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Research paper

Good student questions in inquiry learning

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Acquisition of scientific reasoning is one of the big challenges in education. A popular educational strategy advocated for acquiring deep knowledge is inquiry-based learning, which is driven by emerging 'good questions'. This study will address the question: 'Which design features allow learners to refine questions while preserving student ownership of the inquiry process?' This design-based research has been conducted over several years with advanced high-school biology classes. The results confirm the central role of question elaboration as an interactive process that leads from vague to complex and adequate. To make this happen, the inquiry process must extend over a long time, learners and teachers should share a knowledge improvement goal, and text produced by students should be structured by question–answer pairs addressing a single concept using authentic resources. Further features are discussion with peers, teacher feedback with respect to answer elaboration and conceptual differentiation, and finally, teacher guidance that should fade out in successive inquiry cycles to ensure student responsibility.

Keywords: inquiry; epistemic complexity; design-based research; question refinement; biology

Introduction

One persisting issue in science education is developing conceptual understanding rather than rote learning of facts or procedures. Inquiry-based science education (IBSE) has often been advocated for achieving that aim. Since 2006, we have been developing and refining an inquiry design implemented in advanced high-school biology classes.

In this contribution, we will focus on the processes of students' question refinement during investigation. We will pay particular attention to the use of resources, peer interaction and teacher intervention strategies, and how they interact to influence guidance of investigation and ownership of questions and in turn allow students to develop scientific understanding.

Question refinement in inquiry learning

In an inquiry-based learning (IBL) design, student-formulated questions are essential since they will guide the investigation (Hakkarainen and Sintonen 2002). Investigation does not automatically lead students to 'good' questions. Refining questions as understanding grows involves concept differentiation, subsumption and reconciliation (Ausubel 1963), which can be supported by writing processes (Klein 1999). Developing adequate conceptual knowledge requires students to formulate their own questions as well as understanding which kinds of question are appropriate. 'Good' questions are those that the community considers valuable and worth investigating (Kuhn 1972). In addition, research suggests that a shared knowledge improvement goal (Scardamalia and Bereiter 2006), iterative writing in a shared writing space and early discussion of questions could guide students from vague questions towards 'good' questions (Hintikka 1992).

The guiding role of authentic resources

We consider here that knowledge (accepted within a given social group) becomes scientific understanding (in the brain of an individual) to the extent that it has been justified in relation to data, discussed in relation to the hypotheses that found these measures,

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and the limitations of the claim discussed (Toulmin 1958). Of course, this definition is very challenging and full scientific understanding is probably out of reach in most education situations. However, this definition, and in particular its focus on justification processes, guided the development of our inquiry designs.

In science education, knowledge is mostly justified by the teacher's authority (Astolfi 2008). In the current biology paradigm, the central question is *explaining* the mechanisms underlying observed phenomena (Morange 2003). Therefore, adequate knowledge must be centred on explanations. In most cases, students are not given any opportunity to justify scientifically their understanding (Astolfi 2008; De Vecchi 2006), which therefore remains knowledge *about* science (Kuhn 1972; Rocard et al. 2006). If we want students to develop scientifically justified understanding, we have to achieve some form of authenticity in the justification process. Although education aims at developing understanding within each individual, exposing and confronting individual knowledge in construction to argumentation with peers can lead to improvement in conceptual learning (Osborne 2010), as we shall argue below.

We postulate a dialectic relationship between good questions and good resources. More authentic (*ie* closer to research) resources are needed to answer *good* questions, and guide towards *better* questions. Simplified resources answer simple questions and develop simple knowledge. This would imply that learners should be exposed to authentic and complex resources as soon as their understanding allows, rather than the usual practice of offering simplified knowledge. Indeed, educational material presented in schools tends to lose, through an inescapable process called didactic transposition (Chevallard 1991), the justification attributes that characterise scientific understanding (Bromme, Pieschl, and Stahl 2008).

We propose the name *centripetal conceptual force* for the guidance towards good questions that authenticity of resources provides. It helps to resolve a critical guidance versus devolution issue. On one hand, maintaining student ownership of the questions (Tabak et al. 1995; Bereiter 2002) and autonomy in the selection of resources (Rouet 2006) are crucial in inquiry. On the other hand, excessive or inappropriate guidance by teachers interfering with the questions investigated could lead to a loss of student involvement. Furthermore, exposing students to a great variety of experimental and bibliographic resources, to produce their own inquiry-supporting document, engages them in a process of evaluation, selection and processing (Rouet et al. 2011) that develops some scientific depth in the understanding that they acquire (Bereiter 2002; Scardamalia and Bereiter 2006).

Roles of teachers and peers

Presenting to peers and discussing these productions in a cooperative structure gives access to some form of argument (Johnson and Johnson 1989). Scientific understanding is tested and strengthened by being exposed to peer discussion. We consider that weaning students from teacher authority with respect to the justification process is an important step towards the acquisition of scientific reasoning. A first step is getting students to accept the responsibility of justifying their understanding towards their peers. Full scientific justification of even a single concept is clearly out of reach. However, justification by conducting experiments or by referring to authentic resources as a proxy for experimentation increases the degree of scientific grounding and more generally the quality of explanations. Of course, the use of academic resources refers mostly to the scientific authority of experts, embedded in these documents, but it dissociates scientific authority (resources) from pedagogic authority (teacher), and that could resolve the paradox of student autonomy and necessary teacher guidance in inquiry.

The research problem

The overall goal of this research (Lombard 2012) is to develop designs and test design rules leading students to in-depth scientific understanding in the information-dense environments of today's society.

The main problem addressed in this article is how to maintain student ownership of questions, necessary for their involvement in the investigation, while ensuring that these questions develop into investigation about complex mechanisms using appropriate resources, within the curricular boundaries. Teacher guidance must take unusual forms to ensure this paradoxical encouragement of autonomous development of ideas while ensuring understanding of adequate knowledge (Sandoval and Daniszewski 2004). We conjecture that clear separation of (1) scientific knowledge validation through resources and (2) the teacher's responsibility of maintaining objectives and assignment quality (Crahay 2006) could guide investigation towards adequate content while maintaining the student's implication.

A preliminary research question that we only briefly address asks:

1 Did students meet desired learning outcomes in line with the standard curriculum?

We will identify some key design rules that ensure both student ownership and adequate question refinement leading to adequate in-depth learning. With respect to these design rules, we investigated three sets of questions:

2 Question refinement: (1a) How did questions effectively guide investigation? (1b) How and when questions were conceptually refined?

3 Epistemic complexity: (2a) How does epistemic complexity increase? (2b) How can refinement (both questions and answers) be linked to authenticity of resources used? (2c) Class discussions and teacher's guiding role.

4 Duration: What time-frame is needed to implement an effective IBL design with a given class? More precisely, can we observe an evolution of epistemic complexity over the year, *ie* between the first and the last IBL modules?

We can then answer our main question:

5 Student ownership: How can we maintain student ownership of questions and yet ensure that questions evolve in the 'right direction'?

Methodology

We chose design-based research (DBR) (Design Based Research Collective 2003) as our research paradigm, (1) for ethical reasons (it offers students the best possible design during full-year research), (2) because it addresses 'phenomena that are contextually dependent or those that result from the interaction of dozens, if not hundreds, of factors. Indeed, such phenomena are precisely what educational research most needs to account for in order to have application to educational practice' (Design Based Research Collective 2003), and (3) because it is appropriate for an exploratory study aiming at identifiying important variables and conceptualising a radically new design.

Participants and curricular situation

The study was conducted between 2003 and 2010 in advanced high-school classes taking biology as the principal branch, totalling eighty-three students. The interventions lasted for most of the year (from August to April, when final examination preparation starts and student involvement shifts). The curriculum covered molecular biology, genetics and immunology.

Data collection

We analysed samples of learner productions in the wiki, administered questionnaires and conducted some in-class observations.

The evolution of four wiki productions produced by groups of three or four students on the same subtopic on humoral immunity was analysed in depth. Each of these four sample productions was taken from a different year and represented a typical volume. The length of the text length and number of question numbers were counted for each revision of the document (typically twenty-five to thirty-five). Question elaboration was established by comparing revisions of texts, and deduced from position replacement and logical links.

We then compared the evolution of epistemic complexity of all final productions (wiki articles) at the end of the first module, at the beginning and at the end of the immunology modules. Responses were rated for epistemic complexity using a four-point scale adapted from Zhang et al. (2007): unelaborated facts, elaborated facts, unelaborated explanations and elaborated explanations.

As there are no standardised examinations, an expert was called to establish the adequacy of the final versions of the same 4-year sample of wiki texts on humoral immunity with respect to curricular objectives and the biology paradigm. Classroom observations took place in 2003–04, 2004–05, 2005–06 and 2009–10 during a total of eighty periods.

Informal (email) follow-up questionnaires 1 year later (at university) were administered to all the students, including students from two previous implementations (2003–2010) (forty-three respondents out of eighty-three). They addressed representations about biological understanding, learning strategies acquired, the notion of science and the role of resources.

Results

Elements of the learning design

The learning design implemented a typical inquiry design (questions, investigation–experimentation, writing, discussion, question redefinition and cycling this process). This also can be described as a knowledge-building community of learners (Scardamalia et al. 1989), which is structured for cooperative learning (Buchs et al. 2008). Activities were scaffolded by a shared wiki in which students wrote their progressive understanding. Learners worked in groups of three or four. Early in the investigation process and close to the end, students presented their understanding to peers, leading to confrontation of understanding and question redefinition. Students' productions were assembled in a brochure critical for their preparation for important examinations, making it a very important document to them. An inquiry cycle lasted for 3–4 weeks, after which the class addressed a new chapter. In Lombard (2012) we identified twenty-seven design rules that, taken together, constitute a description of the design, and discussed their dependencies and relationships.

We want to stress that within this design-based research study we do not compare this particular design with a more traditional reference design. The aim is to confirm the adequacy of a design whose features are derived either from conjectures grounded in theory or by adjustment during the design cycles. This research collects and discusses data about the educational effects of design features. Of the twenty-seven design elements that could be adapted, and possibly be refined in other settings, we shall address four of these.

A first design rule states the importance of *getting students to express their ideas by writing them and presenting them to peers in order to create opportunity for sociocognitive conflict* (Buchs, Gilles, and Butera 2012) and knowledge building (Scardamalia and Bereiter 2006).

A second design rule stresses the crucial *importance of frequent feedback in students' writing*. This has been highlighted by others: 'Any arbitrarily assigned topic, with an error-hunting teacher as the sole audience, may do little for the writer, whereas a topic the writer cares about and an audience responsive to what the writer has to say are the essential ingredients for a profitable experience' (Bereiter 2002).

As a consequence of separating pedagogic and scientific authority, a related design rule states that teacher feedback does not correct errors, *but flags discrepancies within texts, between student texts and with authentic resources, effectively transferring scientific authority for validating to experiments and authentic texts*. We argue that this allows students to break free from the validation authority of the teacher, leading to more autonomy and, finally, to deeper understanding.

Another important design rule states that *text produced by students should be structured by series of question–answer pairs addressing a single concept*. We refer to this design rule as conceptual unicity of questions and answers. It is designed to keep the investigation efforts focused and lead to conceptual refinement. Such a strategy could be compared with the subgoaling principle in cognitive theories pioneered by Newell and Simon (1972).

Let us now examine results that answer the questions that we asked at the beginning.

1 Adequacy of the design with respect to curricular objectivess

We first established that the design allowed students taking biology as the principal branch to acquire adequate understanding for final examinations. Results averaged 5.1 out of 6 (N = 43), 6 being the maximum grade in the Swiss system. However, since examinations are not standardised, the grades cannot be taken into account. The expert's report indicated that adequate to very good knowledge of biological mechanisms was produced in the sample texts examined, and that the curriculum was well covered. In an open question of the post-secondary survey (eighteen responses), 89% of students considered that 'this course had well prepared them for university' and 11% had slight reservations.

Together with other data (in-class observer journals), these results suggest that students developed some in-depth understanding of the biological mechanisms involved.

2 Question refinement

Progressive refinement of questions and answers includes splitting and sometimes joining questions. We observed that applying the rule of *conceptual unicity of questions and answers* led to conceptual differentiation and subsumption in student productions. As student production in the wiki writing space grew, text contained more than one concept, outgrowing the initial question and addressing implicit new questions that were 'better'. This rule led to new questions being made explicit and refined during presentations and discussion with peers or after teacher feedback. This produced better organised text, differentiating the concepts and finally leading to elaborate explanations.

For example, the first question: 'What is humoral immunity?' became 'What causes antibody production?', then 'What are B lymphocytes and what is their role?', which led to 'What are memory and plasmocytes?' and 'How do T4 lymphocytes interact with B lymphocytes to activate them?', while another question appeared: 'Can B lymphocytes work without T lymphocytes?' The very vague and descriptive initial question generates an investigative process through which the questions become more precise, more explanatory (interactions between B and T lymphocytes) and therefore more adequate to the current biology paradigm. There was a move towards the structuring concept of T4–B interactions that cause double activation (Figure 1). It is noteworthy that the questions evolved during that phase through interaction of the students within groups and with texts but not with the teacher.

Other learner groups showed similar sequences over 2 days during a first phase of inquiry. The number of questions could be seen to increase rapidly (Figure 2). Later, the number of questions evolved at a slower pace while the total text length (Figure 3) steadily increased. We hypothesise that these phases are triggered by teacher-initiated activities. The initial phase (I), characterised by a burst of questions and mostly descriptive text, is transitioned to a second phase (II) by setting deadlines for presentation to peers and assessment of documents by the teacher.

Phase II is characterised by text development with few new questions, a slow increase in word count

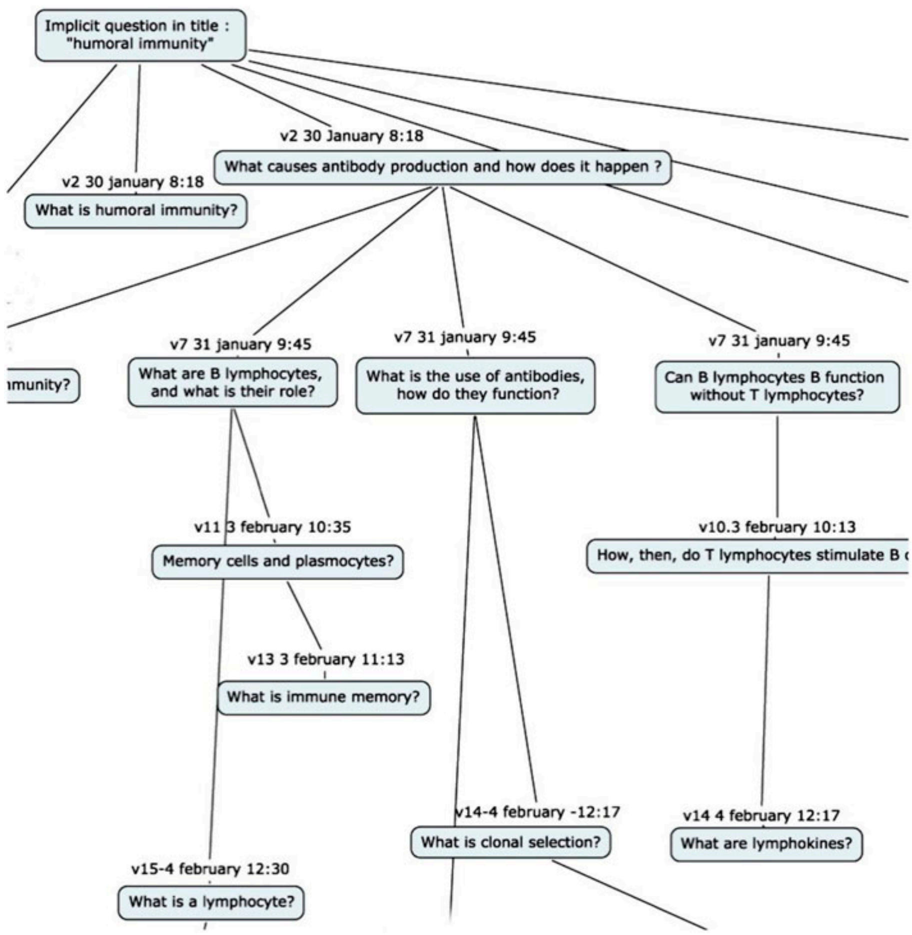


Figure 1. Sample of question elaboration. Questions were translated from French

and an increase in explanations (mostly unelaborated). We interpret this as a deepening of inquiry guided by the questions that emerged in phase I and which have been put into perspective during peer presentation and discussion. This phase lasts for about 2 weeks and could probably last indefinitely. It is transitioned to phase III by deadlines for a final presentation to peers, assessment of documents by teacher and final revision of the document. The final version is printed and is of critical use to students for revision before examinations. This phase is characterised by an increase in text length, a slight increase in question count and a strong increase in epistemic complexity.

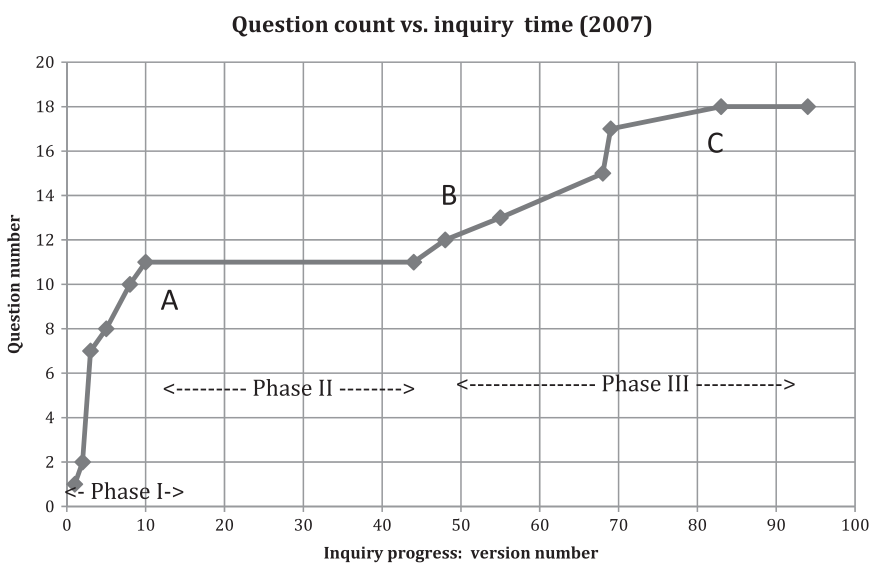


Figure 2. Example of question number during inquiry progression (year 2007). The roman numbers refer to teacher-initiated activities (A/C = assignment deadline and marking; B = peer presentation, discussion of findings and questions)

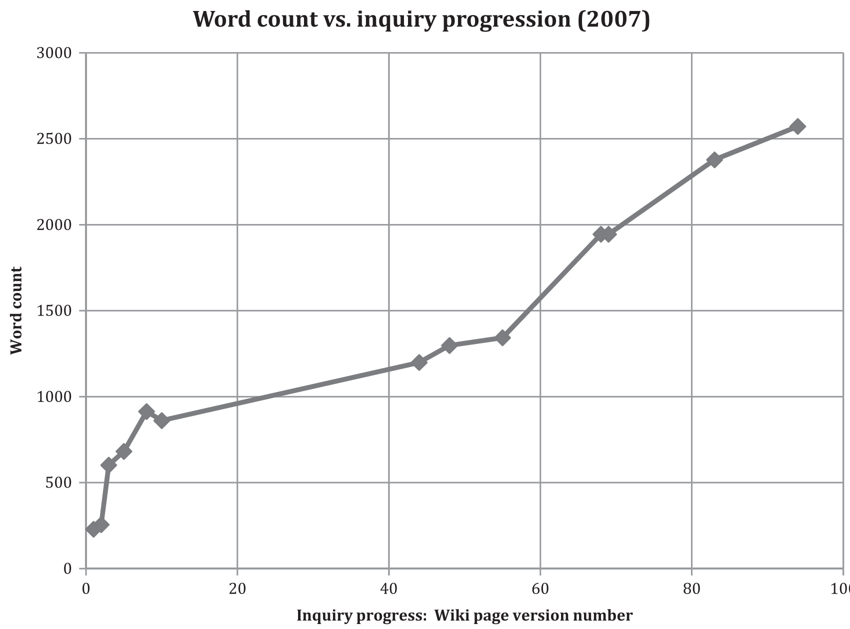


Figure 3. Example of word count during inquiry progression (year 2007)

To summarise, our results show a refinement from students' simple finalistic questions referring to descriptions towards elaborate questions leading to explanations of underlying phenomena.

3 Epistemic complexity

As the number of elaborate explanations grows relative to simple descriptive answers, epistemic complexity increases (Figure 4). Few elaborate explanations were found before a longer process into the investigation had taken place.

With respect to concept differentiation, we found that more authentic final answers could be traced to more authentic resources such as academic online books. Resources used became increasingly authentic, from simple online searches, through high-school textbooks, to academic online books. Students proved their capacity to find, select from overabundant resources and synthesise adequate knowledge by producing a document critical for peers in preparing their examinations. On average, in about 3 weeks, groups of three or four students produced 3171 words in the final versions. Let us recall that the expert judged content as adequate, although nearly none of it came from the teacher. We interpret this result as a good indicator of adequate student understanding.

Every year, the questions that structure the chapter (about the interactions of T4 and B lymphocytes, double activation, *etc*) were approached from different initial questions but finally addressed in a similar appropriate way. Teacher feedback took the form of flagging discrepancies within texts, between student texts and with authentic resources, ensuring that the students were aware of these. In some cases, another form of intervention was to provide experiments or resources to elicit questions when a whole part of the conceptual field had not been addressed. Therefore, most of the guidance towards the 'good' questions came from reading (more) authentic texts.

Other authors (*eg* Zabel and Gropengiesser 2011) have shown that there are many conceptual paths in evolution. Our results confirm this, but also that the structuring concepts of a field, embedded in the conceptual structure of documents, guides students in a manner that we name 'centripetal conceptual force'. Indeed, texts read by students to find answers to a simple question suggested many new questions, which were in line with the paradigm of the resource used. As an example, one group formulated the question as: 'How are the good types of lymphocytes activated, *ie* what is double activation?' See the original sample in Figure 5.

This fragment of student text explains how double activation relies on the antigen itself to ensure selection of specific cells for both types of immune response. It is noteworthy that the reference for this figure is in English (Janeway et al. 2001) and that French-speaking 19-year-old students overcame the language barrier to find an adequate answer to their question. Together with the amount of writing (about 300 words added per group of three or four students per week), this indicates an unusual level of involvement by the students.

The wiki data suggest that in-depth knowledge about explanations of the mechanisms of immunology is being produced by the students, *ie* that in-depth learning may have taken place.

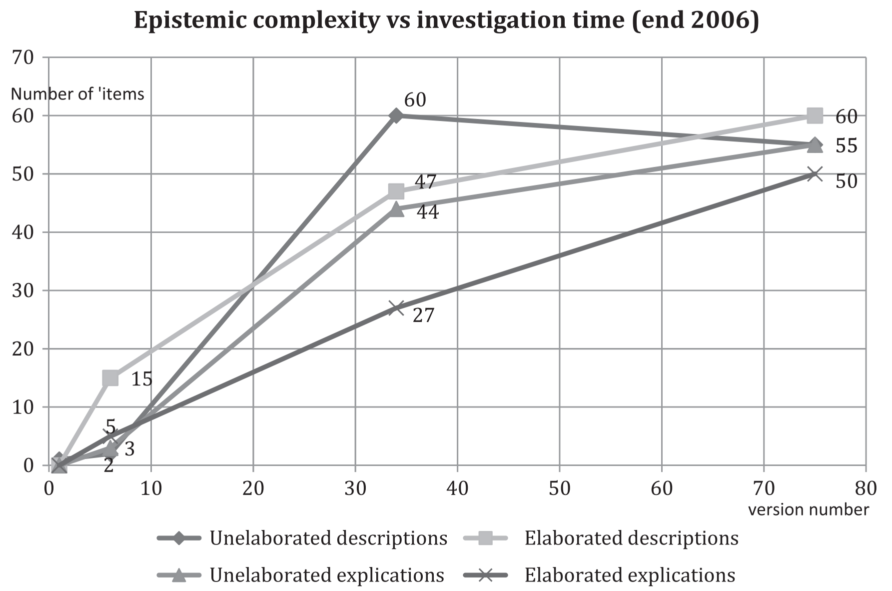
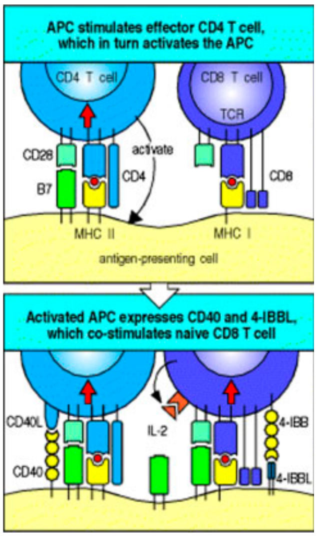


Figure 4. Example of increasing epistemic complexity

Student question :

How is the correct type of lymphocytes activated by cytokines, *ie* what is double activation?



Student commented figure from Janeway et al. (2001): Double activation. Certain Tc responses require Ta: Tc recognising antigens on weakly co-stimulatory cells can only be activated in presence of Ta linked to the same APC. This happens mainly by way of a Ta recognising an antigen on an activated APC inducing high levels of co-stimulatory activity on the APC, which in turn activates Tc to produce its own IL-2. *(Translated from French)*

Figure 5. Sample of content (elaborate explanation) produced by students in response to a complex question that appeared late in the investigation

4 Evolution of epistemic complexity over longer periods

Epistemic complexity was low at the end of the first investigation cycle of 3–4 weeks (Figure 6). After the final cycle at the end of the year, elaborate explanation represented more than a quarter of the 188 knowledge items produced.

In accordance with the literature (Furtak et al. 2012; Songer, Lee, and Kam 2002), we interpret these results as the time (months) needed for inquiry learning competencies to develop and produce educational effects (autonomously justified, deep relevant scientific knowledge). Even once mastered, inquiry needs some time before the complex questions can be addressed, as shown above.

5 Student ownership of questions

Our question was how to maintain student ownership of questions, necessary for their involvement in the investigation, while ensuring that these questions develop into investigation about complex mechanisms using appropriate resources, within the curricular boundaries. We found that: (1) questions could effectively guide investigation in inquiry, and student ownership could be maintained if pedagogic authority was separated from scientific authority; (2) questions were conceptually refined by students assuming responsibility towards peers for a share of knowledge, and confrontation with (more) authentic resources where scientific authority was found; (3) authenticity of the resources that students encountered and class discussions could guide refinement towards the structuring concepts of biology; and (4) the teacher's guiding role includes firm pedagogic authority with respect to objectives, assessments, criteria and deadlines, but not justification authority. The teacher should, rather, just indicate inconsistencies within the text or with authentic resources.

Discussion and conclusion

Taken together, the results suggest that student investigation can evolve towards 'good' questions embedded in the activities and texts of the paradigm, provided that some conditions are satisfied. These include iterative co-writing in a shared writing space of a meaningful document, early presentation and exposure of understanding to peers as opportunities for sociocognitive conflict, teacher feedback flagging discrepancies with authentic resources, progressive transfer of justification to students, and opportunities for confrontation with authentic resources.

Three interdependent overarching requirements could be abstracted from the design: (1) a shared goal of knowledge improvement in complex biology; (2) a responsibility of students for a share of the knowledge; and (3) confrontation with very diverse resources including most authentic resources as a proxy for experimentation. These rely on theoretical backgrounds, which are: knowledge-building pedagogy (Scardamalia and Bereiter 2002; Bereiter 2002), cooperative structure (Buchs et al. 2004; Johnson and Johnson 2009; Mugny et al. 2003) and authenticity of heterogeneous resources (Kuhn 1972; Colburn 2000; Yarden et al. 2009).

We found that one can rely on an IBL design for full-year biology learning of complex understanding of complex phenomena. Question elaboration is a long, interactive process from vague to complex and adequate. If implemented with enough time to develop fully, IBL can be an efficient learning design that can cover the curriculum in the standard duration and be relied on for preparing high-school high-stakes examinations.

Most of our design conjectures for inquiry learning are aimed at conceptual elaboration. They formulate the role and the interplay of iterative writing, authentic resources, question negotiation, peer presentation and discussion. The main instructional principles are: (1) teachers and learners must share a knowledge improvement goal; (2) text produced by students should be structured by question–answer pairs addressing a single concept; (3) the availability of authentic resources, discussion with peers and teacher feedback support answer elaboration and conceptual differentiation; and (4) teacher guidance should fade out in successive inquiry cycles i to ensure student responsibility.

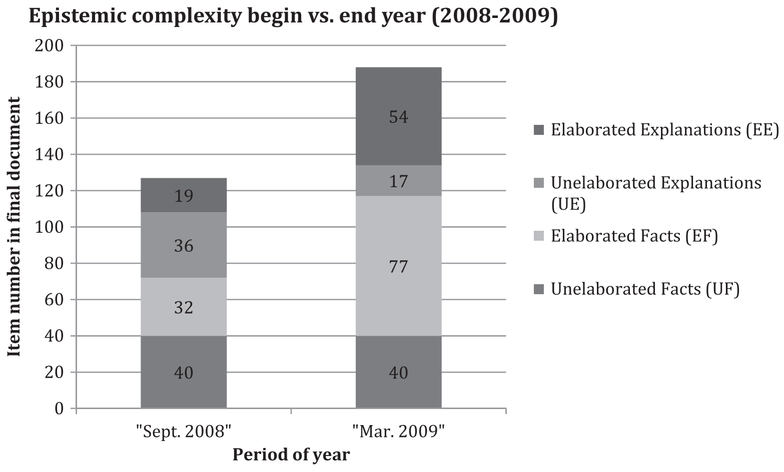


Figure 6. Epistemic complexity: comparison of final productions at the beginning versus the end of the year

Generalisability of this design may not be realistic. Some design rules from this design experiment could be generalised to other science education scenarios aiming to improve conceptual refinement. Since the design rules imply rather radical changes in teachers' status, their full deployment is probably not achievable in many settings. However, some could help in designing and guiding different interesting designs; for example, the rule that question–answer pairs must address a single concept could help to maintain focus in many forms of student investigation. The necessity for confrontation with heterogeneous resources with the aim to practise justification should be relevant in many other educational fields.

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