The transition towards critique: discussing capillary ascension with beginning teachers

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Abstract

This investigation focuses on possible links between the development of critical attitude and conceptual understanding among beginning teachers. In eleven in-depth interviews with pre-service teachers, we sought their opinions about the explanatory value of a number of texts on the topic of capillary ascension. The goal was to finely analyse each participant's transition from critical passivity to explicit critique. In processing the transcripts, we followed two lines of analysis, addressing conceptual understanding and critical attitude. Coding of the interviews centred on four main critiques of the texts. The prevalence of "*delayed critique*" - a long time interval of critical passivity or instability commonly observed for three of the four critical arguments considered *a priori* - aligns with previous results from studies on radiocarbon dating, survival blanket and osmosis. It also became clear that better comprehension of the phenomenon did not in itself mean that future teachers would critique an inappropriate diagram in current use. This finding suggests that when constructing a critical analysis, participants had difficulty relating a qualitative explanation of the phenomenon to how to model the situation, as confirmed by the triggering effect of a new diagram introduced by the interviewer. The paper concludes by discussing the implications for teachers' formation and for future research.

Introduction

Reading official reports about science education (e.g. [1]), advocacy for critical thinking as a priority objective in this field seems universal. However, a dilemma arises when attempting to balance the formation of this competence (among others) with conceptual comprehension—that is, how critical thinking relates to conceptual achievement. This is a long-discussed issue that has prompted countless studies. While some researchers have argued that 'critical thinking' competencies are cross-cutting and can be applied to many areas (for instance [2] to [5]), others (e.g. [6] to [9]) have highlighted the specificity of critical thinking criteria in each of these areas.

In operational terms, the possible links between critical thinking and comprehension in various conceptual domains lead to a central question: can we develop critical thinking in students without conceptual comprehension?

This study follows on from a number of others addressing this question [10] to [12]), based on individual interviews with future physics teachers at the end of their university studies (in fourth or fifth year at Paris-Diderot university). In all of these studies, we chose to focus on the entanglement of participants' conceptual development and their evolving critical attitude in respect of the given topic during individual interviews a propos of texts presenting incoherent or incomplete arguments. We consider it particularly appropriate to study future teachers in this context because teachers' preparation seems relevant to the promotion of critical thinking in science education.

Given that our line of research focuses on the possible links between conceptual and critical development, it seemed useful to situate our investigations in the context of various topics. The chosen topics were *radiocarbon dating* [10], *how a survival blanket works* [11], and *molecular interactions and osmosis* [12]. All were assumed to be at once non-obvious and partly accessible to the participants. In relation to critical attitude, then, our approach aligned with Gunstone's view of metacognition: "One aspect of content appropriate for the achievement of metacognitive purposes is that it is neither already understood nor totally unfamiliar" ([13], 1. 45).

Our first results converge ([12] [14]) to suggest that two main intellectual dynamics are likely to be observed in such a context. In the most frequent case - a *delayed critique* -, the participant offers no critique of a given text until they reach a certain threshold of conceptual comprehension, beyond mere logical necessity ([10] to [12]). This means that even if the significance of some sentences is clear to them and might in principle invite a critical question, participants do not react critically until they have deepened their comprehension of the topic. At that point, they prove capable of posing critical questions and thoroughly reconsidering their previous critical passivity. A second typical (though less frequent) intellectual dynamics, *expert anaesthesia* ([15] [10]) occurs in people who know the given topic very well but offer no critical judgment of a related text, however incoherent or incomplete it may be. While *delayed critique* links critical passivity to deficient conceptual mastery, *expert anaesthesia* suggests an opposite connection between conceptual comprehension and critical attitude. This may seem very surprising and, for the time being, we can only speculate on the reasons for this phenomenon. In particular, this can hardly be equated with what Renkl *et al.* call ‘inert knowledge’ [16] or with transfer difficulties observed in the context of problem solving, precisely because what is at stake here is not problem solving but the critical analysis of explanations constructed by others. Beyond the probable influence of teaching rituals, there might be a tendency to unconsciously supplement or correct inaccurate documents in the “experts” concerned ([15] [12]).

We also observed – much more rarely ([11], [12]) - cases of ‘*early critique*’, in other terms a very short delay before the activation of a critical attitude despite a very incomplete comprehension of the phenomenon at hand.

At this point, several research questions arise. First (RQ1), to what extent can these (still preliminary) results be confirmed in a new topic context? Second (RQ2), is the process by which critical attitude is triggered during interview limited in time and are these critical judgments stable over time once formulated? Finally (RQ3), to what extent can we identify *critical activators,* that is, conceptual elements introduced by the interviewer that trigger the participant’s critique?

For present purposes, the chosen topic is capillary ascension. Here, too, the content is *a priori* non-obvious while partly familiar to the interviewees (referred to here as *participants*), in this case, 11 beginning teachers. Nine held master degrees and were at the end of their university studies, and two had been in-service for a few months. After describing our rationale in more detail along with a content analysis of the topic, we describe the structure used to frame the interview. Finally, we consider the extent to which our findings address the research questions (RQ1, RQ2 and RQ3 above).

Rationale

From our epistemological standpoint - that science aims at a coherent and parsimonious description of the world (e.g. [17]) - the minimum requirement for critique is the ability to detect self-contradictory statements or statements that contradict basic laws of physics, and to recognize incomplete or meaningless explanations. Here, we envisage situations where documents can be contested on the basis of relatively simple arguments, given what may be expected of the population in question.

In relation to critical thinking, our focus is more restrictive than the very general definitions proposed by cognitive scientists (e.g. “the correct assessing of statements” [2] or “the appropriate use of reflective skepticism within the problem area under consideration” [4]). First of all, it should be noted that we focus here on critical analysis of *documents* and not on the implementation of critical thinking in experiments. The latter is the subject of numerous studies (e. g. [18] [19) and, to a greater or lesser extent, the whole research literature about inquiry based science education). From a critical perspective, text analysis has to date generated less interest among physics education researchers so far, although individual work on documents is encouraged in emerging learning environments [20]. Secondly, components of critical thinking not considered here include the ability to criticize the sources of texts in terms of power asymmetries [21] or those listed by Jiménez-Aleixandre and Puig [22].

Instead, we focus on “*critical attitude*”, as evidenced by interviewees’ comments about inaccurate documents and/or self-critique of their own previous responses during their search for comprehension and coherence. The term *critical passivity* designates an absence of such indicators, and the interval during which an interviewee moves from passivity to a firm critical attitude is termed *transition towards critique*. More speculatively, we posit that a critical attitude indicates the activation of *critical potential*— that is, the new attitude does not imply an overall change in the interviewee’s intellectual resources but reflects a pre-existing ability to formulate critical comments.
Among the factors that may influence activation or blockage of critical potential, we are especially interested in psycho-cognitive aspects, as the adoption of a critical attitude to a given explanation requires some awareness of one’s own state of comprehension, and some idea of what it is to learn science [23]. In that sense, we view critical attitude as a component of metacognition—that is, as an essential condition for active self-regulation of one’s own learning processes. In a more affective register, enacting a critical attitude evidences a search for “intellectual satisfaction” ([24] [25]) and some degree of frustration in this respect. The present inquiry therefore documents the extent to which the path proposed to interviewees fosters this intellectual satisfaction. We also take the view that questions that directly challenge an explanation imply an active search for meaning, beyond an attitude of mere doubt.

The decision to pose a question depends in part perhaps on psychological factors such as self-esteem. What Bandura [26] calls ‘self-reflectiveness about one’s capabilities, quality of functioning, and the meaning and purpose of one’s life pursuits’ is most probably a relevant factor in this regard. We see these metacognitive and affective components of students' critical attitude as *a priori* difficult to unravel (designated here by the compound label *metacognitive-critical-affective* or *MCA*), and we examine how these *MCA* factors may evolve in conjunction with conceptual comprehension and willingness to articulate critical comments. In so doing, our aim is to characterize students' *intellectual dynamics* during the interview as a *process* of conceptual and critical co-development. Table 1 recapitulates the meanings of some key expressions introduced above to formulate our research questions.

Table 1. Some key ideas informing the research questions

Conceptual comprehension (a level of)	A (level of) knowledge of concepts related to a given phenomenon or class of phenomena, including the meaning of related terms and links between concepts, all this being referred to a class of physical situations, and oriented by a search of a coherent and parsimonious description of the world.
Critical attitude/passivity	Attitude evidenced (/or not) by participant' comments about inaccurate documents and/or self-critique of their own previous responses during their search for comprehension and coherence.
Critical potential	A (hypothetic) pre-existing ability to formulate critical comments
Critical development	More frequent occurrence of a firm critical attitude in a given individual
Intellectual dynamics	The interplay (here: in the course of the interview) between critical attitude and the development of conceptual comprehension, including metacognition and affects (here: metacognitive-critical-affective aspects or *MCA*) such as the search for intellectual satisfaction, pleasure or frustration in this regard, views on learning, self-esteem, doubt and self-critique.
Delayed critique	When the participant offers no critique of a given text until they reach a certain threshold of conceptual comprehension (specific of the individual) beyond mere logical necessity
Early critique	When the participant quickly exhibits a critical attitude despite incomplete comprehension of the phenomenon at hand
Expert anaesthesia	When a participant knows the given topic very well but offers no critical judgment of a related text, however incoherent or incomplete it may be
Transition towards critique	When a participant moves from passivity to a firm critical attitude
Critical activators	Conceptual elements (here: introduced by the interviewer) that trigger the participant's critical attitude
Stability/instability of critique	Absence/presence in the participant's discourse of withdrawal(s) of a critical comment previously expressed

This demands fine-grained analyses of long interactive sessions (about 1h) with each participant. The interviews adopt the framework of "teaching experiments [27] which take the form of a discussion that is strongly structured and guided, and allows students to expose their initial thoughts and their reactions to various questions and requests. Consequently, we don't consider that such an interview *directly* provides the pattern for a possible sequence. In this regard, it is important to reiterate that the main goal of our investigation is to address the three research questions rather than to evaluate a particular teaching sequence. However, we would also expect this investigation to provide useful information for future research on the design and evaluation of teaching sequences addressing capillary ascension.

Capillary ascension: A content analysis

To begin, it is worth noting that existing explanations of capillary tension have long been criticised ([28] to [30]). Although it is well known that capillarity phenomena are a consequence of molecular interactions, it is difficult to accept that there is a tensile tangential stress in the surface of a liquid on the sole basis of dominant *inward* attractive interactions, as currently suggested. For the purposes of this interview, we did no more than pinpoint this difficulty (signalling that an explanation such as Berry's [28] was available), recalling the definition of a tensile force (or the equivalent "surface tension"). For instance, imagining a line drawn on the free surface of a liquid in the presence of vapour, the γ_{LV} coefficient (of liquid-vapour surface tension) expresses the mutual attractive forces between the portions of liquid situated at each side of this line by unit length, close to the surface, at a thickness of a few molecular diameters.

To calculate the angle of contact between a solid and a liquid in the presence of a gas, current academic texts use a diagram such as Figure 1, where three interfacial coefficients (or tensile forces by unit length, or else "surface tensions") are represented as if "acting" on the line of contact between solid, liquid and gas (Figure 1). Balancing the vertical components leads to the correct expression of the angle of contact. However, apart from the unbalanced horizontal "forces", it may be remarked that a free-body diagram of an immaterial line is meaningless; in saying that the forces in play are acting on the water molecules near the surface, it might be asked why they would not also be acting on the molecules of gas or glass.

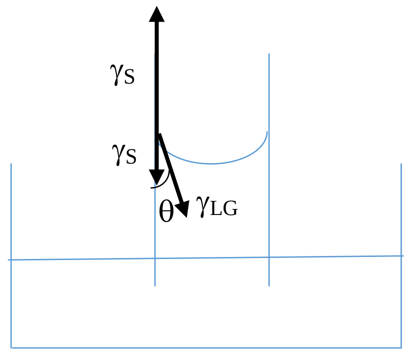

Figure1. The well-known diagram introducing Young's formula $\gamma_{LG} \cos\theta = \gamma_{SG} - \gamma_{SL}$, where γ_{LG}, γ_{SG} and γ_{SL} are surface tensions (forces by unit length), corresponding respectively to liquid/gas, solid/gas and solid/liquid interfaces, and where θ is the angle of contact.

Das *et al.* [31] and Marchand *et al.* [32] (see also [28] to [30]) critiqued the diagram on that basis. Instead, they proposed explanations based on forces acting on well-specified objects. In particular, they stressed that a (locally) plane and homogeneous wall of glass attracts molecules perpendicular to the interface, that is, horizontally rather than vertically. In cases of partial or total wetting, this effect is of same order of magnitude as molecular interactions inside the liquid and tends to press this liquid onto the wall. The overall outcome is an accumulation of molecules, squeezed against the wall. In a thin layer near the wall, the density of the liquid is greater than in the bulk of the liquid; this compressed area near the wall accounts for the upward force on the liquid. Given that such a force is not exerted by the wall (where it is locally plane and homogeneous), another element external to the liquid must be found. A repulsive interaction with the horizontal bottom of the recipient may fulfil this role, but it is also noteworthy that the symmetry requiring the attraction of the liquid by the solid to be normal to a locally plane wall ceases to hold at the lower rim of this wall. In any case, this effect cannot be properly analysed without taking account of the system as a whole beyond the forces intervening at the upper surface of the liquid.

Based on these analyses, we designed a *dislocated diagram* that separately represents several objects in actual contact: a thin ring of water, near the wedge-shaped edge of the meniscus; the rest of the water in the column; and the vertical walls of the tube (Figure 2). The interest of such a diagram is the absence of ambiguity about which forces are acting on what material "system" while enabling confirmation that Newton's second and third laws are not violated.

As is well known, partial wetting can also be interpreted in terms of potential (free) energy. The molecules squeezed against the wall lose some potential energy, linked to the wall's attraction. In so doing, they gain some forms and lose other forms of potential (free) energies linked to other interactions. Equilibrium is reached when the rates of change of potential energy during displacement of the meniscus balance—in other words, when total potential free energy is minimal for a given change. Concerning the value of θ, the three surface tensions are involved (independent of the gravitational aspect). However, for the height of the water column, the energy budget should comprise the gravitational energy and surface free energies of the liquid/solid and solid/gas interfaces only at the given θ, with no change in liquid/gas surface free energy.

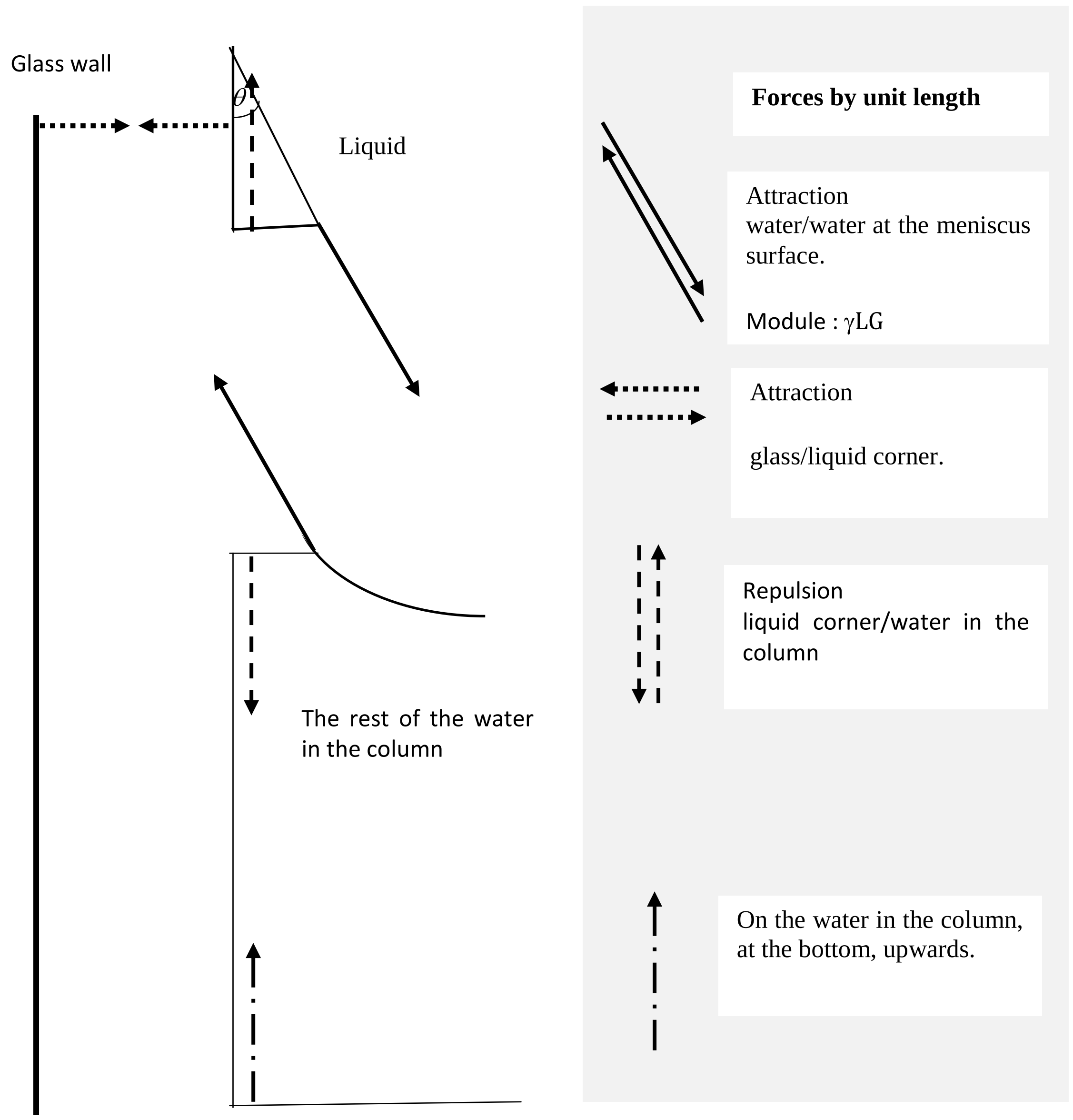

Figure 2. *Dislocated diagram* of capillary ascension, in which several objects, defined by a unit length of the contact line and actually in contact, are represented separately (see text). The only complete free-body diagram (by unit length of the line of contact) is on the liquid corner. The weight of the liquid corner is negligible with respect to the other forces, and the weight of the liquid column, **P,** is not represented (for a column of height h, $\mathbf{P}=\rho_{eau}\pi r^2_{tube}h\ g= \gamma LG\ \cos\theta\,.2\pi r_{tube}$). The role of gas pressure (here, atmospheric pressure) is not represented; it generates a normal force exerted on each external surface (even immersed) of the various objects in play (liquid corner, liquid column, glass wall, …) whose total contribution to the Newtonian balances is zero [27].

The difficulty described above arises from the fact that this energy-based analysis is commonly "told" as if some forces (why three, why two?) were acting upward locally at the place where an upward motion is most visible—that is, at the line of contact between solid, liquid and gas. That said, the interviewer's target is not to teach these conceptual elements but to assess the extent to which participants detect (or fail to detect) what is contestable in the documents as presented.

The interviews

The interviewees were eleven beginning teachers: nine at the very end of their pre-service formation and two with only a few months of in-service practice.

In line with the teaching experiment method [27], we used the *concept-driven interactive pathway* format (CDIP: [33], p.3): "This takes the form of a series of events—input from interviewer, reactions from the student, possible experiments, questions and requests, discussions—orientated towards conceptual acquisition". The CDIP is progressive, in that what is understood at one step serves to construct the next stage of knowledge. It also offers opportunities for students to critique presented explanations. Within this framework, previous knowledge can be reorganized and extended during the interview.

Here, the general structure of the interview is a series of discussions about documents describing liquids, tensile forces and capillary ascension. Although in current use, these documents comprise elements that have been critiqued in the cited research papers ([28] to [32]). In each case, the opening questions were as follows. *Do you consider this explanation appropriate and useful for yourself? For your students? If yes, which elements justify your positive judgment? If no, what would you add or change? Why?* In conducting the discussion, the interviewer kept in mind four critical arguments (detailed in the next section) and sought to evaluate the participant's position in relation to these. Each time the participant failed to express any critique of a given document, the interviewer progressively introduced conceptual arguments and tools that might be expected to foster such a critical attitude. Following a brief outline of the interview phases, these critical arguments and conceptual inputs are described below.

Phases of the interview

Prologue phase

After a short exchange about gas and liquids as described in secondary school books, each interview continued with a discussion about current explanations of the origin of tensile forces at the interface between liquid and gas, based on attractive molecular interactions in liquids. Whatever their response, the participant was led to recognize the inadequacy of this argument for understanding the origin of surface tension. Presenting the analysis by authors like Berry ([28] or Brown [29] offered an opportunity to remind the interviewee about what is meant by *tensile force by unit length* or *surface tension*. To this end, the interviewer recalled the two factors intervening in pressure (p) in liquids: the "kinetic" term (p_{kin} = ckT) linked to molecular volume concentration (c) and absolute temperature (T, k being the Boltzmann constant); and the "interactive" term (p_{int}) linked to molecular interactions. This phase was purposefully limited in time to less than 10 minutes. The prologue phase was conducted in a mainly authoritative style, mentioning the possibility of returning to it at any point in the interview if so required. Given this authoritative style, we consider this phase *a priori* poorly indicative of interviewees' personal dynamics, for which reason their comments during this phase will not be analysed here.

Core phase: Critiquing the "Young" and "Capillary ascension" documents

Participants were then asked to comment in succession on two documents currently used in teaching or found online (e.g. Wikipedia: 'angle of contact formula'). The first of these ("*Young*") is shown in Figure 1. The second ("*Capillary ascension*") is shown in Figure 3. It combines a diagram commonly used in teaching and a sentence extracted from a popular science book [34], which also reflects a current argument.

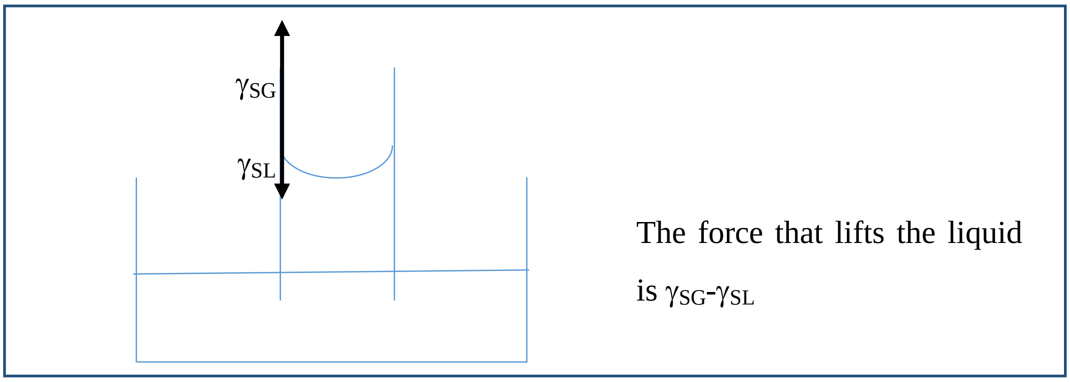

Figure 3. *Capillary ascension* document (for notations, see Figure 1).

In each case, the interviewer's style was very neutral at first, becoming increasingly focused on a particular point—that is, one of the critical arguments presented in the next section. These two documents were discussed for varying lengths of times, with possible to-and fro between these, depending on the participant's responses and interests.

Final phase

During the final phase of the interview, participants were invited to articulate the interest and possible benefits of the discussion as a whole. Students were invited to express their views about what they have learned, their intellectual pathway during the interview and their level of intellectual satisfaction.

Four critical arguments

The discussion was conducted with particular attention to four critical arguments. We consider these to be relevant in the search for coherence, and we believe that they might be expressed without thorough comprehension of the topic.

C1—Young document (Figure 1): Were the arrows intended to represent forces (by unit length of the contact line), and the diagram seen as a free-body diagram, this would not be balanced in the horizontal direction.

C2—Young (Figure 1) and *Capillary ascension* (Figure 3): Were the arrows intended to represent forces (by unit length of the contact line), these forces would be acting on a immaterial line, which does not allow use of Newton's second law.

C3— C2—Young (Figure 1) and *Capillary ascension* (Figure 3): It is not possible to understand on this basis why the column of water remains above the level of water in the recipient.

C4—Capillary ascension (Figure 3): The idea of a force vertically pulling the liquid upwards from above (glass-liquid attraction prominent) is incompatible with the fact that a vertical, plane, smooth glass wall can attract water only along the horizontal ([35] [36]).

Principal conceptual resources introduced by the interviewer

With these concerns in mind, the interviewer adapted to participant responses and demands by introducing certain conceptual resources. As well as being careful to satisfy any query about the nature of the "tensile forces" or "surface tensions", she discussed (on request) how these concepts link to a free energy approach. Additionally, there were three other main inputs.

- Concerning the attraction of water molecules by glass molecules, the interviewer pointed to the fact that, in the case of a vertical wall of glass that was perfectly smooth and plane (or cylindrical with vertical generatrix), the resultant attractive force would be horizontal for reasons of symmetry (code: *HORI*). Understanding this point constitutes the conceptual target of this input (**hori**).
- Concerning *C2* and *C3*, an analysis using dislocated diagrams (Figure 2) was presented to facilitate activation of these critiques while resolving the difficulty concerning the weight of the suspended column(code: *DDIA*). The main conceptual target (**ddia**) is that, in order to lend themselves to meaningful use of the second law, the forces in a free body diagram should relate to a clearly identified material body.
- Concerning *C4*, an analogy(code: *ANA*) was proposed, based on the scenario of a centrifuge partly filled with liquid water [35]. In the case of stationary rotation, the profile of the free surface is a paraboloid of revolution (Figure 4). A horizontal centrifugal force can be seen as analogous to attraction by the glass wall, piling up water molecules along this wall. As the level of water near the wall is higher than at rest, as is the centre of mass of the liquid, a force larger than the weight of the water has necessarily been exerted on the water during the acceleration phase, and this force has been exerted by the bottom of the recipient. In a stationary regime, the pressure at the bottom of the recipient is larger near the wall than near the axis of rotation.

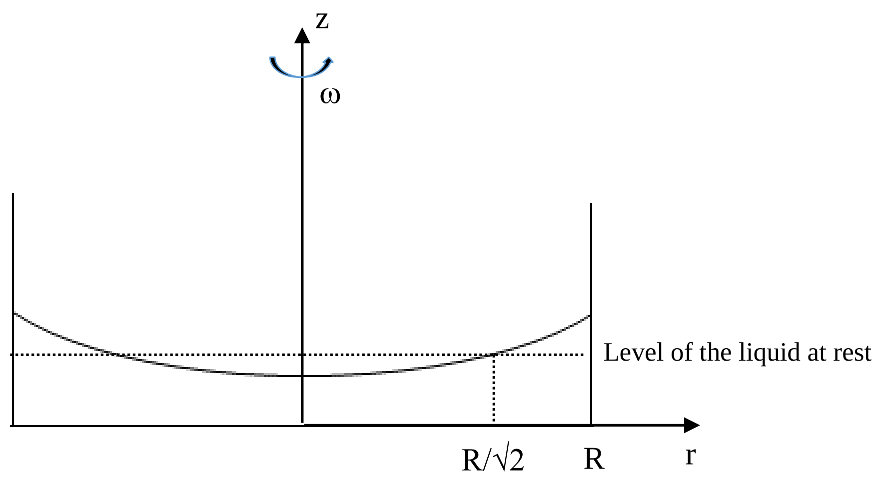

Figure 4. Rotating centrifuge filled with liquid (angular velocity ω): level of liquid in the absence of a lid in stationary regime ([35], [36]).

This analogy is of course incomplete, especially in terms of the dimensional scale of the phenomenon of interest. Nevertheless, it draws attention to the need to consider the *whole* system in order to understand a situation that is at first sight paradoxical: a horizontal force that seemingly has a vertical effect. The conceptual targets of this analogy are to realise that a fluid may rise up a vertical wall without being pulled from above (**ana**), and that – by considering the whole fluid - it can be understood how a force exerted on it from below can produce the observed effect (**push**).

When the interviewer decided to introduce this analogy into the discussion, she would start by asking the participant whether they could suggest an analogous situation in which there would be a "hole" or "depletion" in the free surface of the water.

Because of the topic's complexity and unforeseen events in the discussion, no attempt was made to program the timing of these main inputs, which arose in various orders, depending on the participant.

Processing the interviews

In processing the interviews, a first level of analysis was devoted to reducing the rich and complex information contained in each transcript—about five hundred exchange turns—into a still relatively detailed account of the discussion's progress. At a second level, we aimed at a more synthetic account by focusing on two aspects: the emergence (or not) of a critical attitude in the interviewees regarding the four critical arguments, and the stability of a participant's critical position once expressed.

First level of analysis

The audio records were transcribed and each exchange turn was referenced with a letter in bold (indicating the participant) and an arabic numeral subscript (exchange turn number in the interview, like in $\mathbf{A}_{256}$). We chose to focus on the most interactive part of the interview—that is, on the second and final phases. The interview transcripts were submitted to thematic content analysis, in which each category was defined by a theme identifiable in the students' comments. Guided by the research questions, we defined the thematic categories *a priori*. These concerned the particular critical argument (*C1* to *C4*) and four types of critical attitude related to a given critical argument (Table 2). *Attitudes regarding critical arguments C1 to C4*

We defined four types of comment for each of the four critical arguments identified above, as shown in Table 2. χ and α designate two opposite attitudes with regard to the diagrams or text in play. Thus, χ denotes a statement or question in line with one the critical arguments *C1* to *C4*, whereas α designates a comment explicitly negating this critical argument, for instance accepting a diagram with forces acting on an immaterial line, contrary to *C2*. We code μ cases of mitigated critique or agreement with respect to the diagrams or text under discussion, and $d\chi$ statements expressing a complete doubt about which attitude to adopt in terms of critique. We defined the subset of exchange turns (or small groups of exchange turns) comprising all of those concerning a participant's critical attitude, i.e. finally coded χ, α, μ or $d\chi$, this in five interviews. On the basis of this subset, coded independently by each of the two authors, we made a reliability test. We obtained a kappa-Cohen coefficient of 0.68 which means a substantial strength of agreement [37].

Based on previous investigations ([9], [10], [11]), we also pinpointed what we felt might be linked to an activation of critical attitude - that is, "questions of meaning" and conceptual "steps forward" as explained in the following.

Questions of meaning and conceptual steps forward

It was a priori important to pinpoint questions about the meanings of concepts in a given text, for two reasons. First, to criticise a text, it seems essential to understand what it is about. Even if the interviews were designed on the assumption that the terms of the text would be understood by the participants, this might not be the case. For a participant, then, asking a question about the problematic term would be a precondition for critique. The second point of interest is that asking a question indicates a proactive attitude: This has often been observed to precede a critical comment, even in relation to points that could be criticised aside from the meaning in question. Here, we focus on questions (coded γ) expressing a lack of understanding in relation to the coefficients of surface tension.

We also identified four conceptual steps forward that we considered potentially decisive for the rest of the discussion (Table 2). These constitute the targets of the interviewer's conceptual inputs detailed above.

Metacognitive-critical-affective (MCA) aspects

As noted above, participants' questions about meanings (γ) might be seen to indicate not only conceptual progress but also *MCA* factors. Additionally, we pinpointed clear expressions of satisfaction (***m***$^+$), dissatisfaction (***m***$^-$), surprise (***!***) and doubt (***d***). It is worth noting that many attenuated expressions of a critique might also be coded as an expression of doubt or dissatisfaction (*e.g. Maybe [I'm] a little worried.* μ_2), but we decided to avoid excessively redundant coding in such cases.

We also use the label ***meta*** for metacognitive comments that are explicit and irreducible to the *MCA* codes as defined.

> V220- (…). I have the impression that, when we try to simplify, we completely lose the meaning of what we want to explain. ***meta***

For the sake of brevity, more details concerning relevant indicators in this respect will appear in the 'Main results' section.

We used these codes to summarise each participant's intellectual dynamics (see *Two contrasting examples* in the Appendix). We also pinpointed exchange turns where a change of code occurred. In this way, we can follow the "life" of each critical argument along each participant's intellectual pathway.

Second phase: A synthetic account

We then used these individual results to extract issues related to each participant's critical attitude regarding arguments *C1* to *C4*. For each participant and each critical argument, Table 3 synthesizes the "final" opinion (that is, not subsequently contradicted) and the associated turn exchange.

To assess the possible instability of a participant's critical attitude prior to this "final" position concerning a given critical argument, we also note in Table 3 what we call *critical withdrawals*—that is, when a participant moves from a firm critique (χ) to a clear acceptance (α), from a firm to a soft critique or doubt (χ to μ or ***d***χ), or from a soft critique or doubt to a clear acceptance (μ or ***d***χ to α) of what was critiqued before.

Table 3. Participants' "final" critical comments (col. a, codes in the text) and critical "withdrawals" (col. b, underlined when from a firm critique toward firm acceptance).

	C1		C2		C3		C4	
	a	**b**	**a**	**b**	**a**	**b**	**a**	**b**

A	-		χ_{256}		χ_{288}		χ_{359}	
J	χ_{58}		χ_{124}	92	χ_{136}		χ_{232}	
Z	χ_{458}	454	χ_{454}	82, 160, 302	χ_{120}		χ_{294}	284
T	χ_{124}		χ_{482}	362, 374	χ_{348}	222	χ_{240}	
W	χ_{110}		χ_{350}	38, 86	χ_{166}	160	χ_{254}	
N	χ_{114}		μ_{422}		χ_{208}		χ_{370}	294
M	χ_{186}		μ_{464}		α_{438}	438	χ_{458}	452
D	χ_{56}		χ_{410}	288	μ_{144}	144	$d\chi_{176}$	
F	χ_{308}		μ_{428}	212, 428	χ_{196}		χ_{420}	284
V	α_{451}		χ_{474}	160	μ_{220}		μ_{390}	304, 312, 390
C	α_{80}		μ_{420}		α_{272}		χ_{520}	206

Main results

This section brings together those results that seem most instructive and their analysis, within the limits of our research questions. We comment first on the types of critique observed and their dependence on a particular critical argument (*C1*, *C2*, *C3* or *C4*). Then, in light of crucial questions and steps forward, we comment on the role of conceptual aspects in participants' intellectual dynamics. Finally, results related to *MCA* aspects are summarized.

Many delayed or soft critiques

As shown in Table 3, the dominant dynamics was delayed and/or soft critique, including its extreme version: persistent absence of critique. More precisely, at the end of the interviews, only five participants had finally expressed (usually very late) a firm critique of the four arguments.

Still more striking are the multiple attenuated formulations, particularly in relation to *C2* and *C4*. These attenuated critiques were an important component of the multiple to-and-fro observed in most participants. Table 3 shows cases (and exchange turns) of what we call *critical withdrawals*. These are concentrated on *C2*, *C3* and *C4*, with *C1* giving rise to only two withdrawals. While these withdrawals and attenuations relate mainly to four participants, 10 of the 11 interviewees fell into this category for at least one of the critical arguments. Only one adhered firmly to all critical positions once expressed.

Different intellectual dynamics according to the critical argument

As already noted, our findings indicate some variability across participants. However, we also observed that a given interviewee might express an early critique for a given critical argument and a long delayed critique for another. This was the case for three participants.

Questions and steps forward

We observed that questions about the meaning of 'surface tensions' or 'γ coefficients' were not as frequent as might have been expected (only four participants posed, in all, 10 questions of that type). All of the participants had learned about this topic during their university studies, and the interviewer had recalled these meanings at the beginning of the interview. The diagrams at hand might have raised questions about why the 'forces' in play were represented on a line, but such questions were surprisingly rare. It is worth noting that they were posed mainly by the two participants who expressed the greatest number of firm critiques without withdrawal.

In contrast, participants took the conceptual steps targeted by the interviewer's inputs with apparent ease, but the outcomes of these conceptual steps in terms of critical attitude were less straightforward.

In relation to the attractive force exerted by the glass on water molecules, it sufficed that the interviewer asked about the possible action of a smooth vertical plane on a molecule; all but one of the participants concluded that it was horizontal. However, the idea that a force would pull the liquid upwards was then quickly rejected by only three participants; six others reached a clear critical position much later, most often after having adopted a mitigated position in between. In brief, while the idea of horizontal attraction of water molecules by the glass wall was easily understood if not spontaneously arrived at, this does not mean that a firm critique of the phrase "the force that lifts the liquid" was quickly expressed or persisted over time.

Similarly, the centrifuge analogy was easily accepted if not arrived at upon solicitation (eight participants in all). All recognised its explanatory power. For six participants, this analogy paved the way for the idea that water molecules would pile up against the wall and would be compressed (as compared to a static situation) while the bottom of the recipient would exert a supplementary vertical force on the liquid. The others took this conceptual step by themselves - without the analogy. Briefly put, the explanation of capillary ascension focusing on the strong attraction of water by the glass was easily understood by most participants (either directly or by analogy), and it triggered some relevant critiques of the idea of forces that would pull the liquid upward. Nevertheless, understanding the phenomenon was not sufficient to prompt stable critiques of the diagrams in question. In this regard, numerous withdrawals or attenuations followed these steps forward and subsequent relevant critiques (Table 3).

In contrast to the poor triggering power of good comprehension of the phenomenon, the dislocated diagrams (Figure 2) proved relatively efficient in provoking both steps forward and firm critiques. For instance, in relation to *C2*, it was the comprehension of the dislocated diagram that finally triggered a clear critique for six participants:

> **C**$_{498}$—OK, this time, there can be no further mistake. … after that, now, it (*diagram in Figure 3*) worries me completely. (χ_2)

But even this success must be considered as relative. For instance, one of these participants (**F**) first employed a soft formulation ("(*this phrase is*) not very appropriate"), and later on, he again used an attenuated expression. Four participants were particularly resistant to the interviewer's prompts to critique. For instance, although one of them seemed to have benefited from the dislocated diagrams, he was still, long after, very reticent to express a firm critique:

> **T**$_{452}$—Yes yes, I like this (*dislocated diagrams*)… err, I can't manage to go beyond what I said before; it's still the problem of the point where forces apply. It worries me, but I can't manage to go further. μ_2

Finally, one participant who had understood that "what is observed at the surface is due to what happens at the bottom" relied on this to exempt the *Capillary Ascension* document from any need to provide a coherent explanation:

> **M**438—Once you have introduced this story of pressure (*against the wall),* it's OK. α_3

Metacognitive-critical affective (MCA) comments

The interviewees' *MCA* comments usefully complete these findings. Numerous expressions of dissatisfaction, doubt or unease were observed in the course of discussions. These were entangled with statements expressing various levels of critique, as illustrated above.

Metacognitive comments are especially useful when participants express the reasons for their difficulties or reluctance to critique. Among these, feelings of incompetence and of difficulty were mentioned:

> **D**$_{304}$—As I have no particular competence in this domain, I am obliged to trust what I am taught *(24 turns).* I have no clear cut position because I am not competent in this… err, I think I am not competent enough.
>
> **Z**$_{296}$ - It's difficult, it's very difficult.

Teaching habits were willingly invoked:

> V$_{430}$—I take it because I always did so, but I never called into question the fact that it was legitimate to apply, err, forces on an immaterial line.

More precisely, the use of forces acting on points—whether "contact points" or "point masses"—was also called on to justify the idea of three forces acting on a line:

> **M**$_{426}$—(*Concerning forces acting on an interfacial line*)—Free-body diagrams on points—we are used to that since grade 11.

A participant also said that forces acting on a line poses a problem because "there is no defined system with constant mass". However, "as that leads to the correct relationship", he was not concerned.

In contrast, explicit judgments about previous teaching were ultimately observed:

> **A**$_{426}$—Yes actually, yes, because it's not relevant, because in fact they make free-body diagrams that have no meaning at all; it may be convenient, but it is totally meaningless, this kind of thing.

When asked about their global impression of the interview, all participants expressed strong satisfaction, often linked to a feeling of novelty.

> **W**$_{318}$—Before, I was a long way from asking myself questions about this phenomenon. (**!**)

This focused in particular on the positive role of the dislocated diagram.

> **D**$_{428}$—Yes, that analogy helped me a little at the time, but with this diagram, I would have understood, even without the centrifuge analogy.

Recapitulation and discussion

Our general approach was to analyse the co-development of conceptual understanding and critical attitude in beginning teachers, focusing on their *intellectual dynamics* and in particular on phases of *transition towards critique*. To sum up, this investigation both corroborates our previous findings and provides some new details. Our samples are small, however, by accounting systematically for the numbers of participants whose responses exhibited a given characteristic, we have been able to observe some convergences in our findings across topics that reinforce their indicative value.

In relation to intellectual dynamics (RQ1), the dominant feature here is *delayed critique*, as was the case in previous investigations. Here, too, psycho-cognitive factors such as feelings of incompetence seem to hinder participants' critical expression. Although rare, *early critiques* indicate that at least some participants can access this pathway. As expected (given the difficulty of the topic), we observed no *expert anaesthesia, stricto sensu* - that is, good previous knowledge of the topic accompanied by total critical passivity.

Given that an interviewee may exhibit different intellectual dynamics, depending on the critical argument in play, we would not label any participant in terms of a single dynamics. This is not surprising if we recall, as in the Introduction, that activation of a critical attitude may be linked to a participant's current level of conceptual mastery in respect of each argument considered. For instance, it may be easier to detect an unbalanced free-body diagram (*C1*) than to analyse the status of arrows situated on a line of contact (*C2*). This should not, however, exclude the possibility that some individuals are globally more inclined to express firm critiques, and to maintain these over time, however poor their comprehension of the domain.

Regarding RQ1, then, our findings align with our previous analyses of other topics, as recalled in the Introduction. However, these results reflect the increased complexity of the present investigation, in that each participant might advert to several possible critical arguments. That said, our research goal was to go beyond this to examine more closely interviewees' *transitions towards critique*—that is, the conditions under which a participant might move from critical passivity to firm critique in respect of a given text. Our previous investigations suggested that a necessary condition for an interviewee to activate their critical potential was that they reach a threshold of comprehension of the given topic. Triggering of such critical moments is typically preceded by comments expressing intellectual frustration, questions and self-critique, until a participant clearly accepts the need to formulate a critical judgment. Two aspects of this *transition towards critique* are documented more specifically here: the clarity and stability of critical judgments (RQ2) and the likely *critical activators* (determinants of a decisive change) (RQ3).

With regard to clarity and stability (RQ2), one very striking feature is the difficulty experienced by almost all participants in expressing firm critiques (with the exception of *C1*). In the cases of *C2, C3* and *C4*, even when a first critical comment had been clearly formulated, multiple withdrawals were observed—from critique to acceptance or, more frequently, to attenuated comments. This occurred in spite of the interviewer's increasing insistence, sometimes resulting in remarkable episodes of intellectual resistance to critique. These findings prompted us to consider that the development of critical attitude among these participants might not be precisely localized in time. In terms of stability, the most frequent pattern was multiple to-and-fro.

The participants' *MCA* comments illuminate the reasons for this hesitation and lack of clarity, with repeated mention of feelings of incompetence, efforts to remember what they "should know" and their obedience to what they "had learned". One interviewee alluded to this previous knowledge as her "only conception". The teaching practice of drawing forces on contact points was said to play an important role in this regard, probably reinforced by current courses in mechanics based on the idea of "point masses". More specifically, these contestable diagrams have acquired the status of *teaching rituals*—that is, they have been in widespread use for a long time and without precise justification (although leading to a correct relationship) [15]. While contesting these rituals requires a not insignificant effort, rare cases of *early critique* show that this is possible without advanced comprehension of the topic.

Turning now to potential *critical activators* (RQ3), we observed that, contrary to expectation, several of the conceptual *steps forward* identified above did not efficiently perform this role. More precisely, after taking some *steps forward*, most of the participants were soon able to analyse the phenomenon using words not far removed from common language ("horizontal attraction", "molecules piling up", "increased pressure"). However, this level of comprehension proved insufficient to trigger firm or stable critiques of the documents presented. In many cases, following a *step forward*, a long path remained to be travelled before the participant declared, for instance, "This diagram is meaningless". In particular, the centrifuge analogy proved to be of limited use. While it certainly helped some participants to make sense of the situation and the mechanism in play, this was not enough to prompt an immediate and decisive change in their critical judgment. Participants seemed to have difficulty in linking an analysis based on relatively familiar entities to more formal modelling resources (i.e. free-body diagrams). In this regard, it is noteworthy that questions about the meaning of the "forces" in play were posed mainly by those participants who reached a firm critical position for critical arguments C_1 to C_4.

In respect of this defective link between a first level of explanation and formal modelling, it is also striking how one participant commented his new comprehension of the phenomenon: *Once you have introduced this story of pressure* (*against the wall) … it's OK!* (to be tolerant vis-à-vis the *Capillary ascension* document). Understanding the phenomenon within a new line of reasoning seemed to legitimate an inaccurate diagram - or at least dispensed with any requirement that it provide a consistent explanation - indicating a process of *substitution*. For the other participants, the interviewer's introduction of a dislocated diagram proved relatively efficient in triggering a firm critical position. By highlighting the system on which the forces at stake were acting, this diagram offered participants a means of linking their first analysis of the phenomenon to a more formal one, and most saw this as a convincing reason to change their mind, and to express a firm critique.

To sum up, the present investigation leads us to refine our previous conclusions. Here, in relation to a threshold of comprehension, we had to distinguish between two levels of comprehension: analysis of a phenomenon by reference to relatively familiar entities (*level of comprehension 1*) and more formal modelling (*level of comprehension 2*). It seems that, to activate their critical potential, most of the interviewees had to progress on both levels. This position is based on our observations rather than logical necessity; for instance, participants might simply have said that a free-body diagram on an immaterial line was meaningless (as one of them commented without any comprehension of the phenomenon). The rarity of such *early critiques* and the prolonged reluctance to critique the diagrams suggests that most participants *de facto* needed to proceed on both levels of comprehension (i.e. physical analysis based on relatively familiar entities *and* more formal modelling) before clearly expressing a critique.

Final remarks

It is perhaps unsurprising that it proved useful in the present context to draw a tentative distinction between levels of comprehension: analysis of a phenomenon by reference to relatively familiar entities (*level 1*) and more formal modelling (*level 2*). In this regard, Fazio *et al.* [38] referred to "the quality of mental models" deployed in creating explanations, distinguishing between "practical or everyday", "descriptive" and "explicative" categories of reasoning (p. 020101-2). Given their definition of an explicative model as "introducing theoretical representations and often containing non-observable quantities" (ibid.), the two levels identified here may both refer to such a model. For present purposes, however, it has been useful to differentiate between them.

These remarks lead us to reflect again on the type of investigation reported here. Commenting on links between the cognitive and the affective, Duit and Treagust ([39], 679) wrote: "There is ample of evidence in research on learning and instruction that cognitive and affective issues are closely linked. However, the number of studies on the interaction of cognitive and affective factors is limited. There are, for instance, many studies on the relations between interests and acquisition of science concepts. However, these studies are usually restricted to correlations between interests and cognitive results of learning”. In the present case, our nuanced findings provide ample support for the view that correlation studies cannot adequately capture the processes in play here. Beyond the complexity of analysing any links between critical attitude and conceptual development, while paying attention to factors such as self-efficacy, the need to distinguish different levels of understanding further accentuates the need for fine-grained analysis. This aligns with the view of von Aufschnaiter, Erduran and Osborne [40]: “A direct link between performance of argumentation and science knowledge is not supported by the data. Descriptions (categories) relating argumentation to science understanding might result in a more precise assumption about students’ knowledge”. We believe that this “more precise assumption about students’ knowledge’ was prerequisite for consistent interpretation of our results.

As said above, this investigation was not designed to evaluate a teaching environment. However, we think that it opens some routes worth exploring concerning students’ education and teacher preparation in physics.

We take the view that conceptual mastery of a scientific topic entails two components: the conceptual and the critical. In this regard, being able to solve classical exercises is a poor achievement if the same person cannot detect an inconsistent explanation and refute a related contestable argument. We contend that our investigation provides several tools that can be used in this way with university-level students. On that basis, a content analysis of capillary ascension is presented and advocated in relation to the main possible critiques of the most current presentations of this topic. For instance, the centrifuge analogy is proposed to facilitate acceptance of an apparent paradox - the horizontal attraction of water by a glass wall, resulting in the vertical motion of this water - and to prompt contestation of sentences like ‘the glass is pulling the water vertically’. Similarly, the introduction of a dislocated diagram responds to the meaningless view of forces acting on an immaterial line. By staging the presentation of content in this way, we suggest that students’ attention is focused on their responsibility for accepting or rejecting the presented explanations, fostering their sense of self confidence.

Our findings also illuminate certain requirements for teacher education. As in our previous investigations, the present study indicates that the process of scientific education should develop critical attitude *alongside* conceptual understanding. But they also highlight the need to assist students to activate their critical potential without waiting for complete comprehension. It seems likely that *MCA* factors play a crucial role in the activation or blocking of critical expression. This may well be a culture-dependent phenomenon, and the issue warrants further investigation, particularly in light of its implications for teacher preparation. In conclusion, we reaffirm the importance of thoroughly documenting the conditions and processes that will afford future teachers and younger students more integrated development of their conceptual and critical capabilities.

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Appendix: Coding the interviews: Two contrasting examples

In the tables used to map interviewees' intellectual pathways (see codes in Table 2), the chronological order of events can be traced both in terms of the numbers of exchanges and by means of left to right and top-down readings. The "life" of a participant's view in relation to each critical argument (*C1* to *C4*) can be traced in the corresponding column, top-down. In relation to conceptual steps forward, one can observe how they follow (or fail to follow) the interviewer's inputs targeting each of them. Two examples follow (Tables 4 and 5).

Table 4. Mapping **A**'s intellectual pathway

Int.'s main inputs	Quest.	Steps forward	*MCA* comments	C1	C2	C3	C4
	γ 148			-	χ 256	χ 288	
	γ 314				χ 346		
HORI 354		**hori** 359					χ 359
	γ 372		***meta*** 380				
	γ 390						
ANA 397		**ana** 406	***m+*** 412				
		push 430	***m+*** 430				
DDIA 463		**ddia** 466	***m+*** 466				
			meta548				
			meta588				

In the case of **A**, we observe the precocity and multiplicity of questions about meanings, driving early and irreversible critiques of *C2* and *C3* (and implicitly *C1*, which was not considered because the diagram was "meaningless") while a question posed by the interviewer and subsequent step forward (**hori**) led her to a firm and irreversible *C4* critique. The other inputs completed her reasons to be satisfied in the end, with retrospective critique of the previous teaching.

Table 5. Mapping **F**'s intellectual pathway

Int.'s main inputs	Quest.	Steps forward	*MCA* comments	C1	C2	C3	C4
					μ 96		
					μ 168		
					μ 199		
					χ 204		
					μ 212		μ 268
	γ 222	**hori** 268					α 284
		push 282				χ 288	
				χ 308	χ 372		
DDIA 347		**ddia** 368	***m+*** 368				
ANA 377		**ana** 404					χ 420
					μ 428		
			meta506				
			m$^+$**!** 506				
			meta 512				

In the case of **F**, there are fewer direct questions about meanings, with multiple attenuated critiques and to-and-fro in relation to *C2* and *C4*, although he was at ease with comprehension of the situation itself (**hori, push, ana**). There is great satisfaction at the end, particularly in relation to the dislocated diagram, even though the final formulation of his critique concerning *C2* remains attenuated.