysis, we considered that posing a critical question or formulating a critical objection demands awareness of one's own state of comprehension and a search for intellectual satisfaction.[9] Beyond an attitude of mere doubt, this suggests an active search for meaning, perhaps related to psychological factors such as self-esteem or self-efficacy.[10] As these metacognitive and affective components of critical attitude seem *a priori* difficult to unravel,

7 See also L. Viennot, *Thinking in physics. The pleasure of reasoning and understanding* (Dordrecht, 2014).

8 N. Décamp and L. Viennot, 'Co-development of conceptual understanding and critical attitude: analysing texts on radiocarbon dating', *International Journal of Science Education*, 37(12), 2038–63; L. Viennot and N. Décamp. 'Co-development of conceptual understanding and critical attitude: toward a systemic analysis of the survival blanket', *European Journal of Physics*, 37(1) (2016), 015702; L. Viennot and N. Décamp, 'Conceptual and critical development in student teachers: First steps towards an integrated comprehension of osmosis', *International Journal of Science Education*, 38 (14) (2016b), 2197–219; L. Viennot and N. Décamp, 'The transition towards critique, Discussing capillary ascension with future teachers', oral presentation, GIREP conference (Dublin, 2017); N. Décamp and L. Viennot, 'A concept-driven interactive pathway (CDIP) about electric current in simple DC circuits', oral presentation, GIREP conference (Dublin, 2017).

9 Viennot, *Thinking in physics*; I. Feller, P. Colin, and L. Viennot, 'Critical analysis of popularization documents in the physics classroom. An action-research in Grade 10', *Problems of Education in the 21st Century*, 17 (2009), 72–96; S. Mathé and L. Viennot, 'Stressing the coherence of physics: Students journalists' and science mediators' reactions', *Problems of education in the 21st century*, 11 (11) (2009), 104–28.

10 A. Bandura, 'Social cognitive theory: an agentic perspective', *Annual Review of Psychology*, 52 (2001), 1–26.

they may be characterized as 'metacognitive-critical-affective' (MCA).

Radiocarbon dating: frequent 'delayed critiques', rare 'expert anaesthesia'

Although well-known as a general topic, the details of radiocarbon dating are far from obvious, and popular accounts offer various incomplete explanations. In fact, beyond the exponential decay of radiocarbon in dead organisms and the role of ^{14}C half-life (5,730 years), a *relatively* complete and coherent explanation of this process should address at least the following points:

1. The need to know the initial proportion of radiocarbon to ordinary carbon in an organism at the time of its death;
2. The uniformity of this quantity in the atmosphere and in living beings;
3. The constancy of this quantity over time;
4. The process of formation of radiocarbon;
5. The process of radioactive decay of radiocarbon;
6. How the balance between corresponding numbers per second of radiocarbon atoms in these two processes results in a steady value of $[^{14}C/^{12}C]$ in the atmosphere;
7. The constancy of the total number of nuclei (radiocarbon + nitrogen);
8. The multiplicative effect of existing numbers of radiocarbon and nitrogen nuclei in the destruction and creation of ^{14}C nuclei, respectively;
9. How this multiplicative structure explains the stable proportion of radiocarbon to ordinary carbon in the atmosphere.

For this investigation,[11] we selected five documents from the Internet offering less complete accounts than the above list. We also designed a sixth document to explain how a steady state ^{14}C population can be achieved and maintained from an unbalanced initial situation. Ten prospective teachers were then presented with these documents in order of increasing completeness. For each document, each interviewee was invited to state the extent to which they were satisfied, or whether they would need further information. An example of a response exhibiting

11 Décamp and Viennot, 'Radio-carbon dating'.

a critical attitude would be, 'How can there be a constant proportion of radiocarbon in the atmosphere? There is no radiocarbon decay in the atmosphere?'

The findings suggest two main intellectual dynamics in such a context. In the most frequent case of *delayed critique* (8/10), the participant offered no critique of a given text until they reached a certain threshold of conceptual comprehension, beyond mere logical necessity. This means that, even where the significance of some sentences was clear to them and might in principle raise a critical question, these participants did not react critically until they had deepened their comprehension of the topic. At that point, they proved capable of posing critical questions and rigorously reconsidered their previous critical passivity. Though less frequent (2/10), a second typical intellectual dynamics, *expert anaesthesia*, occurred in people who knew the given topic very well but offered no critical judgment of the given text, however incoherent or incomplete. *Delayed critique* links critical passivity to deficient conceptual mastery, as also observed in a study with student journalists (12/14) involving hot air balloons.[12] In contrast, *expert anaesthesia* suggests an opposite connection between conceptual comprehension and critical attitude, as in the case of the teaching rituals analysed above.

Early critiques: the case of osmosis

Another case serves to complete our description of advanced students' intellectual dynamics. *Early critique* designates an individual's expression of a critical view even when they know very little about the topic in question. Although observed in one participant in a study about survival blankets[13] this intellectual dynamics seems rare where the topic is unfamiliar to the participants.

Consider, for example, the topic of osmosis, which none of the five participants in that study mastered. When two compartments (e.g. of a U-tube), separated (e.g. at their bottom) by a semi-permeable membrane, are filled with equal volumes of two solutions with the same solvent and different concentrations of solute, the solvent passes from the less concentrated to the more concentrated solution. When equilibrium is reached, each compartment contains different levels

12 Mathé and Viennot.

13 Viennot and Décamp, 'Survival blanket'.

and concentrations of the solutions. In this complex topic, several conceptual nodes must be understood, including the following: what is equal on both sides of a semi-permeable membrane at osmotic equilibrium is a physical characteristic of the *solvent* (chemical potential); in particular, it is not solute concentration. Participants were presented with diagrams found in Wikipedia[14] or with statements from a textbook[15] suggesting that osmotic equilibrium is reached when solute concentration is identical in both compartments (then at different levels).

Two early (and highly relevant) critiques were observed. In the first of these, the disputed statement was compared to a situation of obvious equilibrium between two identical solutions, with the same level in both compartments:

> I would have conducted a similar experiment with the same levels … So, in order to convince people that it's not possible when starting from this situation, I would add some height to one of the compartments, saying that I have just disrupted the equilibrium, and that the system will necessarily evolve.

The second early critique was also very relevant, based on the simple idea that beginning with plain water in one compartment, it was impossible to reach zero concentration in the other compartment just by adding plain water:

> With zero solute concentration in the right-hand compartment, the water would pass endlessly from right to left.

Although these future teachers knew very little about osmosis, they were able to localize an inconsistency at a very early stage and to argue about it.

Critique: 'vertical' or 'horizontal' connections'

One might wonder why most of the participants in our investigations seemed so reluctant to express a firm critique in the case of unfamiliar topics, even where they had (in principle) sufficient knowledge to do

14 http://fr.wikipedia.org/wiki/Osmose; http://en.wikipedia.org/wiki/Osmosis.

15 A. Bouissy, M. Davier, and B. Gaty, *Physique pour les sciences de la vie*, 3 (Paris, 1987), 110.

so, and why few of them were more liberated. Beginning from a state of uncertainty and defective memories from school, a participant might be tempted to adopt a safer approach by seeking to deepen their knowledge of the topic in what we describe as a 'vertical' progression, resulting in 'delayed critique'. Alternatively, they might choose to remain at the level of basic knowledge, as when the situation of obvious mechanical equilibrium is used to reject the equilibrium view of osmosis proposed in Wikipedia, or when an elementary knowledge of concentration and dilution suffices to reach the same conclusion. In such cases, we speak of 'horizontal connections'.

The role of MCA factors

In this context, *MCA* factors may play a decisive role, as numerous expressions of dissatisfaction, doubt or unease were observed in the course of the interviews. Metacognitive comments are especially revealing when participants articulate the reasons for their difficulties or their reluctance to critique. Among these, a feeling of incompetence was often mentioned:

> As I have no particular competence in this domain, I am obliged to trust what I am taught …
>
> I was not necessarily at ease with these notions, and I find myself in a situation where I don't have an opinion of my own. So, if someone finally offers me one, it integrates easily with what I accept.

Habits were often invoked:

> I accept it because I always did so, but I never questioned the fact that …
>
> It was my only conception, and this actually shakes up conceptions.

It may well be that, in delayed critique, the search for deeper understanding of the physics content reflects feelings of incompetence and difficulty in achieving distance from one's habits. A finding from a recent investigation involving capillary ascension[16] supports this hypothesis. Seven of the 11 participants articulated a relevant critique of a teaching ritual (capillary 'forces' represented on a line of contact)[17]

16 Viennot and Décamp, 'Capillary ascension'.

17 See, for instance, S. Das, A. Marchand, B. Andreotti, and J.H. Snoeijer, 'Elastic deforma-

but subsequently withdrew it, as if they did not dare to advance a critical judgment of a current practice.

In the case of one participant who enthusiastically accepted a new model of capillary ascension, we also observed a variant of expert anaesthesia, which we called *substitution*:

Once you have introduced this story of pressure (against the wall) … it's ok [to be tolerant vis-à-vis the document at hand]!

This comment clearly expresses the idea that, where we have a valid explanation, we do not need to criticize others. It seems clear that, for this participant, the most important thing is not to critique but to understand, moving from a state of frustration ('It doesn't explain anything!') to a sense of intellectual satisfaction:

It made me think, thank you.
This engages us to go further.

In the light of these findings, we contend that *MCA* factors should be seen as decisive in the evolution of critical attitude in student teachers' formation.

Recapitulation and final remarks

This presentation considers the possible connections between the conceptual development of advanced students – in this case, student teachers – and their critical attitude in relation to various texts purporting to explain physics phenomena. In-depth interviews enabled us to characterize participants' main intellectual dynamics – that is, the interplay of conceptual and critical elements in their responses to more or less contestable texts. Several physics topics were explored in this way to check the robustness and contextual variability of our initial findings.

In this context, the most frequently observed intellectual dynamics was delayed critique – the need to reach a certain threshold of conceptual

tion due to tangential capillary forces', *Physics of Fluids*, 23 (2011), 072006.

comprehension beyond mere logical necessity before expressing a critique of a given text. It seems useful in this regard to speak of a 'vertical' process of searching to deepen one's comprehension before expressing and committing to any critical argument. The rare opposite cases of early critique suggest that those participants were able to establish 'horizontal' connections between the proposed explanation and what they already knew, so remaining at a non-specialist conceptual level. Their thought experiments revealed an efficiency in posing critical arguments, even if the subsequent stability of their critical attitude was unwarranted. Finally, in the further observed dynamics of *expert anaesthesia*, experts in a given topic revealed their inability to articulate any critique, even in the case of texts that were inconsistent or incomplete. Symptomatically, a case of *substitution* – the idea that the availability of a relevant explanation dispenses with the need to critique others – might offer a better understanding of expert anaesthesia.

Our findings illustrate how we might help future teachers (and students more generally) to reduce the duration and effects of their critical passivity when they struggle to master the domain in question. Our studies to date support the view that the process of formation should develop critical attitude *alongside* conceptual understanding, in line with Willingham's position: 'Critical thinking is not a set of skills that can be deployed at any time, in any context'.[18] This further highlights the need to actively assist students rather than waiting for complete comprehension to activate their critical potential. It seems likely that *MCA* factors play a crucial role in the activation or blocking of critical expression. More generally, our findings suggest that much more can be learned from students' responses to an educational setting if analysis of their comments is not confined exclusively to conceptual aspects but encompasses possible *interconnections* between conceptual and metacognitive-critical-affective awareness.

In conclusion, we reaffirm the importance of thoroughly documenting the conditions and processes that allow future teachers and younger students to make more 'connected' development of their conceptual and critical capabilities.

18 D.T. Willingham, 'Critical Thinking: Why Is It So Hard to Teach?', *Arts Education Policy Review*, 109 (4) (2008), 22; on this 'critical debate', see also R.H. Ennis, *The degree to which critical thinking is subject specific: Clarification and needed research* (New York, 1992), 21–37 and J. McPeck, *Critical thinking and education* (New York, 1981).

Laurence Viennot is Emeritus Professor at Denis Diderot University. After her research in astrophysics, she moved to didactics of physics in 1971. She has been a member of the national committee in charge of preparing new curricula in physics for secondary schools in France (1995–2000) and a member of the first executive board of the European Science Education Research Association. She founded and headed a masters' in Didactics of Scientific Disciplines. Her professional interest in the quality of the teaching learning process has led her into research on common ways of reasoning in physics, design and evaluation of sequences, and teachers' reaction to innovative interventions. This topic gave rise to the European project Science Teacher Training in an Information Society (STTIS 1997–2001). In 2008 she helped launch the MUSE project (More Understanding with Simple Experiments) under the auspices of the Physics Education Division of the European Physical Society.

A large part of Viennot's research is synthesized in two books, *Reasoning in Physics* (2001) and *Teaching Physics* (2003). The links between conceptual understanding, critical reasoning, and intellectual satisfaction are now her main topic of research. Her present work is an original combination of the exposure of confusing or false explanations common in much everyday physics teaching and an acute analysis of their origins and causes, together with practical tested proposals for doing better and real evidence that these can work to give students and their teachers genuine intellectual satisfaction from their study of physics. Her latest book, *Thinking in Physics The pleasure of Reasoning and Understanding* (2014), is widely inspired by this concern. Viennot was awarded the medal of International Commission of Physics Education (2003) and the GIREP medal (2016).