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Abstract

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A method to reveal fine-grained and diverse conceptual progressions during learning*

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\textbf{ABSTRACT}
Empirical data on learners’ conceptual progression is required to design curricula and guide students. In this paper, we present the Reference Map Change Coding (RMCC) method for revealing students’ progression at a fine-grained level. The method has been developed and tested through the analysis of successive versions of the productions of eight cohorts (N = 100 total) of high school biology students groups, involved in a year-long inquiry-based learning design. Concepts and causal links expressed in students’ gradually refined explanations of biological phenomena are charted onto reference model maps. Trends within variability in all cohorts are measured by a consolidated Prevalence Index (cPI) counting the occurrence of each item across all versions of the students’ explanations. Results of a case study presented reveal great variability in patchwork progressions. Learners’ diverse and often surprising conceptual paths challenge the view of learning as a linear process. For example, some items consistently appear later, thereby offering empirical evidence of slow spots that require attention. We discuss possible causes, educational implications, and show that our method offers crucial insight into the process of learning as it happens. We finally argue that RMCC also could become a follow-up tool for interested teachers.

\section{1. Introduction}

Pedagogies that demand a large degree of autonomy from learners – such as the heavily-promoted inquiry-based science learning (Bueno-Ravel et al. 2010) – are often associated with unguided exploration. This often causes difficulties to teachers (Capps and Crawford 2013). However, there is consensus across the pro-/anti-constructivist divide that strong instructional guidance is more likely to result in effective learning than minimal guidance (Hattie 2008; Kirschner, Sweller, and Clark 2006). The debate is about the nature of this guidance (Tobias and Duffy 2009).

According to Schwarz et al. (2012), modelling is central for developing and evaluating explanations of the natural world. Therefore, science learning is a process in which students’ naïve explanatory models of phenomena are progressively refined and more complex and better explanatory models are developed. A model is an ‘abstract, simplified, representation of a system that makes its central features explicit and visible and that can be used to generate explanations and predictions’ (101; after
Harrison and Treagust (2000). To guide effectively, student progression data is required. Much research analyses the knowledge present in classrooms and its transformations, in particular the large body of French research on didactical transposition (Chevallard 1991). More recently, Legitimation Code Theory (Maton 2013) assesses organising principles of knowledge in classroom practice, in terms of dimensions like their semantic ‘density’ and ‘gravity’. While knowledge explicitly presented clearly influences learning, the focus of this article is on assessing its effects: the resulting understanding by learners. Of course, it is impossible to directly assess the understanding in a learner’s mind, but researchers can analyse student productions as reflections of their understanding, without making assumptions regarding the psychological constructs considered (e.g. Bereiter 2002).

While in research models of different scope and relevance can coexist, in education a specific reference model is chosen as a learning goal for a given topic, and as such, it may not represent the best model according to researchers. In this study, we first discuss some assumptions about learning progressions and then propose a method to collect evidence about actual progressions of understanding. As an example, we analyse eight cohorts of a full-year inquiry design for high school students majoring in biology. We discuss the educational implications of this method and propose new research avenues.

2. Background and rationale

Any learning design organises, to some degree, the sequence of learner activities, often assuming that the sequence of knowledge presented automatically determines the conceptual progression. In research, but also in curricula and guidelines, the learning process is often considered to be linear and sometimes referred to as climbing a ladder. This underlying conceptualisation of learning as a linear trajectory has been debated, as some suggest that individual learners explore conceptual landscapes by different winding paths, drawing various individual trajectories (Zabel and Gropengiesser 2011). Both linear and winding path views assume that for every expert concept ‘B’ there is one or many paths from the simple naive concept ‘A’. However (diSessa 2002) even reject the conceptualisation of a path, with the argument that both naive and expert concepts are complex systems consisting of many interacting parts and that the expert concept could include modified and recombined elements from the naive concept (see Figure 1).

Research about Learning Progressions (LP) explores ‘successively more sophisticated ways of reasoning within a content domain that follow one another as students learn’ (Smith et al. 2006, 2). LPs do not imply linearity, and ‘it is not assumed that students’ progress is a single developmental trajectory. Rather, there may be several viable paths and the progress is likely more akin to ecological succession than to constrained lock-step developmental stages.’ (Duncan and Hmelo-Silver 2009, 607). Duncan and Gotwals (2015) suggest that patterns differ across students, creating multiple ‘messy middles’ in which no single path can be identified, but where constraints on learning might result in a predictable learning path. Discussion of developmental constraints probably begins with Bachelard (1947), who challenged the common view of learners as blank slates. He argued that learners have prior naive explanations of natural phenomena, which are quite satisfactory and resistant to change and therefore act as conceptual obstacles to new understanding. Later studies focused on changing naive models rather than eliminating misconceptions (e.g. Posner et al. 1982; diSessa 1988; Vosniadou 1994). More recent

![Figure 1. Winding path view (left) vs. gradual reorganisation of concepts (right). Note: Redrawn after diSessa (2002).](image-url)
research including fMRI suggests that naïve and expert models coexist in learners, and that learning involves activating and inhibiting coexisting models (e.g. Masson et al. 2012). Recently, Coley and Tanner (2015) argued that misconceptions may have common origins in intuitive cognitive construals; namely, teleological, essentialist, and anthropocentric thinking. These developmental constraints may have considerable influence on progressions and possibly delay the acquisition of some model items that are counter-intuitive.

LPs can be evidence-based sequences of comparatively large chunks of knowledge that are effective when applied to large numbers of learners. For example, Duncan, Castro-Faix, and Choi (2014) find that molecular genetics should be taught before Mendelian genetics. By contrast, we explore progression on a much finer-grained scale, i.e. single concepts and links within a model rather than within chapters. Moreover, our research also relies on evidence of learners’ progressions as they occur, rather than on assuming that curricular sequences always produce the same sequence of learning. The question remains whether ‘constraints are strong’ with ‘only a few, perhaps only one, path(s) that will maximise learning’ (Duncan and Gotwals 2015, 411) or whether there are ‘a large number of possible paths, and multiple messy middles’ (412).

Identifying students’ difficulties is problematic for teachers, especially in rapidly expanding biology fields such as genetics, bioinformatics, and immunology (e.g. Yarden, Norris, and Phillips 2015). Classic pre-/post-tests do not inform on the paths and patterns that students follow as they develop understanding of scientific phenomena. The focus of this study is an assessment method to reveal the progressions – during learning – of students’ understanding, as reflected by their productions. This paper’s goal is to (i) present a method to assess understanding as learning happens, (ii) apply it to study fine-grained conceptual progressions in one design chosen as an example, (iii) discuss the variability of the progressions to explore the ‘messy middles’ view and possible developmental constraints. We focus on three research questions:

**RQ1**: How can we describe and assess the conceptual progressions that students follow?

**RQ2**: Can this method identify time patterns for the mastery of concepts and causal chains in students’ conceptual progressions?

**RQ3**: Could the identified – possibly diverse – progressions and time patterns inform the discussion about developmental constraints and messy middles?

### 3. Research design and assessment method

The Reference Map Change Coding (RMCC) method allows to assess individual and collective progression. It was developed and tested with data collected from a long-term study (started 2006) of an inquiry learning design discussed elsewhere (Lombard and Schneider 2013). Below, we briefly introduce the context and the learning design and then present the method. We will demonstrate its usefulness through a case study, followed by a discussion.

The data was collected in advanced high school courses, with students who selected biology and chemistry as their main option, in Geneva, Switzerland. The study included eight classes, or cohorts, of 10 to 16 students, who were 18 to 19 years old, with a total of 100 students; the class compositions were pre-determined by the school administration. Successive topics in the curriculum were learned through inquiry cycles repeated throughout most of the school year, producing a very large data-set over the years. Students iteratively write their understanding of concepts in an online writing space (wiki), e.g. the explanation of a given biological mechanism, such as immune responses to pathogens. In an inquiry cycle that last approximately 3–4 weeks, student groups repeatedly revise their questions and answers and complete an increasingly detailed textual explanation of the biological phenomena being investigated. Changes in the recorded versions of their wiki writing reflect change in their progressively refined understanding. Groups of three to four freely peer-chosen students were assigned a topic by the teacher. Therefore we analyse group progression and do not have specific data on individual conceptual progressions. We analysed a selection of four topics: humoral immunity, cellular
immunity, allergy and cancer. We analysed a total of 2804 wiki page versions. Final revisions contain, on average, 3538 words (1519–6116 words). Two researchers analysed the data until interrater reliability exceeded 90%. Then, one researcher (M. M.) coded the rest of the data. Each group produced on average 88 versions of their explanations (min. 45, max. 163). Many modifications are minor ones (orthography, layout), but some include greater modifications, such as the addition of new concepts or new links between concepts.

To code learning progression as expressed in wiki pages, all revisions containing significant conceptual change are selected, i.e. page versions that introduced a new concept, or a new causal link between concepts. Modifications concerning only orthography, grammar or layout are not considered significant. Across all cohorts we found, on average, 8.8 significant versions for each topic (min. 5, max. 15). Significant versions are charted onto reference maps that formalize the learning goals (see Figure 2). Any item (concept or link) appearing in the text is marked on the map, thus allowing a visualisation of the progressive completion of the model. Maps are produced for studying student productions, they are not shown to the students. Coding time is about 4 to 6 h for a single group and topic.

The prevalence index (PI) of items allows analysing trends across cohorts. The PI is the mean count of model items appearing in each significant version of one group. For example, if the item B lymphocyte appears in six of ten significant versions, its PI is 60 (percent). The consolidated PI (cPI) computes the average across cohorts. Items present since the early versions in most cohorts receive a high cPI, while items appearing later (or never) exhibited a low cPI (see Figure 5 for the topic allergy). cPI is not a temporal measure per se, but since low indexes indicate items that typically appeared late, they do inform about possible time dependencies. To explore in more detail the variability of progressions, we computed the standard deviation (SD) of the PIs for each model item of each cohort against the cPI.

Figure 2. Concept-map like visualisation of the reference model of allergy that we used to chart conceptual student progression – not as a teaching tool.
4. Findings and comments from a case study

This section presents and comments three examples of analysis conducted with RMCC method on the topic of ‘allergy’ and how they can contribute to answer further research.

4.1. ‘Paths’ revealed: variable, mosaic progressions

Data from the eight cohorts revealed important variations in progression for all topics studied, i.e. student progress did not unfold along a single, linear path. While most students mastered the reference model at the end of the inquiry cycle, they went through a variety of unexpected paths. Students created little causal islands in distinct areas of the concept map and gradually connected them (Figure 3). These mosaic progressions did not match the structure of knowledge displayed in the resources that the learners consulted, nor the sequence of concepts and links that the teacher expected. These seemingly incoherent paths could be described as ‘jumps’ pieced together in a patchwork-like way.

4.1.1. Comments

The data that our method produced suggest that (at least in this inquiry design) students do not necessarily develop their understanding along the lines of the knowledge structures with which they are confronted, i.e. neither the reference model implicitly used by the teacher to guide them, nor the structure of the main references used by learners (Janeway et al. 2001).

Rather, the learners mastered the reference model through multiple variable and unpredictable jumps, and their progressions did not appear to obey strong developmental constraints. This conclusion fits well with the ‘messy middles’ (Duncan and Gotwals 2015) conceptualisation. However, analysis of final versions show that some forms of constraint, either in the development or in the design, such as the structure of assignments and teacher interventions, clearly affects progression that converge as most learners finally mastered most of the conceptual landscape.

4.2. Revealing intermediate models

Further analysis of these progression maps (Figure 3) offers empirical data to ground discussion of apparent gaps: they might not be perceived as gaps in the students’ minds. Rather, visually connecting the incomplete causal chains suggests that these explanatory models may make sense for the learners. For example, their first explanations of the allergy mechanism describe simple but satisfactory and possibly internally coherent models. ‘Allergies are reactions of our immune system to some substances (…). The causes of these allergies are called allergens’ (our translation of student text, revision no. 2). Once mapped onto the reference model, their incompleteness, while obvious, may obscure the limited explanatory power of the learners’ model at this stage of their progression (see Figure 4, top).

As an example, in their second significant version of the same text (revision no. 4), students express refined explanations: ‘After initial contact between the allergen and the immune system, macrophages stimulate an immune response, which causes the production of IgE antibodies by B plasma cells. These bind to mast cells’ receptors (…). When there is a second contact, the allergen binds to mast cells (on the IgE) and bridges between IgE molecules are created. Mast cells then release histamine, which produces allergic symptoms’. At this stage, the model that the students produced explains more of the observed phenomena, such as the effect of antihistaminic medication (see Figure 4, bottom). However, it still appears quite incomplete when mapped to the reference model. Our method revealed another eight significant versions produced by the students of this cohort as they progressed towards the reference model (only 2 versions illustrated here).

4.2.1. Comments

Observations of our data reveal that the learners’ erratic conceptual progressions should not necessarily be thought of as arbitrary completions of the pieces of a jigsaw puzzle. Our method shows ‘jumps’
Figure 3. Coded maps of three selected versions of a single student group’s text. Dark-coloured items are new in that revision; light-coloured items are already present in the previous versions. The figure shows the apparent unpredictability of the appearance of items in the students’ text (random-like ‘jumps’ rather than linear completion). Topic: Allergy, cohort 2016.
in completion of the reference model that may reveal different stages of internally coherent models. These steps in conceptual progressions are coherent with a gradual increase in the complexity and refinement of the learners’ models. This fits rather nicely with diSessa (2002)’s view of the reorganisation of the conceptual ecology (see Figure 1). This is also coherent with a conceptualisation of science as the progressive change of explanatory models (Schwarz et al. 2009). More research is needed to identify possible internal coherence in the intermediate productions our method revealed. Overall, the conceptual paths chosen by the students in each cohort remain fuzzy and partly predictable.

4.3. Trends in progressions: prevalence indexes

To synthesise the temporal dynamics of this progression and reveal possible trends, we computed the consolidated prevalence indexes (cPIs) of all items and charted them on concept maps for each topic. Some items tended to appear early in the students’ progression (high PI): for example, antibodies (cPI = 100), pathogen (cPI = 98), and allergic symptoms (cPI = 100). Other items tended to appear in later versions or sometimes never (low cPI). Sections of the models, such as the central branch in Figure 5 (the role of eosinophils in fighting parasitic helminths), showed low cPIs. These slow spots in the learners’ progressions can be explained as developmental or external constraints.

The variability of progressions – measured by the standard deviation (SD) of PIs across cohorts – was greater in the middle; i.e. some items appeared quite early in some cohorts and quite late in others. These statistical observations provide further evidence for many messy-middle, diverse progressions anchored between two more stable start and end points.
4.4. Discussion of low prevalence

The RMCC method first produced data about progressions and revealed that learning is messy, variable, patchwork-like, and that diverse patterns can lead to the same learning goals. Then, through PI analysis, we explored trends in time sequences for concepts and links across many years, and identified recurrent, late-appearing (low PI) items that focused attention on specific areas of the conceptual landscape.

The literature suggests at least three different types of causes for the low PIs that our method revealed: (1) knowledge field constraints such as conceptual dependencies; (2) internal constraints such as cognitive construals; and (3) design constraints such as shortcomings of the teaching design. We will now briefly demonstrate how the method can contribute to empirical analysis.

(1) Items of an explanatory model that rely on other concepts could be more difficult to grasp. For example, in the immune system, we assume that students must have a clear understanding of how T-cells and B-cells are activated before they can understand how their simultaneous
activation is necessary to produce plasma cells and memory B cells (double activation of B-lymphocytes). Indeed, the PI values computed from our data reveal that the items ‘memory B cells’ and ‘plasma cells’ never appeared before the model items that explained the activation of T-cells and B-cells. This gives empirical evidence to discuss if, and how, conceptual dependencies are constraining the progressions. This data opens new research questions and guides reflection regarding possible teacher interventions.

(2) Some low PI items can be interpreted as more difficult to grasp because intuitive thinking, hinders students’ scientific understanding of biological phenomena (Coley and Tanner 2015). For example, our method shows that the crucial concept of negative clonal selection in immunology appeared generally late in students explanations (PI = 30). This data could be explained by teleological naïve models acting as obstacles. Understanding clonal selection requires overcoming the powerful finalist preconception that the specific antibodies against a disease are produced because they are the ones needed. Contrary to that preconception, current scientific models explain that an almost infinite diversity of randomly-generated B-cells coexist in the body; some of them are activated to produce antibodies when randomly encountering their specific pathogen. More research is needed to confirm that this type of cognitive construal may play a role in the delayed appearance of several items in their productions.

(3) Our teaching design was applied over the span of ten years, during which scientific knowledge on topics such as allergy has substantially progressed, and curricular expectations have evolved. This was reflected in the guidance of students towards some questions rather than others and certainly constrains early explanations. Low PI’s produced by our method unearthed a possible case where the teaching design constrained the progression of learners.
The understanding of allergy as a collateral effect of a vital helminth-fighting pathway has been relatively recently recognised by researchers, and subsequently integrated relatively late by the teacher in his instruction. Thus, low PIs in some parts of the explanation could reflect an evolution of the teaching design, rather than other conceptual constraints.

Of course, low PIs could be caused by more than one type of constraint. By suggesting possible interpretations, we demonstrate that our method offers empirical data to determine areas of the reference model that require special attention. Moreover, these results suggest where further research is needed to explore the constraints that may exist and what inescapable messiness will remain.

5. Usefulness, limits and perspectives for the RMCC method

This first presentation of the RMCC method shows that it provides fine-grained data about students’ effective learning progressions. It has shown its usefulness for a variety of related analysis. Firstly, it offers rare insight into the many steps of student’s understanding as it progresses (RQ1). This data is crucial to teachers, educational authorities and researchers. The example design analysed with our method shows that time patterns for concepts and causal chains can be identified in students’ conceptual progressions (RQ2). Consolidated PIs over many cohorts offer data for research on model change over time (Schwarz et al. 2009). Furthermore, this method has shown its potential to reveal progressions and time patterns in order to inform the discussion about developmental constraints and messy middles (RQ3). Our method clearly pinpoints slow spots that require attention and anchors within empirical data the discussion of possible constraints and their interpretation (Duncan and Gotwals 2015). It calls for new research to distinguish external and internal constraints of low PI, late-appearing model items.

Results from our case study show diversity of progression and support the messy middle conceptualisation. Limits and inconsistencies in learners’ explanations – empirically shown as gaps in our visualisations – suggest that learners’ understanding goes through several steps, using different models before mastering the reference model. These results question pedagogical approaches that try to organise conceptual progressions in a single predetermined way, as well as the assumption that instruction sequences determine conceptual development. They suggest that guiding learners in a linear fashion should, at a minimum, take into account diverse understandings at any given moment. Our results also underscores the importance of bringing to the learners’ attention the limits of their models and helping them deepen their understanding, through feedback and questions from teachers and peers, for example.

Applying this method in a comparative study on the effects of different designs on learning progressions could contribute to the debate about how the messy middle interacts with the knowledge field, internal constraints, and design constraints, and how this should influence education.

RMCC does have limits and challenges. While this item-wise analysis of concepts and links mapped onto a reference map assesses the presence of expected causal links, it does not reveal other aspects of learner’s models such as social and cultural context, notion of science, etc. However, we believe that this methodology provides relevant data about the development of explanatory models in learners, independently of pedagogies. Furthermore, it could be used to research the learning effects of various types of guidance (Tobias and Duffy 2009). Obviously, traces of student productions at multiple stages of their learning are required, but with increasing use of technology-supported learning designs, opportunities for such traces are becoming frequent. In this particular collaborative design we analysed progressions of groups of three to four students, which may differ from individual progressions. However, this is not a limit of our method, which can also be applied to individual learning progressions.

Creating the reference map and coding require domain knowledge or a collaborative effort. Mapping and computing indexes for research purposes are as time consuming as other structured qualitative method. Our experience with pre-service teachers suggests that using reference maps for follow-up is realistic. Maps can be shared, coding reliability is less important, and the teacher can choose to
examine less versions. We believe that the required coding effort is equivalent to the one needed for structured feedback, e.g. evaluation rubrics. But let us recall that in inquiry learning, maps should not be shown to the student. Instead they should help the teacher ask questions and point out elements in the students’ texts that need work. They could also be used to further assess if and how specific interventions are useful in developing the reference model, and – with imaginative new ways of retrieving more expressions of learners’ models – could allow research on threshold concepts (Meyer, Land, and Baillie 2010). For teachers and instructional designers, the fine-grained analysis allowed by the RMCC method offers important empirical data to guide learning as it progresses, design instruction, and opens fascinating avenues of research into conceptual change and the interplay of constraints and variability.

Disclosure statement

No potential conflict of interest was reported by the authors.

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